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**NONDESTRUCTIVE EVALUATION OF
CERAMIC CANDLE FILTERS**

by

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EXECUTIVE SUMMARY

Nondestructive evaluation (NDE) techniques have been used to reduce the potential mechanical failures and to improve the reliability of a structure. Failure of a structure is usually initiated at some type of flaw in the material. NDE techniques have been developed to determine the presence of flaws larger than an acceptable size and to estimate the remaining stiffness of a damaged structure (Chen, et. al, 1995). Ceramic candle filters have been tested for use in coal-fueled gas turbine systems. They protect gas turbine components from damage due to erosion. A total of one hundred and one candle filters were nondestructively evaluated in this study.

Ninety-eight ceramic candle filters and three ceramic composite filters have been nondestructively inspected using dynamic characterization technique. These ceramic filters include twelve unused Coors alumina/mullite, twenty-four unused and fifteen used Schumacher-Dia-Schumalith TF-20, twenty-five unused and nine used Refractron 326, eight unused and three used Refractron 442T, one new Schumacher-T 10-20, and one used Schumacher-Dia-Schumalith F-40. All filters were subjected to a small excitation and the dynamic response was picked up by a piezoelectric accelerometer. The evaluation of experimental results was processed using digital signal analysis technique including various forms of data transformation. The modal parameters for damage assessment for the unexposed (unused) vs. exposed (used) specimen were based on two vibration parameters: natural frequencies and mode shapes. Finite Element models were built for each specimen type to understand its

dynamic response. Linear elastic modal analysis was performed using eight nodes, three-dimensional isotropic solid elements.

Conclusions based on our study indicate that dynamic characterization is a feasible NDE technique in studying structural properties of ceramic candle filters. It has been shown that the degradation of the filters due to long working hours (or excessive back pulsing conditions and high temperature transient) could be reflected from the shift of vibration frequencies. These shifts are due to changes in structural properties such as stiffness, which are directly related to the Young's modulus of the candle filters. Further studies are necessary in implementing and verifying the applicability of dynamic NDE characterization methods for actual in-situ conditions, and in establishing a systematic testing procedure for field applications. Also investigations on the filter's natural frequency due to the effect of dust cake or due to the change of boundary conditions may provide insight as to how the filter will perform in the field.

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CHAPTER I

INTRODUCTION

1.1 GENERAL REMARKS

To expand the utilization of U.S. coal reserves, it is necessary to develop an effective and economical coal-fired power generation technology. Advanced, coal-fired power generation systems use a combination of a steam turbine and a gas turbine. It is necessary to filter coal ash from high-temperature, high-pressure gas streams to protect the gas turbine from erosive damage. In general, process conditions may include, temperatures up to about 1500 °F with pressures up to about 300 psi, and potentially corrosive components in the gas stream (Bishop and Goldsmith 1994). The filtration medium is formed from ceramic materials and normally used in the form of candles, which are cylindrical tubes with permeable walls. One end is closed with a cap of the same material and the other end is open. These have proven to be effective filters for the ash laden gas streams, and therefore, ceramic candle filters play a key role in advanced coal-fired gas turbine technology (Lippert et al. 1994).

The ceramic candle filters have been used under high pressure and extreme thermal cyclic loading. Breakage of ceramic filters can be attributed to overheating, thermal shocks from back pulsing, and excessive pressure drop (Huynh et al. 1998). Crack growth is found to be generally originated from the internal diameter surface implying that thermal fatigue has occurred due to the contact with cold pulse cleaning gas (Alvin et al. 1994). Strength degradation and crack growth of alumina/mullite and

clay bonded silicon carbide filters, after being used in the demonstration plants have been reported (Spain and Starrett 1997; Alvin et al. 1998).

In recent years a significant amount of efforts have been devoted to analyze the performance and characterization of ceramic candle filters (Alvin et al. 1998). Studies were also conducted to develop more durable filter elements by optimizing material properties regarding to mechanical, chemical and thermal resistance (Schulz and Walch 1998). Destructive and nondestructive tests have been used to describe physical, mechanical and thermal properties of the filters and to relate these properties and behaviors to in-service performance (Pontius and Starrett 1995; Kamiya et al. 1998; Spain and Starrett 1998; Chen and Kiriakidis 1998). Nondestructive tests have been conducted on different filter materials to identify the structural properties of the ceramic candle filters (Chen and Parthasarathy 1996). Chen et al. (1997) has indicated that vibration frequency shifts of the used filters were observed and can be used to assess the level of degradation of the filter.

This report is focused on the development and application of a nondestructive evaluation technique to inspect new and used ceramic candle filters and to describe the relationships between the candle's vibration response and its structural properties. The study includes both nondestructive testing using vibration method and numerical analysis. A total of 98 ceramic candle filters and 3 composite were evaluated. 72 filters were virgin (unused filters) and twenty-nine were used at different sets of exposure times at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama. The structure's geometry, distribution of mass, stiffness, and boundary

conditions are factors that influence the dynamic behavior of a structure. Understanding its dynamic behavior, which is defined by a discrete number of natural frequencies and corresponding mode shapes, the mechanical properties of a structure can be determined (Chen et al. 1995). With the proposed nondestructive evaluation technique, repeated inspection of a given structure over a period of time can be made to ensure the integrity of the structure.

Finite Element Analysis and theoretical investigations are also conducted to confirm the experimental results. The ceramic candle filters tested are classified in four different groups depending on their brand name, namely Coors P-100A-1, Refractron 442T, Refractron 326, Schumacher TF-20, and Schumacher F-40. Discussion on vibration signatures, material properties and structural degradation levels due to different operating hours are presented. A modal strain energy procedure has been studied and can be used to detect a damaged section in a filter that has been exposed to extreme conditions.

1.2 OBJECTIVES

The present research is focused on the development of an effective non-destructive evaluation technique based on dynamic characterization to evaluate the relationship between changes in the vibration frequencies of ceramic candle filters and different levels of damage. This study aims at enhancing inspection process during power plant annual maintenance shutdowns. The objectives of the present study are:

- Establishment of the vibration signatures of new ceramic candle filters and used filters with varying degradation levels due to different operating hours.
- Development of an effective non-destructive evaluation technique to predict the remaining useful life of ceramic candle filters.
- Study of various factors involved in the establishment of the vibration signatures.

1.3 SCOPE

This report describes the detailed study of nondestructive evaluation (NDE) of virgin and used candle filters using the dynamic response. The study includes both vibration testing method and numerical analysis. A total of 98 ceramic candle filters, which were manufactured by Pall Vitropore Inc., Coors Inc., and Schumacher Inc, have been tested. Three advanced ceramic filters have been also tested. The ceramic filters were tested at different sets of exposure times at the Power Systems Development Facility (PSDF).

This report is divided into 6 chapters. Literature review is described in Chapter 2. Chapter 3 addresses the structural properties of the new ceramic candle filters. Chapter 4 shows the results on the structural deterioration of the used ceramic candle filters. The conclusions are stated in Chapter 5 and the recommendations for future studies are listed in Chapter 6. Appendix A shows the frequency response function in ten locations for one typical filter. Vibration frequencies for all new ceramic filters are presented in Appendix B. Appendix C shows vibration frequencies for the composite filters. Appendix D shows pictures of some ceramic filters tested.

CHAPTER II

LITERATURE REVIEW

2.1 HOT GAS FILTER SYSTEM

The Westinghouse barrier filter design consists of stacked arrays of filter elements supported from a common tube-sheet structure. Each of these arrays is formed by individual candle elements attached to a common plenum section. Figure 2.1 shows a sketch of the Westinghouse candle filters system used at PSDF (Galloway and Hendrix 1997). All the dirty gas filtered through the candles within a single array is collected in the plenum section and is discharged through a pipe to the clean side of the tube-sheet structure. Each array of filter elements is cleaned from a single pulse (pulse pressure of about 565 psi) nozzle source. The individual arrays are stacked vertically from a common supporting pipe, forming a filter cluster. The cluster is then supported by a high alloy tube-sheet structure with an expansion assembly that spans the pressure vessel and divides the vessel into “clean” and “dirty” gas sides. The cluster holds one plenum with 36 candles in the upper part and one plenum with 55 candles in the lower part. The cluster attaches to the tube-sheet structure by a specially designed split ring assembly. The plenum discharge pipes, ducting the filtered gas to the clean side of the tube-sheet structure, are contained within the cluster support pipe and terminated at the tube-sheet structure (Bruk et al. 1995). Typical operating conditions of this hot gas filter system at PSDF are plenum temperature up to 1375°F and system pressure up to 210 psi.

Figure 2.1 Westinghouse Barrier Filter – Hot Gas Cleaning System (Galloway and Hendrix 1997, with re-sketch).

2.1.1 Ceramic Candle Filters

Ceramic filter devices, are tubular in shape, and are made from ceramic particles and fibers that are bonded to form a porous structure. These devices have been shown to be basically absolute filters on ash materials (Alvin et al. 1994), and can be operated at relatively high temperature with acceptable pressure differential and are cleanable by simple reverse pulse-jet methods. Gas temperature and allowable pressure differential affect the tube sheet material, the thickness, the method of suspension, and the kind of ceramic to be used for filter elements. The feed gas chemistry and the ultimate corrosive nature of the feed gas also affect the choice of ceramic material for filter elements (Zievers et al. 1997).

Laboratory and field evaluation of these materials are being conducted to compare their respective chemical and thermal stability for Integrated Gasification Combined Cycles and Pressurized Fluidized Bed Combustion applications (Alvin et al. 1993). Clay-bonded filters (Schumacher and Refractron) and alumina mullite (Coors) filters have shown to be susceptible to thermal micro-crack during pulse cleaning process (Pontius et al. 1994). The choice of ceramic material and supplier can affect performance of coal-fired gas filter systems. A decision must be made as to what minimum tests should be performed to satisfactorily determine the suitability of products for process application and what percentage of the product should be tested.

2.2 NONDESTRUCTIVE TESTING

Nondestructive tests on new ceramic filters have been conducted to evaluate structural integrity and the material properties, such as stiffness (Chen et al. 1997). Also, they are being conducted to characterize and to compare their properties and to establish the vibration signatures at varying degradation levels due to different operating hours (Chen and Kiriakidis 1998). Recent advances and new technology in the field of digital electronics and computers have made the structural engineers adopt NDE methods for the analysis of structures more rapidly (Sami et al. 1994). NDE embraces all test methods for the inspection of the significant properties of materials, parts, or structures, which do not impair the product's serviceability. These NDE methods are in worldwide usage for detecting imperfections such as deformations of structure and presence of cracks (Venkatesh 1990), to determine structural properties (Chen et al. 1995), and to measure geometric characteristics such as the thickness of a structure. NDE methods have been chosen because repeated checks of a given specimen over a period of time can be made. In this way, the rate of service damage and its correlation with failure may be established clearly.

Tests like radiography, spectral acoustic, and mercury porosimetry were conducted to determine mechanical properties such as bulk density, open porosity, and sonic velocity on ceramic filters (Spain and Starrett 1994). The tests were performed on three candidate filter materials – Refractron SiC, Schumacher SiC TF40, and Coors alumina/mullite. The results on the unused Coors alumina/mullite filters showed that the average bulk density was 1.67 gr/cm³. The result on virgin Schumacher F40 and

Refractron filters showed that the first one has higher average bulk density value than the second one has (1.88 gr/cm^3 and 1.77 gr/cm^3 , respectively).

The knowledge of the dynamic characteristics of any structure is essential to monitor and control the vibration levels and also to ensure efficient and safe performance of these structures. The dynamic responses of the structure are correlated with stable and measurable parameters that vary with damage. A feasibility study has been conducted in the past few years to establish the dynamic characterization technique as a viable technique for ceramic candle filters (Chen et al. 1996).

Chen and Parthasarathy (1996) used dynamic characterization to determine the ceramic candle filter material properties. The tests were performed on one Refractron and on 11 Schumacher F40 ceramic candle filters. The 11 Schumacher F40 filters were classified into two different groups. The first group was composed of those filters that were used for 420 hours (4 filters) and the second group constitutes those filters used for 1705 hours (7 filters). The results showed that the elastic modulus for the unused Refractron was 6.88×10^6 psi. The average elastic modulus for the Schumacher F40 used 420 hours was 5.3×10^6 psi and for the one used 1705 hours was 4.9×10^6 psi. These results for used the Schumacher F40 indicate that after the filters were used for 1285 hours the Elastic Modulus decreases in 8%.

2.3 IMPACT EXCITATION

A simple shock (Broch et al. 1986) may be defined as a transmission of kinetic energy to a system which takes place in a relatively short time compared to the natural

period of oscillation of the system. In the impulse vibration testing technique, the structure is excited by striking it with an instrumented impacting hammer, in order to generate a short duration force. For a full range modal study, the impact load can be applied at several locations and the responses measured at a single location, or vice versa. The measurement of the response of the structure to this shock (impulsive load) can be measured using geophones, velocimeters or accelerometers. The responses obtained are the results of the superposition of various natural vibration modes of the structure. The data collected in the time domain can then be transformed into frequency domain and processed into vibration frequencies and mode shapes.

Impact testing is frequently used on small structures or components of large structures. Allampalli (1992) and Chen et al (1995) conducted impact testing on a laboratory specimen as a means of damage assessment in reinforced concrete bridges and steel bridges, respectively. The specimens showed decreasing of fundamental frequencies, which were related to the increasing damaged levels. Venkatappa (1997) compiled in his work some of the most recent testing methods in bridges, using the impact techniques.

2.4 FINITE ELEMENT MODAL ANALYSIS

Finite Element Method (FEM) has long been a fertile research field in computational mechanics. It has also been increasingly used as a tool for numerical experimentation. Due to the improvement of computers, FEM has now become an important structural analysis and design tool.

Jaleel and Sundararajan (1993) developed a plane strain finite-element model to study the elastic propagation and scattering of waves in general anisotropic media. They conclude that simulation can play an important role in understanding the wave propagation phenomenon, and help in the planning of NDE experiments in such complicated media as orthotropic plates. Venkatesh (1990) and Venkatappa (1997) used finite element model to investigate the changes in modal properties due to damages on a simple metallic structure. The results show that the correlation between the numerically obtained modal properties and the experimentally determined properties was good. Calculation of the strain energy distribution on the modal data obtained from both experiment and FEM analysis can be used to locate damages. The strain energy damage detection procedure has been worked successfully in detecting damage location and crack length of metal specimens (Kam and Lee 1994; Venkatappa 1997).

2.5 THEORETICAL ANALYSIS

While the experimental techniques for vibration testing are well developed (Ewins 1985), the interpretation of the measurement is far from being unique; presently, several aspects are still unsettled (Friswell and Penny 1997). Hearn and Testa (1991) used a sensitivity analysis to relate damages in a structure to the changes of natural frequencies. This method was found to be suitable where damage affects a single member of a skeletal structure, but not structures with plates or shell elements, where the vibration responses are affected by geometrical parameters.

Despite of the difficulties, good results from structural identification analyses were obtained in some cases, for example simple beams (Liang et al. 1992). Usually these studies concern simple structures where the theoretical model can well describe the experimental circumstances. Venkatesh (1990) used two different simplified analytical models (beams on an elastic foundation with different boundary conditions) to relate the vibration frequencies resulting from experimental investigations on post-tensioned rods in stressed timber systems.

In order to confirm the natural vibration frequencies obtained experimentally and to evaluate the accuracy of the testing method, two theoretical beam equations have been used in this study. The Bernoulli-Euler and the Timoshenko beam theory is summarized in Chapter 3.

The natural frequency of a beam ω , for the different combinations of boundary constraints and modes from the Bernoulli-Euler theory, can be expressed using the following formula:

$$\omega_n = \frac{C_n}{l^2} \sqrt{\frac{EI}{m}} \quad n = 1, 2, 3, \dots \quad (2.1)$$

where C_n is a coefficient that depend on the boundary constrains, E is the Young's modulus. I is the moment of inertia about the cross-section. l is the total length of the beam, n is the mode number, and m is the mass per unit of length.

Table 2.1 The First Five Coefficients for the Calculation of Vibration Frequencies (Graff et al., 1975).

Boundary condition	C ₁	C ₂	C ₃	C ₄	C ₅	C _n n > 5
Clamped-free	1.875	4.694	7.855	10.996	14.137	$(n - 1/2)\pi$
Pinned-pinned	3.142	6.283	9.425	12.566	15.708	$n * \pi$
Pinned-free	3.927	7.068	10.210	13.352	16.493	$(n + 1/4) \pi$
Free-free	4.730	7.853	10.996	14.137	17.279	$(n + 1/2)\pi$

It can be seen from equation 2.1 that changes in stiffness and/or mass will result in changes of natural frequencies for a specific structure. Defect or deterioration in a structure are characterized by the reduction in stiffness, which is usually much greater than the influence from changes in the structure's mass. Therefore, the change in natural frequency is directly related to structural damage.

CHAPTER III

STRUCTURAL PROPERTIES OF NEW CERAMIC CANDLE FILTERS

3.1 INTRODUCTION

This chapter presents dynamic characterization tests aimed at identifying the structural stiffness of new ceramic candle filters. A total of sixty-nine new ceramic candle filters have been tested nondestructively. All filters were subjected to an excitation force and the response was picked up by an accelerometer in a free-free boundary condition. The experimental results were evaluated using digital signal analysis to obtain the frequency response functions and vibration mode shapes of each filter. Finite element models were built to calculate the filter's dynamic response. Results from this study indicate that the vibration signatures can be used as an index to quantify the structural properties of ceramic candle filters. Three fiber ceramic composites filters were also tested following the same procedures as for the ceramic candle filters.

3.2 EXPERIMENT

The modal testing experimental setup for the ceramic candle filters (Figure 3.1) consists of excitation, sensing, and signal analysis. The instrumentation involved in the testing are an impact hammer, an accelerometer, two battery-powered signal conditioners, and a digital oscilloscope. The filter specimens are tested individually.

Each candle filter is weighed and the dimensions are measured before beginning the testing procedure.

As shown in Figure 3.1, the candle filter was freely suspended by its open end (head) using elastic tubes tied at the top of a rectangular frame, simulating a free-free boundary condition. The filter is subjected to an excitation using an impact hammer, and the response is picked up by an accelerometer. The accelerometer is placed perpendicular to the filter surface using hot melt glue at $0.55 L$ measured from the open end, where L is the length of the candle filter. Hammer blows are given at ten impact locations, beginning at one-tenth from the filter head and following every $L/10$ until reaching the bottom (L) of the filter. Each impact blow is performed as normal to the filter surface as possible. The time domain waveform from both the impacts and the acceleration responses are stored in a digital oscilloscope and then processed using signal processing software. This procedure is repeated three times at each impact point for averaging purposes.

The sampling rate used is $20 \mu s$, with 4000 data points stored in each time history, which gives a frequency resolution of 12.5 Hz. This resolution is not adequate for accurate signal processing in the frequency domain. Hence, 32768 data points are artificially added in the time history before transferring into the frequency domain, as a result, a frequency resolution of 1.36 Hz is achieved.

Fast Fourier Transform (FFT) is performed on the signals to get the Frequency Response Function (FRF) (Ewins 1985). A typical FRF plot is shown in Figure 3.2. As shown in this figure, the FRF shows a plot with various peaks that correspond to

the natural frequency of vibration in different modes. The first eight flexural vibration modes, covering a frequency range up to about 3100 Hz, are obtained. From the FRF plots the frequency and amplitude values are noted and the mode shapes are constructed. The frequencies obtained are averaged to minimize experimental errors arising from improper impacts.

3.3 TEST SPECIMENS

Ceramic candle filters are tubular in shape and are made from ceramic particles or fibers. The ceramic filter has been shown to be an absolute filter on ash materials (Lippert et al. 1995). These filters can be operated at relatively high temperature with acceptable pressure losses, and are cleanable by simple reverse pulse-jet methods. The ceramic candle filters tested are grouped by their product name: a) Coors, b) Refractron, and c) Schumacher TF-20. Table 3.1 shows the sixty-nine new filters that were tested. The filter specimens tested are described as follows:

a) Twenty-four new Schumacher TF-20 clay-bonded SiC filters: The Schumacher TF-20 candle filters tested are from three different batches, which are the 324H, the 344E, and the 379H series. These filters consist of silicon carbide grains that are bonded together via a silica-rich binder phase, and have an aluminosilicate fibrous membrane coating (Lippert et al. 1994). The nominal length for these filters is 1.52 m (59.8 in), with an outer diameter of 60 mm (2.36 in) and inner diameter of 40 mm (1.57 in). The wall thickness along the length is 10 mm (0.39 in).

b) The new Refractron clay-bonded SiC filters tested are divided in two groups, which are Refractron 326 and Refractron 442T. Twenty-five Refractron 326 and eight Refractron 442T filters were tested. The structure of these elements is mainly a coarse-grained silicon carbide (SiC) bonded by a clay-based binder. The elements are provided with a fine-grained SiC outer skin that serves as the filtration surface (Spain and Starrett 1994). The nominal dimensions of both groups of filters are 1.5 m (59.25 in) long, 60 mm (2.36 in) outer diameter and 40 mm (1.57 in) inner diameter. The wall thickness along the length is 10 mm (0.39 in).

c) Twelve new Coors P-100A-1 alumina/mullite filters: The porous alumina/mullite filter matrix consists principally of mullite, which co-exists within an amorphous phase that also contains anorthite and corundum. This Coors alumina/mullite filters does not have an external membrane or coating. The nominal dimensions of these filters are 1.51 m (59.65 in) long, 60 mm (2.37 in) outer diameter and 41 mm (1.62 in) inner diameter. The wall thickness along the length is about 9.5 mm (0.37 in).

The advanced ceramic filters tested are one 3M-oxide, one Dupont-Lanxide and one McDermott. The 3M 8004 ceramic composite filter is 1.50 m (59.31 in) in length and has an outer diameter of 60 mm (2.37 in) and an inner diameter of 58 mm (2.28 in). The Dupont-Lanxide 641 filter is 1.52 m (59.8 in) long, it has an outer diameter of 60 mm (2.37 in) and inner diameter of 46 mm (1.81 in). The wall thickness along the length is 7 mm (0.28 in). The dimensions of the McDermott 8-130-1 filter are 1.53 m (60.20 in) long, 60 mm (2.37 in) outer diameter and 50 mm (1.97 in) inner diameter. The wall thickness along the length is 5 mm (0.20 in).

3.4 THEORETICAL ANALYSIS

The modal frequencies obtained experimentally are compared to theoretical calculated frequency values to study the accuracy of the testing method and to study the vibration behavior of the candle filter in comparison with the fundamental beam vibration. Two theoretical beam equations have been used in this study. In both cases, the filter is assumed to have uniform properties along the length. The equations used are the Bernoulli-Euler beam equation and the Timoshenko beam equation. Chen and Parthasarathy (1996) used the Bernoulli-Euler beam equation to compare with the experimental results.

The transverse vibration of a beam is analyzed with free-free boundary conditions. The free-free boundary conditions are defined as

$$\left(\frac{d^2 Y}{dx^2} \right)_{x=0} = 0 \quad \left(\frac{d^3 Y}{dx^3} \right)_{x=0} = 0 \quad \left(\frac{d^2 Y}{dx^2} \right)_{x=l} = 0 \quad \left(\frac{d^3 Y}{dx^3} \right)_{x=l} = 0 \quad (3.1)$$

The Bernoulli-Euler (B-E) beam theory solution for the candle filter, which considers the elementary case with homogeneous and constant material properties, can be expressed as:

$$EI \frac{\partial^4 y}{\partial x^4} + m \frac{\partial^2 y}{\partial t^2} = p(x, t) \quad (3.2)$$

This assumption is valid since the transverse dimensions of the filter are sufficiently small compared to the length of the filter. The derivation of equation (3.2) using the specified boundary conditions gives the natural vibration frequency, ω , for the different modes, n (Graff 1975).

$$\omega_n = C_n \sqrt{\frac{EI}{mL^4}} \quad (3.3)$$

where, C_n is the coefficient that depends on the boundary constraints, E and m are the candle filter's Young's modulus and mass per unit length, respectively. I is the moment of inertia of the filter's cross-section and $P(x,t)$ is the load per unit length.

The basic equation of the Timoshenko beam theory applying to the ceramic candle filter (Chen and Kiriakidis 1998), considering the rotary inertia and deflection due to shear, can be expressed as:

$$EI \frac{\partial^4 y}{\partial x^4} + m \frac{\partial^2 y}{\partial t^2} - rI \left(1 + \frac{E}{k'G} \right) \frac{\partial^4 y}{\partial x^2 \partial t^2} + \frac{r^2 I}{k'G} \frac{\partial^4 y}{\partial t^4} = 0 \quad (3.4)$$

In the above equation, the third and fourth terms correspond to the rotary and shear effects. k' is a numerical factor that depends on the shape of the cross section (Cowper 1966), A is the cross sectional area, G is the shear modulus, and ρ is the mass density. Solving equation (3.4) with respect to time, the following expression can be obtained

$$a^2 Y^{IV} + L w^2 Y^{II} + (w^2 B - 1) w^2 Y = 0 \quad (3.5)$$

where $a^2 = \frac{EI}{rA}$, $L = r_g^2 \left(1 + \frac{E}{k'G} \right)$, $B = \frac{r_g^2 r}{k'G}$, and $r_g^2 = \frac{I}{A}$.

The roots of the differential equation (3.5) using $Y(x) = e^{\lambda x}$ can be calculated as follows

$$I_1 = -I_2 = \bar{b}^{1/4} \sqrt{g + \sqrt{g^2 - 1}} \quad (3.6)$$

$$I_3 = -I_4 = \bar{b}^{1/4} \sqrt{g - \sqrt{g^2 - 1}}$$

where $\bar{b} = \frac{w^2}{a^2} (w^2 B - 1)$, $g = \frac{a}{2\sqrt{B}}$, and $a = -\frac{Lw^2}{a^2}$.

The solution of these roots can be real, imaginary or complex depending upon the frequency and wave number (γ factor). Three different cases, namely $\gamma = 1$, $\gamma < 1$, and $\gamma > 1$, must be studied to solve the roots in equation (3.6). For a nontrivial solution, the determinant of coefficients in the system equations for each case is set to zero in order to obtain the frequency equations. For the first case ($\gamma = 1$) the vibration frequency equation is given by

$$\sin^2(Kl) - \frac{Kl}{3} \sin(Kl) \cos(Kl) = 0 \quad (3.7)$$

where $K = \bar{b}^{1/4}$. The frequency equations given by the other two cases are the same and are expressed as

$$1 - \cos(K_1 l) \cos(K_2 l) + \frac{1}{2} \left(\frac{K_1}{K_2} + \frac{K_2}{K_1} \right) \sin(K_1 l) \sin(K_2 l) = 0 \quad (3.8)$$

where $K_1 = \bar{b}^{1/4} (g + \sqrt{g^2 - 1})^{1/2}$ and $K_2 = \bar{b}^{1/4} (g - \sqrt{g^2 - 1})^{1/2}$.

3.5 FINITE ELEMENT ANALYSIS

Finite element method is also used to evaluate the dynamic response of the ceramic candle filters. Four finite element models, one for each of the ceramic filter type, are built for this study. The filter model is constructed using 8-node 3-dimensional brick elements. This surface mesh is automatically extended by rotating it around the longitudinal-axis, creating a 3-D structure. The created elements are distributed uniformly along the length. The geometry used in each model is obtained from taking the nominal dimensions of each type of filter. The material properties such as Young's modulus, Poisson's ratio and weight density are given as input to the program. Free-free boundary conditions are given to the models.

The first model has the dimensions and material properties of the Coors P-100A-1 (Alumina/mullite). This model consists of 2208 brick elements with 4178 nodes. The Schumacher TF-20, Refractron 326, and Refractron 442T models, with their respective dimensions and material properties are made of 3390 brick elements with 4985 nodes. The weight density for the filter models is obtained by dividing the

average weight by the volume of the filter in consideration. The averaged weights are 8.38 lb (Coors), 10.70 lb (Schumacher TF-20) and 10.02 lb (Refractron 326 and 442T). Hence, the weight densities used in the calculation are 0.062 lb/in³, 0.073 lb/in³, and 0.069 lb/in³, respectively. The FEM models for the advanced ceramic filters are still under construction for future testing and evaluation.

From these models, the first eight bending modes are extracted and the mode shape analysis is performed. Figure 3.3 shows a sample of the first four bending mode shapes for a Schumacher TF-20 filter model. The figures show both the original (undisplaced) views of the model and the displaced modes shape for each mode.

3.6 RESULTS AND DISCUSSION

The average vibration frequencies for the first few bending modes of new 3M, McDermott, and Dupont-Lanxide filters are list in Table 3.2. It can be seen that for the 3M filter the third flexural mode was highest mode obtained, while for the McDermott and Dupont-Lanxide the frequencies were obtained until the fifth and sixth mode, respectively. This difference in number of modes is due to the surface properties of these filters.

Table 3.3 shows the average vibration frequencies for the first eight bending modes of each new Coors P-100A-1 filter. The vibration frequencies shown are the average frequency values at every impact location, for each flexural mode. The vibration frequencies that are shown in Table 3.4 correspond to the averaged results for each of the new Schumacher TF-20 filter specimens and the frequencies obtained

for each of the new Refractron 326 and 442T filters are shown in Table 3.5 and Table 3.6, respectively. The standard deviation of each mode at different impact locations for all the filters tested is less than 1.0 Hz. Therefore, it is confirmed that the impact location has minimal influence on the vibration frequencies (Appendix B). Tests performed with metal tip impact hammer obtained up to 8 vibration modes, while tests with plastic hammer tip received typically up to about 6 modes. It is noted that the Refractron 442T 4-878 can only reach 4 vibration modes using plastic hammer tip excitation due to noises appeared in the FRF.

The averaged frequencies of all vibration modes for every new filter are calculated, and are listed Table 3.7. These frequencies obtained are used as representative frequencies for all the filters in the different filter groups. As shown in this table, the magnitude of the natural frequency of the Refractron groups at each vibration mode are higher than the values of the Schumacher TF-20, which in turn is higher than Coors P-100A-1 filters.

The standard deviation and coefficient of variation (COV) for each group of filters are also shown in Table 3.7. To better understand the COV on each filter type, a plot was generated showing the percent of variation (COV) as a function of vibration modes. Figure 3.4 shows the comparison of COV for the averaged frequencies of Coors P-100A-1, Schumacher TF-20, Refractron 326 (A series) and Refractron 442T filters. The COV of each group is almost constant at different modes. The COV for Coors filters has a range between 1.4 and 1.6, while the range of COV for the Schumacher TF-20 is between 2.2 and 2.5, for the Refractron 326 (A series) is between

3.1 and 3.3, and for the Refractron 442T is between 2.7 and 3.0. No calculation of COV is being done for the Refractron 326 (# series) due to insufficient number of specimens (2 filters). Refractron groups have highest variance values followed by Schumacher TF-20 and Coors P-100A-1 filters. The same conclusions can be said about the standard deviation of the three filter types. This comparison shows that Refractron filters have the highest natural frequency, which will provide higher stiffness, however, the variation in properties is also the largest.

Table 3.8 shows the average frequency results of the Schumacher TF-20 filter specimen calculated using the Bernoulli-Euler and the Timoshenko filters equations. It can be seen that the frequency results using the Timoshenko equations are equal to the Bernoulli-Euler frequency results when the shear and rotary inertia effects are neglected.

The calculated frequencies are compared with the vibration frequencies obtained from the experimental testing to study the validity of the assumed theoretical beam equations. Figure 3.5 summarizes the comparison of the experimental results with the calculated results from both the Bernoulli-Euler and the Timoshenko models. The Timoshenko frequency values compare better with the experimental results than the Bernoulli-Euler frequency results, especially in the higher modes. The progressive increment of frequency along the vibration modes confirms the influence of the rotary and shear deformation. The maximum percentage difference between the Bernoulli-Euler equation and experimental frequency values varies from 6% at the first mode to 22.5% at the eighth mode. When the Timoshenko equation is used, the percentage

difference in frequency values varies from 6 in the first mode to 9.8% at the eighth mode.

Finite element analysis is used to calculate the values of Young's modulus and Poisson's ratio. The experimental frequency values are compared to the calculated frequency at each vibration mode for the refinement of Young's modulus and Poisson's ratio assumption. After obtaining a good approximation of the actual E value, three different Poisson's ratio values are assumed for the analysis keeping the E value constant. Table 3.9 shows the frequency results of the Coors filters using a Young's Modulus equal to 4.26×10^6 and three different Poisson's ratios (0.15, 0.20, and 0.30). The percentage difference between FEM and experimental results, when the Poisson's ratio is 0.30 are less than 0.6 %. The shaded section of this table shows the frequency results using a Poisson's ratio of 0.20. As can be seen, the difference between results drop to 0.3%. Following the same procedure, the Young's Modulus and Poisson's ratio values for the averaged frequencies of new Refractron 326 (A series), Refractron 442T and Schumacher TF-20 filters are listed in Table 3.10. For the Refractron 326 filters the Young's Modulus and Poisson's ratio values are 7.40×10^6 psi and 0.25 respectively, with a difference of frequency values less than 0.6% between experimental and FEM. For Refractron 442T filters the E value is 8.08×10^6 psi, the Poisson's ratio is 0.25, and the difference between experimental and FEM frequency values is less than 0.7%. For Schumacher TF-20 filters the E value is 6.23×10^6 psi, the Poisson's ratio is 0.20, and a frequency difference less than 1% with respect to the experimental values. It is also noted that the influence of Poisson's ratio values on the

vibration frequency is minimal. Also noted that the FEM model can correctly simulate each modal frequency of the candle filter up to the eighth bending mode.

Figure 3.6 shows a scatter plot of the Young's Modulus obtained for each ceramic candle filter tested. As shown in this figure, E values of the Refractron 326 (A series) group vary from 6.42×10^6 psi (specimen 2-21-A) to 8.18×10^6 psi (specimen 4-31-A), with an average of 7.40×10^6 psi. The young modulus for the two Refractron 326 (# series) are 7.58×10^6 psi for the 3-1290 filter and 7.77×10^6 psi for the 7-1289 filter (not shown in the figure). Refractron 442T group has the highest averaged E value (8.08×10^6 psi) of all the groups tested. The E values of this group vary from 7.60×10^6 psi (specimen 2-850) to 8.90×10^6 psi (specimen 4-878). For the Schumacher TF-20, the highest E value is 7.03×10^6 psi (specimen 329H162) and the lowest value is 5.82×10^6 psi (specimen 324H08), with an averaged Young's modulus of about 6.23×10^6 psi. For the Coors alumina/mullite, E values vary from 4.08×10^6 psi (specimen KC026) to 4.44×10^6 psi (specimen KC015), with an average of 4.26×10^6 psi. Again, both Refractron groups have higher averaged E value than Schumacher, which in turn is higher than Coors. It is also noted that the distribution of Young's modulus values for the Coors filters are narrow while the Schumacher and both Refractron groups are disperse reflecting the filter variation among these ceramic candle filters. It should be noted that the Young's modulus value obtained is just an averaged property of the entire candle filter, which can only be used as an index of the candle filter's overall stiffness.

The Young's modulus values published by the filter's manufacturers and other researchers using destructive tests are also shown in Figure 3.6. Hendrix (1998) reported the data from Schumacher (SUT), Southern Research Institute (SRI) and Coors (Figure 3.6). For example, a general E value of Schumacher TF20 filter is about 5.7 to 6.5×10^6 psi (by Schumacher), Coors filter is about 4.3×10^6 psi (by SRI) or 4.7×10^6 psi (by Coors) and Refractron filter is about 5.7×10^6 psi (by SRI). It is noted that the destructive tests were conducted on different samples than those evaluated in this study. The current filter specimens were sent to PSDF and will be traced using NDE to understand their performance in HTHP conditions. The advantage of nondestructive evaluation has an obvious benefit for both the filter manufacturer and the user.

The vibrational mode shapes from both the experiments and FEM are compared graphically for all the filter specimens. The mode shapes from the FEM analysis are three-dimensional. Therefore, the FEM points are extracted along the same single line on which the experimental data is collected. Figure 3.7 shows the comparative plots for the first four bending modes of the experimental and FEM results for a typical candle filter. The specimen filter that is used for this figure is the KC028 Coors alumina mullite filter. The experimental mode shapes were plotted using 10 data points while the ones for the FEM used 20 data points. For the purpose of comparison, both the experimental and FEM mode shapes were normalized at the same point in all the cases. The resulting mode shapes match well verifying the accuracy of the current dynamic characterization technique.

Figure 3.1 Experimental Set-Up and Filter Details.

Figure 3.2 Typical Frequency Response Function.

Figure 3.3 a) First, b) Second, c) Third, d) Fourth Bending Mode Shapes for the Coors P-100A-1 Model.

Table 3.1 New Ceramic Candle Filter Specimens.

	Series	# of Filters	Specimen #
Schumacher TF-20 (24 Filters)	324	11	H01, H03, H04, H05, H06, H07, H08, H09, H10, H11, H21,
	344	1	E 232
	379	12	H145, H146, H147, H148, H149, H150, H151, H160, H161, H162, H163, H164,
Refractron 326 (25 Filters)	(A Series)	23	1-22A,1-35A,1-37A,1-38A,1-39A,1-40A,1-69A,1-71A 2-21A,2-23A,2-29A,2-37A,2-41A,2-49A 3-25A,3-29A,3-35A,3-38A,3-68A 4-27A,4-31A,4-71A,4-87
	(# Series)	2	3-1290, 7-1289
Refractron 442T (8 Filters)	(# Series)	8	1-830, 1-854, 2-752, 2-850 4-869,4-878, 5-879, 6-737
Coors P-100A1 (12 Filters)	KC	11	013, 014, 015, 016, 025, 026, 028, 029, 030, 031, 032,
	LC	1	023
TOTAL		69	

Table 3.2 Averaged Frequency (Hertz) for Ceramic Composite Filters.

Mode #	3M Oxide 8004 Hz	Mc-Dermontt 8-130-1 Hz	Dupont 641 Hz
1	94.6	57.1	30.5
2	270.4	163.9	85.4
3	535.3	316.1	170.2
4	-	538.9	280.1
5	-	799.0	422.7
6	-	-	585.4

Table 3.3 Averaged Frequency (Hertz) for each Coors P-100A-1 Filters.

Mode #	SPECIMEN NUMBER											
	KC											LC
	013	014	015	016	025	026	028	029	030	031	032	023
1	111.4	110.0	114.4	112.9	111.4	110.0	112.9	112.9	114.4	111.2	109.9	113.7
2	303.5	300.3	311.6	306.7	302.0	300.6	306.4	307.2	311.3	303.6	300.6	311.4
3	584.1	582.0	602.7	590.5	584.3	573.9	591.9	593.6	602.7	585.9	581.4	599.7
4	947.6	941.5	973.4	958.3	943.0	930.8	958.3	959.3	970.5	944.7	936.9	967.4
5	1374.8	1364.1	1413.0	1391.6	1371.8	1352.1	1391.6	1390.1	1406.9	1371.8	1364.1	1408.4
6	1855.5	1840.7	1907.3	1876.8	1847.8	1828.0	1875.4	1878.7	1901.2	1852.4	1838.7	1895.1
7	2392.9	2348.5	2461.1	2420.0	2383.4	2365.3	2429.8	2432.6	2449.0	2386.6	2369.5	2446.6
8	2950.4	2915.8	3035.0	2986.8	2945.3	2916.1	2966.3	2997.3	3022.5	2954.1	2925.1	3027.3

Table 3.4 Averaged Frequency (Hertz) for each Schumacher TF-20 Filters.

Mode #	SPECIMEN NUMBER											
	324H											344
	01	03	04	05	06	07	08	09	10	11	21	E242
1	119.0	122.1	122.1	120.5	122.1	117.5	116.0	117.5	122.1	117.5	125.1	119.0
2	326.5	332.6	337.2	328.1	334.2	320.4	320.4	323.5	332.6	322.0	341.8	322.0
3	636.1	647.0	654.6	636.3	650.0	624.1	624.1	630.2	648.5	625.6	666.7	627.1
4	1031.5	1052.9	1063.5	1034.5	1055.9	1016.2	1014.7	1023.9	1055.9	1019.3	1081.8	1019.3
5	1506.0	1536.6	1551.8	1510.5	1535.0	1484.7	1477.1	1493.8	1541.1	1486.2	1574.7	1486.2
6	2043.0	2085.9	2104.2	2049.3	2082.2	2015.7	2006.5	2027.9	2087.4	2015.7	2134.7	2020.4
7	2647.8	2705.8	2725.1	2661.0	2696.2	2615.4	2598.7	2619.9	2704.2	2614.9	2770.2	2610.8
8	3288.6	3344.7	3375.5	3291.5	3344.7	3241.0	3222.7	3253.2	3341.7	3231.8	3418.3	3249.7

Mode #	SPECIMEN NUMBER											
	379H											
	145	146	147	148	149	150	151	160	161	162	163	164
1	123.6	117.5	122.1	120.5	120.7	122.1	123.6	117.5	123.6	128.2	123.6	118.9
2	337.2	323.6	334.3	329.6	331.1	334.2	338.9	325.0	338.7	354.0	337.2	326.5
3	657.7	634.8	654.8	643.9	643.9	653.1	663.8	638.0	660.7	686.6	657.7	636.3
4	1071.2	1033.0	1062.0	1045.2	1048.3	1062.0	1077.3	1039.1	1072.7	1115.4	1068.1	1036.1
5	1561.0	1507.6	1547.3	1524.9	1528.9	1550.3	1571.7	1515.2	1564.0	1625.5	1557.9	1509.4
6	2122.5	2050.9	2105.7	2073.7	2078.2	2105.7	2137.8	2061.5	2127.4	2203.4	2118.1	2053.8
7	2743.7	2652.0	2720.8	2677.9	2685.5	2722.2	2762.1	2662.7	2749.6	2844.2	2737.5	2653.5
8	3407.3	3300.5	3381.3	3332.5	3340.1	3382.9	3433.7	3313.4	3418.0	3533.9	3404.2	3300.6

Table 3.5 Averaged Frequency (Hertz) for each Refractron 326 Filters.

Mode #	SPECIMEN NUMBER												
	1-22A	1-35A	1-37A	1-38A	1-39A	1-40A	1-69A	1-71A	2-21A	2-23A	2-29A	2-37A	2-41-A
1	130.0	143.4	138.9	138.9	137.6	138.9	140.4	139.0	127.0	131.4	135.8	138.9	138.9
2	354.0	390.6	379.7	377.1	376.4	377.8	381.5	378.9	346.4	358.7	367.7	379.5	379.9
3	690.0	759.9	740.2	735.2	730.7	733.8	741.6	737.0	677.3	698.9	714.1	740.1	738.5
4	1118.5	1226.8	1194.8	1187.1	1179.5	1184.1	1196.3	1188.7	1095.7	1129.2	1153.6	1194.8	1185.6
5	1628.1	1783.8	1738.0	1725.8	1715.1	1723.0	1741.0	1730.3	1594.5	1640.9	1675.4	1738.6	1725.8
6	2205.0	2415.5	2356.3	2337.3	2323.9	2333.1	2357.6	2413.8	2160.6	2224.7	2269.0	2357.5	2337.6
7	2847.3	3118.9	3042.8	3017.4	3001.4	3018.2	3043.8	3102.7	2788.1	2869.7	2926.6	3044.1	3018.2
8	3529.5	3863.8	3770.4	3738.4	3715.5	3743.0	3770.4	3753.7	3457.8	3555.8	3627.0	3773.5	3741.5

Mode #	SPECIMEN NUMBER											
	2-49-A	3-25-A	3-29-A	3-38-A	3-35-A	3-68-A	4-27-A	4-31-A	4-71-A	4-87-A	3-1290	7-1289
1	134.4	130.0	135.0	138.9	141.9	138.9	137.3	145.0	138.9	141.9	139.2	141.0
2	366.4	354.2	366.3	379.9	387.6	376.9	370.2	395.2	378.9	387.6	379.0	383.9
3	712.6	688.3	714.1	737.3	755.3	732.3	720.2	762.9	736.7	753.3	734.3	743.4
4	1150.5	1115.4	1153.6	1190.2	1219.2	1182.6	1162.7	1231.4	1188.7	1214.6	1185.3	1200.6
5	1670.8	1622.0	1678.8	1731.9	1774.6	1721.2	1689.1	1791.4	1727.3	1768.5	1725.5	1749.3
6	2265.9	2195.9	2272.0	2345.1	2403.3	2331.5	2288.8	2426.1	2340.7	2394.1	2337.6	2367.6
7	2923.6	2834.8	2931.4	3028.9	3103.2	3010.6	2952.6	3131.1	3022.8	3091.4	-	-
8	3625.3	3511.0	3633.6	3750.3	3843.7	3782.3	3660.6	3878.8	3747.7	3831.5	-	-

Table 3.6 Averaged Frequency (Hertz) for Refractron 44T Filters.

Mode #	Specimen Number							
	1-830	1-854	2-752	2-850	4-869	4-878	5-879	6-737
1	142.8	140.4	139.2	138.6	148.0	149.5	148.0	142.8
2	394.9	384.5	378.6	381.5	405.9	408.9	406.0	391.8
3	757.5	749.2	739.1	740.9	782.8	794.7	784.9	756.2
4	1225.6	1211.6	1193.9	1199.3	1266.5	1285.4	1269.5	1223.1
5	1786.5	1767.0	1739.5	1746.2	1844.8	-	1850.9	1781.0
6	2422.5	2392.6	2356.6	2368.2	2504.0	-	2510.1	2413.0
7	-	3091.4	-	-	3231.8	-	3242.5	-
8	-	3831.5	-	-	4008.5	-	4023.7	-

Table 3.7 Total Averaged Frequency for Different Types of New Filters.

Mode #	SCHUMACHER TF-20			COORS P-100A-1			Refractron 326			Refractron 442T		
	Av (24) Freq.	STDEV Hz	COV	Av (12) Freq.	STDEV Hz	COV	Av(23) Freq.	STDEV Hz	COV	Av(7) Freq.	STDEV Hz	COV
1	120.9	3.0	2.5	112.1	1.7	1.5	137.5	4.4	3.2	142.8	4.43	3.0
2	331.3	8.2	2.5	305.4	4.3	1.5	374.5	12.3	3.3	391.9	12.1	3.1
3	645.9	14.6	2.3	589.4	9.1	1.6	728.4	23.1	3.2	758.7	20.3	2.7
4	1050.0	23.0	2.2	952.6	13.8	1.5	1176.0	35.9	3.1	1227.1	33.1	2.7
5	1531.1	33.3	2.2	1383.4	19.8	1.4	1710.3	52.6	3.1	1788.0	48.5	2.7
6	2079.6	43.5	2.1	1866.5	26.3	1.4	2320.0	73.7	3.2	2423.8	67.2	2.8
7	2690.9	55.8	2.1	2407.1	37.3	1.6	2994.3	95.1	3.2			
8	3339.7	67.6	2.0	2970.2	43.1	1.5	3709.0	115.0	3.1

Figure 3.4 Graphical Comparison of COV between Filter Types.

Table 3.8 Comparison between Bernoulli-Euler and Timoshenko Model Results.

Mode #	Bernoulli-Euler	Timoshenko	
	E= 6.23x10 ⁶ psi m= 0.00046 lb/in	E= 6.23x10 ⁶ psi v= 0.2	
	Hz	No Shear / Rotary Hz	Hz
1	128.300	128.582	128.213
2	353.665	354.442	351.111
3	693.333	694.849	681.453
4	1146.113	1148.620	1111.582
5	1712.092	1715.840	1633.826
6	2391.273	2396.504	2239.695
7	3183.631	3190.613	2920.533
8	4089.201	4098.167	3667.896

Figure 3.5 Comparison of Experimental and Theoretical Results (Schumacher TF-20).

Table 3.9 Young's Modulus and Poisson's Ratio Effect on Frequency Values (Coors P-100A-1 Filters).

Mode #	EXP.	E= 4.26x10 ⁶		E= 4.26x10 ⁶		E= 4.26x10 ⁶	
		v= 0.3	%	v= 0.2	%	v= 0.15	%
1	112.10	112.40	0.27	112.42	0.28	112.43	0.29
2	305.43	306.01	0.19	306.19	0.25	306.28	0.28
3	589.38	588.75	-0.11	589.48	0.02	589.84	0.08
4	952.61	949.75	-0.30	951.67	-0.10	952.63	0.00
5	1383.35	1378.10	-0.38	1382.08	-0.09	1384.09	0.05
6	1866.48	1862.70	-0.20	1869.78	0.18	1873.35	0.37
7	2407.11	2393.12	-0.58	2404.40	-0.11	2410.08	0.12
8	2970.16	2959.95	-0.34	2976.52	0.21	2984.88	0.49

Table 3.10 Young's Modulus and Poisson's Ratio Effect on Frequency Values for Refractron 326, Refractron 442T and Schumacher TF-20 Filters.

Mode #	REFRACTRON 326			REFRACTRON 442T			SCHUMACHER TF-20		
	EXP	E= 7.40x10 ⁶ v= 0.25	% Diff	EXP	E= 8.08x10 ⁶ v= 0.25	% Diff	EXP	E= 6.23x10 ⁶ v= 0.2	% Diff
1	137.43	137.12	-0.23	143.66	143.28	0.27	120.93	121.82	0.73
2	374.42	374.81	0.10	394.03	391.65	0.60	331.33	334.44	0.93
3	728.28	723.97	-0.59	763.18	756.51	0.87	645.89	646.19	0.05
4	1175.79	1172.42	-0.29	1234.36	1225.11	0.75	1050.00	1046.80	-0.31
5	1710.26	1707.57	-0.16	-	-	-	1531.14	1525.30	-0.38
6	2319.81	2316.29	-0.15	-	-	-	2079.64	2069.90	-0.47
7	2994.33	2986.02	-0.28	-	-	-	2690.91	2669.60	-0.80
8	3708.92	3705.86	-0.08	-	-	-	3339.66	3314.00	-0.77

Figure 3.6 Young's Modulus Distribution for all New Ceramic Candle Filters.

Figure 3.7 First Four Mode Shapes for Coors Filter (Specimen KC028).

CHAPTER IV

STRUCTURAL DETERIORATION OF USED CERAMIC CANDLE FILTERS

4.1 INTRODUCTION

This chapter presents an interpretation of dynamic characterization tests aimed at the identification of the structural stiffness degradation of used ceramic candle filters. These candle filters were used in a coal-fired power demonstration plant over a extended periods of time. The filters need to withstand an extreme thermal and chemical environment. A total of twenty-nine candle filters have been tested nondestructively. All filters are tested under simulated free-free boundary conditions. The specimens are excited using an impact hammer and the response is picked up by an accelerometer. Finite Element models are built to calculate the filter's natural frequencies and mode shapes. A damage detection procedure based on modal strain energy is applied. This procedure successfully detects damaged sections in the filters that were exposed to extreme conditions. Results from this study indicate that the stiffness degradation of the filters is dependent on the filter's exposure time and can be successfully determined by its dynamic response.

4.2 ANALYSIS

4.2.1 Natural Frequency and Mode Shapes

The principle of using vibration technique for damage detection relies on the fact that dynamic response can be a sensitive indicator of the structural properties. The natural vibration modes are constituted basically by modal frequencies and mode shapes, which depend on the structural mass and stiffness characteristics. Deterioration or defects in a structure are usually characterized by a reduction in stiffness and/or a change of mass, which in turn alter the vibrational characteristics of the structure. It is observed that in ceramic candle filters, changes in stiffness is more significant than mass (Chen and Parthasarathy 1996). Therefore, in formulating the eigenvalue problem, we assume that the structural damage only affect the stiffness matrix and not the mass matrix. The equation of motion is given as

$$([K] - \omega^2 [M])\{u\} = \{P\} \quad (4.1)$$

where $[K]$ is the stiffness matrix, ω is the eigenvalue or natural frequency, $[M]$ is the mass matrix, $\{u\}$ is the displacement eigenvector, and $\{P\}$ is the applied impact load vector. By solving the equation of motion when the impact force is applied, we are able to describe the complete solution by a single matrix, known as “mobility matrix” (Ewins 1985). The elements of this matrix are frequency-dependent and each element is a frequency response function (FRF). The FRF can be defined as the ratio between the displacement response $u(\omega)$ and the excitation force $P(\omega)$ in the frequency domain.

$$T(\omega) = \frac{u(\omega)}{P(\omega)} \quad (4.2)$$

The input force signal and the relevant output response signal are transformed using Fourier Transform:

$$G(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} g(t) e^{-i\omega t} dt \quad (4.3)$$

where , $g(t)$ is a function in time domain, and $G(\omega)$ is the transferred function in frequency domain.

4.2.2 Strain Energy Algorithm

The candle filter's damage detection algorithm developed in this study is based on the dynamic modal strain energy. The damage section of a structure can usually be characterized by a local stiffness reduction. Therefore, this reduction leads to an increase in the curvature at the damaged section. The dynamic strain energy involves the multiplication of the squares of the modal curvatures (second derivative of the mode shape, ϕ'') and the mode shape (ϕ) in consideration as (Weaver 1984):

$$U_{ab}(x) = \frac{1}{2} \int_{a(x)}^{b(x)} EI(f) (f'')^2 dx \quad (4.4)$$

The strain energy distribution along the structure is defined in a segment between two finite locations $a(x)$ and $b(x)$. A constant segment length between $a(x)$ and $b(x)$ was chosen to calculate strain energy. The segment length is 1/30 of the

entire candle length. The strain energy distribution on the whole span is calculated as the superposition of each segment.

Defining the strain energy distribution for undamaged and damaged specimens as U^o and U^d , the strain energy difference is calculated as

$$\Delta U = U^d - U^o \quad (4.5)$$

The energy difference distribution along the span of a damaged specimen will show an increase in the energy difference around the damaged zone, while a fall in the energy difference levels away from the damaged zone is sometime noticed due to inadequate data resolution. Therefore, a positive sudden increase of energy difference denote damage zones.

4.2.3 Finite Element Method Analysis

Finite element models are built for each specimen type to understand the filter's dynamic response. The model's geometry is obtained from taking the nominal dimensions of each type of filter. Linear elastic modal analysis is performed. Eight nodes, three-dimensional isotropic solid elements are used. The Coors model consists of 2208 brick elements with 4178 nodes. The Schumacher TF-20 and Refractron 326 models are made of 3390 brick elements with 4985 nodes. The material properties such as Young's modulus, Poisson's ratio and weight density are given as input to the program. FEM analysis is conducted using free-free support constraints. A damaged FEM filter model is also constructed to calculate the damage location and damage zone

size. The result was also used to verify the strain energy algorithm. The FEM damage model also provides an estimation of material properties in the damage zone.

4.3 EXPERIMENTS

The experimental setup used in this chapter consisting of excitation, sensing, and signal analysis is the same as described in Chapter 3. Vibration parameters such as natural frequencies, mode shapes and frequency response functions (FRF) are used as the basis of our nondestructive evaluation. Frequency Response Functions (FRF) are obtained for each impact location. From the FRF plots at each impact location, the frequency and amplitude values at each peak are collected and the mode shapes are constructed. The frequencies obtained are averaged to minimize experimental errors arising from improper impacts.

4.3.1 Test Specimens

The specimens in this study are nonoxide-based ceramic candle filters, which were tested at the PSDF. These candle filters were operated at high-temperature and high-pressure, and were cleaned by reverse pulse-jet methods during the coal-fired operation. After being used for a period of time, candle filters are covered with a layer of ash. Therefore, in order to determine its influence on the frequency vibration signatures, some of the filters were tested before and after cleaning with water. There are 29 used ceramic candle filters which include fifteen Schumacher TF-20, one

Schumacher T10-20, one Schumacher F-40, nine Refractron 326, and three Refractron 442T as shown in Table 4.1.

For Schumacher TF-20 filters, five of them (TF-20 324H04, 324H05, 324H06, 324H07, and 344E232) were exposed for 500 hours at temperatures up to about 1400 °F. Four filters (TF-20 324H01, 324H03, 324H08 and 324H10) were used for 982 hours. One filter (TF-20 324H21) was used for 483 hours. Filters TF-20 324H01, 324H04, 324H08, 324H21 were tested again after surviving a fire in October 1998 at PSDF. These filters have the same number of hours than before the fire, since it occurred during start up. These ten filters were nondestructively tested when they were new (Chen and Kiriakidis 1998). Comparing with their virgin status, these used filters have the same geometry and present no significant change in weight. Filter TF-20 324H14 was exposed for 822 hours and was not tested previously. The nominal length for these filters is 1.52 m (59.8 in) with an outer diameter of 60 mm (2.36 in.) and inner diameter of 40 mm (1.57 in.). The wall thickness along the length is 10 mm (0.39 in.).

One used Schumacher T-10-20 SiC filter (324-H17) was exposed for 822 hours. This filter has the same dimensions as the TF-20 series. One used Schumacher F-40 clay-bonded SiC filter (317B115) was exposed for 1060 hours. This filter was tested previously by Chen and Parthasarathy (1996), at that time the filter was used for 460 hours. The nominal length for this filter is 1.52 m (59.8 in), with an outer diameter of 60 mm (2.36 in.) and inner diameter of 30 mm (1.18 in.). The wall thickens along the length is 15 mm (0.59 in.).

There are nine Refractron 326 clay-bonded SiC filters specimens. These Refractron filters are divided in two series, #-series and A-series. The #-series filters are the 4-981, 2-992, 2-977 and 4-1069 which were used for 203 hrs, 1251hrs, 1321hrs and 3214hrs respectively. Filters 1-51A, 2-69A and 3-79A are from the A-series and were used for 400 hours. Filters 2-24A and 1-26A are also from the A-series and were used for 203 hrs and 429 hrs, respectively. All filters were exposed at temperatures up to about 1400 °F. Filters 4-981 and 2-24A (203 hour) are survivors of the fire in April 1997 at PSDF. The nominal length for these filters is 1.52 m (59.8 in), with an outer diameter of 60 mm (2.36 in.) and inner diameter of 40 mm (1.57 in.). The wall thickness along the length is 10 mm (0.39 in.).

Three used Refractron 442T clay-bonded SiC filters were tested. These filters, 4-13A, 5-8A and 3-754, were used for 616 hrs, 1251hrs and 1867hrs, respectively. The nominal dimensions of these filters are the same as the Refractron 326 filters.

4.4 RESULTS

4.4.1 Natural Frequencies

Schumacher TF-20

Natural frequency reduction of the used filters compared with new filters is noticed for most of the filter specimens. Table 4.2 shows the measured natural frequency comparison between new and used Schumacher TF-20 filters due to 483 hrs, 500 hrs, and 982 hrs of exposure at the PSDF. The frequency values of filter 324-H21 decrease about 9.2 % from new to 483 hours. This value is an average of all the

vibration modes and in general, every modal frequency has a similar change. Frequency values of filters 324H04, 324H05, 324H06, and 324H07 after 500 hrs use decrease about 3.1%, 4.2%, 2.8%, and 1.6%, respectively. The percentage frequency shift between new and 982 hrs for filters 324H01, 324H03, 324H08, and 324H10 is about 5.7%, 7.4%, 4.9%, and 7.9%, respectively. These results show a progressive deterioration in terms of frequency reduction with respect to exposure time. However, the frequency of the 344E232 filter increases about 1.6 % from new to 500 hrs, which is the only exception with increasing frequency values. Table 4.3 shows the frequencies for the filters that survived the October 1998 fire at PSDF. These filters have a frequency reduction of about 1.7% (filter H01), 7.5% (filter H04), 2.0% (filter H08) and 1.8% (filter H21). The reduction of natural frequencies was produced by thermal conditions in the chamber during the accident of October 1998 since the filters have no additional exposure hours before the accident. The frequency values for the 324H14 Schumacher TF-20 and 324-H17 Schumacher T-10-20 filters, which were used for 822 hours are listed in Table 4.4. Since these two filters have no virgin natural frequency data, the results of these filters are compared with the averaged frequency of 24 new Schumacher TF-20 obtained previously (Chen and Kiriakidis 1998). The frequency shift is about 8.5% for the 324H14 and 6% for the 324-H17.

Schumacher F40

The frequency results for the Schumacher F-40 filter used for 1060 hrs (317B-115), are shown in Table 4.5. The frequencies obtained when this filter was tested at 460 hrs (Chen et al. 1996) and the averaged frequency results for seven Schumacher F-

40 used for 1705 hrs are also listed in this table. It can be seen progressive decrease in frequency values among the exposure times for the 317B-115 Schumacher F-40. The average percentage differences between 460 hrs and 1060 hrs and 460 hrs and 1705 hrs exposure times are about 1.2% and 6.5 %. It is noted that in the case of 460 to 1060 hrs even though the first mode reduced 3.0% the average of all modes is 1.2%. Since the frequency resolution is 1.36 Hz, more accurate results are obtained in the higher modes.

Refractron 326

In the case of the A-series Refractron 326 filters, the averaged frequency values for the new filters and the frequencies of used filters are listed in Table 4.6. The averaged frequencies for the new A-series filters (Chen and Kiriakidis 1998) are higher than the frequency results for the 3-79A (400 hrs), 1-51A (400 hrs), and 1-26A (429 hrs). The percentage frequency reduction for these filters is about 2.8%, 3.7% and 4.3%, respectively. Although filter 2-69A has higher frequency values than the averaged frequency, there are three new Refractron filters with high frequency. Therefore, comparing filter 2-69A with the average of those 3 new filters, the frequency values decrease about 0.7%. Filter 2-24A shows a strangely high and non-uniform frequency reduction compared with the rest of the filters. This particular result indicates damage occurred on the filter during the fire at PSDF in April 1997. The vibration frequencies that are shown in Table 4.7 correspond to the used #-series Refractron 326. No frequency comparison is made between new filters and filters 4-981, 2-992, 2-977 and 4-1069 because not enough data for new filters of this series

were acquired. It can be seen in this table that filters 2-992 and 2-977 have similar number of exposure hours and therefore similar frequency. These frequencies are higher than filter 4-1069, which has more than 3000hrs. The percentage frequency for this filter is about 10% less than the averaged frequencies of filters 2-992 and 2-977. These filters with long exposure hours have similar frequency values as filter 4-981, which has been used for a couple hundred hours. The 4-981 filter experienced the April'97 fire, which might have caused damage to the filter since the frequency values are low. However, no localized damage can be identified for the frequency values.

Refractron 442T

Table 4.8 shows the frequency results of Refractron 442T filters for the average of seven new and three used #-series filters. Filter 3-754 (1867 hours) shows a frequency reduction of 4.43% when compared with the averaged frequencies of 7 new filters. Specimens 4-13A (616 hrs) and 5-8A (1251 hrs) are A-series filters. Hence, they are not compared with the averaged frequencies of the new filters. The frequency shift of these two filters with a difference exposure time of 636 hours is about 0.6%.

4.4.2 Stiffness Degradation

Finite element analysis is used to calculate the overall stiffness in terms of values of Young's modulus. The experimental frequency values are compared to the calculated frequency at each vibration mode for the refinement of Young's modulus. Figure 4.1 shows a scatter plot of the Young's Modulus obtained for each Schumacher

TF-20 filter tested. The Poisson's ratios of the used filters are assumed unchanged since the effect of the Poisson's ratio on the natural vibration frequency is minimal. A reduction of stiffness with respect to the exposure time for the Schumacher filters is clearly noticed in this figure.

Schumacher TF-20

After 483 hours of exposure at the PSDF, filter 324-H21 has a Young's modulus value of 5.56×10^6 , which is 16 % lower than when it was new. Young's Modulus values for filters 324H04, 324H05, 324H06, and 324H07 (after being used for 500 hours) are 6.05×10^6 psi, 5.62×10^6 psi, 5.93×10^6 psi, and 5.68×10^6 psi, respectively. The stiffness reductions of these four filters are about 5.6%, 7.8%, 5.9%, and 3.2%, respectively. Although filter 344E232 was also used for 500 hours, the E value of this filter increases about 3.52%, from 5.91×10^6 psi to 6.12×10^6 psi. The results for specimens 324H01, 324H03, 324H08, and 324H10 (982 hours) show Young's modulus of 5.41×10^6 psi, 5.42×10^6 psi, 5.28×10^6 psi, and 5.41×10^6 psi. These values correspond to a stiffness reduction of 10.5%, 13.9%, 9.2%, and 14.3%, respectively. Filters 324H14 and 324-H17 (822 hrs) were not tested previously; their E values are in the similar trend as shown in Figure 4.1.

Refractron 326

Figure 4.2 shows the Young's Modulus distributions for the Refractron 326 filters. Because the used filters have not been tested previously, they are compared with the averaged results (solid line) of all new filters. One can notice that the used filters 1-51A, and 3-79A have lower stiffness (6.90×10^6 psi and 7.02×10^6 psi) than the

average stiffness of the new ones. The percentage of stiffness shift is about 6.8% and 5.2%. Filter 1-26A that was used for 483 hours has an E value about 6.80×10^6 psi. Although filter 2-69A has been used for 400 hours, its stiffness value (7.96×10^6 psi) is higher than the average of the new filters. As explained before, this filter's results were compared with the average of filters 1-35A, 3-35A, and 4-31A, and show a stiffness reduction about 1.5%. The E values of filter 2-24A, after locating the damaged zone along the length, are about 7.20×10^6 psi for undamaged zones and 2.88×10^6 psi for the damaged section. The E value shown in this Figure 4.2 is the E for the undamaged zone. Considering the #-series filters, it is noticed that filter 4-981 (203 hrs) has a similar E value (8.65×10^6 psi) to filters 2-992 (1251 hrs) and 2-977 (1321 hrs), which have E values of 8.60×10^6 psi and 8.70×10^6 psi. Filter 4-1069 has an E value of 7.03×10^6 psi. This value is about 18.7% lower than the average of filters 2-992 and 2-977.

Refractron 442

The Young's modulus values for the Refractron 442T with respect to time are shown in Figure 4.3. After 1867 exposure hours specimen 3-754 has an E value of 7.40×10^6 psi, which is about 8.4% lower than the average Young's modulus of the new filters. The E values of filters 4-13A (7.65×10^6 psi at 616 hrs) and 5-8A (7.50×10^6 psi at 1251 hrs) are also shown in Figure 4.3.

Average Stiffness of Different Filter Groups

The average of the E values of all the filters in each filter group are shown in Figure 4.4 as a function of exposure hours. The average stiffness shifts for the

Schumacher TF-20 after 500 hrs is about 5.6% and after 982 hrs is about 13.6%. The stiffness reduction of the specimen 317B-115 (used Schumacher F-40) between 460 hrs (5.5×10^6 psi), and 1060 hrs (5.25×10^6 psi) is about 4.5% and the average stiffness reduction between 460 hrs and 1705 hrs (4.9×10^6 psi) is about 6.7 %. The average stiffness drop between new and 400 hrs for Refractron 326 (A series) is about 5.9 %. The stiffness reduction of Refractron 326 (# series) is about 18.7% with a time difference of about 1900 hours (from 1321 hrs to 3214 hrs). The average stiffness values for the Refractron 442T after 1867 exposure hours are reduced about 8.41%.

4.4.3 Damage Location

The results of the damage location detection study on ceramic filters are a combination of experimental and FEM mode shapes, and dynamic strain energy analyses. For the specimen 2-24A, a special FEM model with a damaged portion at the midspan is built as shown in Figure 4.5. The FEM analysis is conducted using two sets of material properties, one for the damaged zone and one for the rest of the filter. The Young's modulus, mass density and the length of the damage portion are calculated using an iteration procedure.

The experimental and FEM results are listed in Table 4.9. The FEM frequency results listed in this table are obtained using Young's modulus for the damaged and undamaged zones equal to 7.30×10^6 psi and 2.90×10^6 psi, respectively. The mass density of the damaged zone has been changed in the same percentage as the Young's modulus. The length of the damaged zone is about 8.85 in (22.48 cm) starting at

20.65 in (52.45 cm) from the closed end (bottom) of the filter. Figure 4.6 shows comparative plots for the first and third bending mode shapes between the FEM and the experimental results of the 2-24A filter (damaged, survived from April 1997 fire at PSDF). These mode shapes are also compared with the FEM results of a new Refractron filter and experimental results of the 2-49A (undamaged). For the purpose of comparison, both the experimental and FEM mode shapes are normalized at the same point in all the cases. Comparative plots of strain energy distribution for the first and third mode are also shown in Figure 4.6. One can clearly see that there is a discrepancy between the mode shapes of the damaged and undamaged filters around the midspan of the filter. This discrepancy is shown in both mode 1 and mode 3. In the strain energy difference plots, it can be seen that the energy levels around the damage location (midspan) are higher than the values along the entire span. While the energy difference levels away from the damage location are negative or zero. It can be noticed the FEM result including the damaged zone matches well with the experimental mode shape 1 and mode shape 3 from the damaged filter 2-24A (Figure 4.6).

Damaged location detection on the filters that survived the October 1998 fire is being studied. No concentrated damage can be identified for Schumacher TF-20 324H01, 324H08, 324H21 and 324H04 filters. We are refining our damage detection procedures to further investigating the filter 324H04 since this filter has more than 7% of frequency drop. The result of this refinement will be reported later.

4.4.4 Ash Cake Effect on Vibration Frequency

Table 4.10 shows the vibration frequencies results of one Refractron 326 and four Schumacher TF-20 filters obtained before and after the filters were cleaned. The vibration frequency results are the average frequency values at every impact location, for each flexural mode. It can be seen that in all the cases the vibration frequency values are always higher for the filters before cleaning than after cleaning. The percentage difference of vibration frequencies between clean and unclean varies. For the Schumacher filters 344-E232, 324-H07, 324-H05, and 324H04, the percentage difference is about 2.0%, 6.5%, 5.5%, 2.6%, respectively. For the Refractron 326 1-51A, the percentage difference is about 4.6%. Such anomalies in results could be due to the formation of temporary stiffer particulate layers on the walls of the ceramic candle filters. These temporary layers are washable.

Table 4.1 Used Ceramic Candle Filter Specimens.

	Series	# of Filters	Time (Hours)	Specimen #
Schumacher TF-20 (15 Filters)	324	1 5 1 4	483 500 822 982	H21 H04, H05, H06, H07, 344E232 H14 H01, H03, H08, H10
		4	Oct'98 Fire	324H01, 324H04, 324H08, 324H21
Schumacher T 10-20		1	822	H17
Schumacher F-40		1	1060	317B115
Refractron 326 (9 Filters)	A Series	1 3 1	203 400 429	2-24A 1-51A, 2-69A, 3-79A 1-26A
	# Series	1 1 1 1	203 1251 1321 3214	4-981 2-992 2-977 4-1069
Refractron 442T (3 Filters)	A Series	1 1	616 1251	4-13A 5-8A
	# Series	1	1867	3-754
TOTAL		29		

Table 4.2 Comparison of Experimental Frequencies of New and Used Schumacher TF-20 Filters.

500 Hours															
Mode #	324-H04			324-H05			324-H06			324-H07			344-E-232		
	New	500 hrs	%	New	500 hrs	%	New	500 hrs	%	New	500 hrs	%	New	500 hrs	%
1	122.1	119.0	-2.6	120.5	114.6	-5.2	122.1	117.5	-3.9	117.5	114.4	-2.7	119.0	120.5	1.3
2	337.2	325.0	-3.8	328.1	314.3	-4.4	334.2	325.0	-2.8	320.4	315.9	-1.4	322.0	326.5	1.4
3	654.6	635.2	-3.1	636.3	611.0	-4.1	650.0	634.6	-2.4	624.1	614.9	-1.5	627.1	636.3	1.4
4	1063.5	1031.5	-3.1	1034.5	995.0	-4.0	1055.9	1026.9	-2.8	1016.2	1001.0	-1.5	1019.3	1036.1	1.6
5	1551.8	1504.5	-3.1	1510.5	1451.1	-4.1	1535.0	1495.4	-2.7	1484.7	1461.9	-1.6	1486.2	1510.6	1.6
6	2104.2	2044.8	-2.9	2049.3	1973.3	-3.9	2082.2	2031.9	-2.5	2015.7	1988.4	-1.4	2020.4	2050.8	1.5
7	2725.1	2641.3	-3.2	2661.0	2549.9	-4.4	2696.2	2627.9	-2.6	2615.4	2569.7	-1.8	2610.8	2652.0	1.6
8	3375.5	3284.9	-2.8	3291.5	3174.0	-3.7	3344.7	3270.0	-2.3	3241.0	3196.9	-1.4	3249.7	3299.3	1.5
982 Hours															
Mode #	324-H21			324-H01			324-H03			324-H08			324-H10		
	New	483hrs	%	New	982 hrs	%	New	982 hrs	%	New	982 hrs	%	New	982 hrs	%
1	125.1	114.4	-9.3	119.0	112.9	-5.4	122.1	112.9	-8.1	116.0	111.4	-4.1	122.1	112.9	-8.1
2	341.8	312.8	-9.3	326.5	309.8	-5.4	332.6	309.8	-7.4	320.4	303.6	-5.5	332.6	308.2	-7.9
3	666.7	608.8	-9.5	636.1	596.6	-6.6	647.0	602.7	-7.3	624.1	593.6	-5.1	648.5	598.1	-8.4
4	1081.8	990.3	-9.2	1031.5	978.1	-5.5	1052.9	981.1	-7.3	1014.7	967.4	-4.9	1055.9	978.1	-8.0
5	1574.7	1442.0	-9.2	1506.0	1425.2	-5.7	1536.6	1431.3	-7.4	1477.1	1408.4	-4.9	1541.1	1425.2	-8.1
6	2134.7	1959.2	-9.0	2043.0	1937.9	-5.4	2085.9	1945.5	-7.2	2006.5	1915.0	-4.8	2087.4	1937.9	-7.7
7	2770.2	2531.4	-9.4	2647.8	2505.5	-5.7	2705.8	2513.1	-7.7	2598.7	2474.98	-5.0	2704.2	2504.0	-8.0
8	3418.3	3144.8	-8.7	3288.6	3114.3	-5.6	3344.7	3125.0	-7.0	3222.7	3080.7	-4.6	3341.7	3115.8	-7.2

Table 4.3 Experimental Frequencies of Filters that Survived October'98 Fire.

Mode #	324-H01			324-H04			324-H08			324-H21		
	982 hrs	Oct	%	500 hrs	Oct	%	982 hrs	Oct	%	483 hrs	Oct	%
1	112.9	110.5	-2.2	119.0	110.5	-7.7	111.4	108.6	-2.5	114.4	112.9	-1.4
2	309.8	303.3	-2.1	325.0	303.3	-7.1	303.6	298.5	-1.7	312.8	307.6	-1.7
3	596.6	590.2	-1.1	635.2	589.6	-7.7	593.6	582.3	-1.9	608.8	595.5	-2.2
4	978.1	961.9	-1.7	1031.5	960.7	-7.4	967.4	948.5	-2.0	990.3	972.9	-1.8
5	1425.2	1402.0	-1.7	1504.5	1400.8	-7.4	1408.4	1382.4	-1.9	1442.0	1416.0	-1.8
6	1937.9	1906.1	-1.7	2044.8	-	-	1915.0	-	-	1959.2	1925.7	-1.7
7	2505.5	-	-	2641.3	-	-	2474.98	-	-	2531.4	-	-
8	3114.3	-	-	3284.9	-	-	3080.7	-	-	3144.8	-	-

Table 4.4 Frequency Results of New and Used Schumacher TF-20Filters

Mode #	New Av	TF-20		T-10-20	
		822 Hrs		822 Hrs	
		324-H14		324-H17	
		822 hrs	%	822 hrs	%
1	120.93	111.7	-8.3	113.5	-6.5
2	331.33	303.3	-9.2	311.9	-6.2
3	645.89	596.9	-8.2	613.4	-5.3
4	1050.00	968.6	-8.4	991.8	-5.9
5	1531.14	1411.7	-8.5	1445.9	-5.9

Table 4.5 Frequency Results for the 1060 hrs used Schumacher F-40 filter (317B-115)

Mode #	B-7 460 hrs	B-7 1060 hrs	1705 hrs AV	% 460-1060	% 460-1705
1	110.0	106.8	102.1	-3.0	-7.2
2	295.0	291.1	279.0	-1.3	-5.7
3	570.0	567.6	539.1	-0.4	-5.7
4	932.5	927.7	882.1	-0.5	-5.7
5	1364.0	1353.5	1286.0	-0.8	-6.1
6	1864.0	1849.5	1752.0	-0.8	-6.4
7	2438.0	2400.2	2274.0	-1.6	-7.2
8	3045.0	2999.3	2827.0	-1.5	-7.7

Table 4.6 Frequency Results of New and Used Refractron 326 Filters (A Series).

Mode #	New		203 Hours		400 Hours							429 Hours	
	AV.(23)	AV.(3)	2-24A	%	3-79A	%	1-51A	%	2-69A	%	%	1-26A	%
1	137.4	143.4	111.4	19.0	134.3	-2.3	132.8	-3.4	141.9	2.0	-1.1	131.2	-4.5
2	374.4	391.1	334.2	10.7	364.7	-2.6	361.6	-3.4	389.1	2.7	-0.5	357.7	-4.5
3	728.3	759.4	634.8	12.8	706.5	-3.0	700.4	-3.8	753.0	2.2	-0.8	697.0	-4.3
4	1175.8	1225.8	-	-	1141.4	-2.9	1132.2	-3.7	1215.4	2.2	-0.9	1126.1	-4.2
5	1710.3	1783.2	-	-	1662.4	-2.8	1646.4	-3.7	1770.0	2.4	-0.7	1640.0	-4.1
6	2319.8	2415.0	-	-	2250.7	-3.0	2230.8	-3.8	2394.1	2.1	-0.9	-	-
7	2994.3	3117.7	-	-	2907.6	-2.9	2882.4	-3.7	3103.6	2.5	-0.5	-	-
8	3708.9	3862.1	-	-	3605.2	-2.8	3570.6	-3.7	3845.2	2.5	-0.4	-	-

Table 4.7 Frequencies Results of Used Refractron 326 Filters (# Series).

Mode	203 hrs	1251 hrs	1351 hrs	3214 hrs	
#	4-981	2-992	2-977	4-1069	%
1	149.5	147.7	149.5	133.7	-10.1
2	404.4	403.7	405.9	364.4	-10.0
3	775.1	782.0	787.4	709.7	-9.6
4	1255.6	1262.2	1269.5	1143.2	-9.7
5	-	-	-	-	-
6	-	-	-	-	-
7	-	-	-	-	-
8	-	-	-	-	-

Table 4.8 Frequency Results of New and Used Refractron 442T Filters.

Mode #	New AV.(7)	1867 hrs		616 hrs	1251 hrs	%
		3-754		4-13A	5-8A	
		Hz	%	Hz	Hz	
1	142.82	137.3	-3.85	139.0	138.9	-0.1
2	391.90	373.8	-4.61	379.8	375.4	-1.2
3	758.67	730.9	-3.66	737.0	733.8	-0.4
4	1227.07	1168.8	-4.75	1190.2	1184.1	-0.5
5	1787.98	1701.4	-4.84	1733.4	1722.7	-0.6
6	2423.83	2305.6	-4.88	2346.8	2331.5	-0.7
7	-	-	-	3031.9	3010.6	-0.7
8	-	-	-	3756.7	3732.3	-0.6

Table 4.9 Experimental and FEM Frequency Values of Filter 2-24A.

Mode #	EXP Hz	FEM Hz	Diff %
1	111.39	112.05	-0.59
2	334.17	334.52	-0.10
3	634.77	640.34	-0.88

Table 4.10 Comparison of Experimental Frequencies of Clean and Dust Filters.

Mode #	Schumacher TF-20												Refractron 326		
	324-H04			324-H05			324-H07			344-E-232			1-51-A		
	Dust	Clean	%	Dust	Clean	%	Dust	Clean	%	Dust	Clean	%	Dust	Clean	%
	Hz	Hz		Hz	Hz		Hz	Hz		Hz	Hz		Hz	Hz	
1	122.1	119.0	-2.5	122.1	114.6	-6.1	123.6	114.6	-7.3	122.1	120.5	-1.3	138.8	132.8	4.4
2	334.2	325.0	-2.7	332.6	314.3	-5.5	337.2	314.3	-6.8	333.3	326.5	-2.0	378.6	361.6	4.5
3	653.1	635.2	-2.7	648.5	611.0	-5.8	657.7	614.9	-6.5	648.5	636.3	-1.9	736.8	700.4	4.9
4	1060.5	1031.5	-2.7	1052.9	995.0	-5.5	1069.6	1001.0	-6.4	1057.4	1036.1	-2.0	1187.1	1132.2	4.6
5	1544.2	1504.5	-2.6	1535.0	1451.1	-5.5	1562.5	1461.9	-6.4	1541.1	1510.6	-2.0	1727.1	1646.4	4.7
6	2099.6	2044.8	-2.6	2087.4	1973.3	-5.5	2122.0	1988.4	-6.3	2093.5	2050.8	-2.0	2337.6	2230.8	4.6
7	2710.0	2641.3	-2.5	2695.0	2549.9	-5.4	2745.1	2569.7	-6.4	2703.9	2652.0	-1.9	3019.7	2882.4	4.6
8	3370.7	3284.9	-2.5	3352.8	3174.0	-5.3	3412.0	3196.9	-6.3	3365.6	3299.3	-2.0	3738.4	3570.6	4.5

Figure 4.3 Young's Modulus Time History of Schumacher TF-20 Filters.

Figure 4.2 Young's Modulus of New and Used Refractron 326 Filters.

Figure 4.3 Young's Modulus of New and Used Refractron 442T Filters.

Figure 4.4 Averaged Young's Modulus of New and Used Ceramic Candle Filters.

Note: The numbers of specimens that are averaged are shown in the parentheses.

Figure 4.5 Three- Dimensional Damaged Filter Model.

Figure 4.6 Damaged location of Filter 2-24A.

CHAPTER V

CONCLUSIONS

5.1 TESTS ON NEW CERAMIC CANDLE FILTERS

In the study of sixty-nine new ceramic candle filters and three advanced ceramic filters, a nondestructive technique has been employed investigating the natural frequencies and mode shapes acquired from each filter specimen. The vibration signatures of the ceramic candle filters can be used as an index to quantify the structural properties of new candle filters. The modal frequencies are independent of the impact locations but are greatly influenced by shear deformation of the filter, especially in the higher modes. Timoshenko's beam equation can reduce the deviation between the experimental and the theoretical frequency values, especially in the higher modes. The average natural frequencies associated with Refractron 326 filter are found to be greater than the average frequencies of Schumacher TF-20, which are greater than the values of Coors P-100A-1. The accuracy of the modal data from the experiment was successfully verified by the beam equation and the FEM analysis.

The average Young's modulus values obtained for the Coors P-100A-1, Schumacher TF-20, Refractron 326 (A series) and Refractron 442T filters are about 4.3×10^6 psi, 6.2×10^6 psi, 7.4×10^6 psi and 8.1×10^6 psi, respectively, assuming nominal dimensional properties. The FEM model used can accurately reproduce the vibration response of the ceramic candle filters. The proposed NDE technique can be used for

the quality control of the candle filter manufacturing. Further research is needed to implement the NDE technique for studying ceramic composite filters.

5.2 TESTS ON USED CERAMIC CANDLE FILTERS

In the study of 29 used ceramic candle filters, a nondestructive technique has been employed investigating the natural frequencies and mode shapes acquired from each filter specimen. The vibration signatures of the candle filters were used to quantify the structural degradation of the filters. The FEM model can accurately reproduce the vibration response of used ceramic candle filters after being exposed to thermal and chemical environment at the PSDF. Results show that used filters have lower natural frequencies, which also indicate lower stiffness, than the new filters of their own group. Average stiffness reduction for the Schumacher TF-20 after 500 hrs and 982 hrs is about 5.6% and 13.6%, respectively, tracing the same filters. The average stiffness reduction between 460 hrs and 1060 hrs, and 1060 hrs and 1705 hrs of the specimen 317B-115 used Schumacher F-40 is about 4.5% and 6.7 %, respectively. Stiffness degradation tracing different filter specimens was also investigated. The average stiffness shift for the Refractron 326 (A series) after 400 hrs is about 5.9 % and for the Refractron 326 (# series), a stiffness reduction of 18.7% is seen from 1286 hrs to 3214 hrs. The average stiffness reduction for the Refractron 442T after 1867 hrs is about 8.41%.

The effect of dust-cake on the filter specimens increases the natural vibration frequencies without producing significant changes in the specimen's weight. This

phenomenon may be due to the hardness of the ash inside the filters' pores when exposed to the humidity. A combination of mode shape and strain energy analysis worked successfully in detecting a damaged zone along the filter span. The proposed NDE technique can be used to estimate stiffness of used candle filters during maintenance shutdowns. Further research is needed to implement the proposed NDE technique for the application of in-situ inspection at the power plant.

CHAPTER VI

APPLICATION AND RECOMMENDATIONS

The knowledge of the dynamic characteristics in many engineering structures is essential to measure changes in condition, and to ensure the efficient and safe performance of these structures. During the past few years, studies of ceramic candle filters have been conducted at West Virginia University. This study was conducted in order to understand the structural integrity of ceramic candle filters. The degradation of the filters due to long working hours was reflected from the shift of vibration frequency.

Attractive features of the proposed NDE method include low cost, nondestructive in nature, easy to conduct and has adequate sensitivity to identify stiffness degradation in the filters. Failures of ceramic filters during operation at the PSDF have been reported (Davidson et al., 1998), but the causes of these failures are not yet identified. Using this NDT method to understand the ceramic candle filter's in-situ dynamic behavior during operation may lead to new understanding of the causes of these failures.

The results of this study can be implemented to develop a nondestructive evaluation method for future in-situ inspection of the ceramic filters.

- Studies are needed to fine-tune the technique by adopting more robust signal processing techniques, and by establishing a more systematic testing procedure for on-site applications.

- More data should be collected with filters of varying ages. Specifically, more data are required for further validation of the experimental results for filters with longer heating cycles. Also, filters with different dust-cake properties and different heating conditions are needed for completion of a useful database.
- The studies conducted on the filter specimens at WVU laboratory worked successfully in a free-free boundary condition, which does not conform to the actual in-situ boundary conditions. Further studies are suggested to investigate the applicability of dynamic characterization method on in-situ conditions, and to establish a systematic testing procedure for field application.
- NDE study of ceramic composite filters is needed due to the increasing usage of these filters. The development of nondestructive testing procedures, FEM models, and damage detection algorithms is recommended for further evaluation of composite candle filters.

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APPENDIX-A

Frequency Response Function for a Typical Ceramic Candle Filter at Each Impact

Location (2-37A Refractron 326)

APPENDIX – B

Appendix B includes data from sixty-nine new ceramic candle filters tested nondestructively

B.1 Frequency Results for 12 New Coors

The frequencies from the tests conducted on the new Coors P-100A1 filters are tabulated in Tables B.1 to B.12. Frequencies obtained at different impact locations are shown on these tables for each one of the specimens.

Table B.1 Filter KC013

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	111.4	111.4	111.4	111.4	111.4	111.4	111.4	111.4	111.4	111.4	0.0
2	302.1	303.6	303.6	303.6	303.6	303.6	303.6	303.6	303.6	303.6	0.5
3	581.4	584.4	584.4	584.4	584.4	584.4	584.4	584.4	584.4	584.4	1.0
4	947.6	947.6	947.6	947.6	947.6	947.6	947.6	947.6	947.6	947.6	0.0
5	1374.8	1374.8	1374.8	1374.8	1374.8	1374.8	1374.8	1374.8	1374.8	1374.8	0.0
6	1855.5	1855.5	1855.5	1855.5	1855.5	1855.5	1855.5	1855.5	1855.5	1855.5	0.0
7	2392.6	2392.6	2394.1	2392.6	2392.6	2392.6	2394.1	2392.6	2392.6	2392.6	0.6
8	2949.5	2951.0	2951.0	2949.5	2951.0	2949.5	2951.0	2951.0	2949.5	2951.0	0.8

Table B.2 Filter KC014

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	109.9	111.4	109.9	109.9	109.9	109.9	109.9	109.9	109.9	109.9	0.5
2	299.1	300.6	300.6	300.6	300.6	300.6	300.6	300.6	299.1	300.6	0.6
3	581.4	582.9	582.9	582.9	582.9	581.4	581.4	581.4	581.4	581.4	0.8
4	941.5	941.5	941.5	941.5	941.5	941.5	941.5	941.5	941.5	941.5	0.0
5	1364.1	1364.1	1364.1	1364.1	1364.1	1364.1	1364.1	1364.1	1364.1	1364.1	0.0
6	1840.2	1840.2	1841.7	1840.2	1840.2	1840.2	1840.2	1840.2	1841.7	1841.7	0.7
7	2348.3	2348.3	2346.8	2348.3	2348.3	2348.3	2348.3	2348.3	2348.3	2348.3	0.5
8	2916.0	2916.0	2916.0	2916.0	2914.2	2916.0	2916.0	2916.0	2916.0	2916.0	0.6

Table B.3 Filter KC015

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	114.4	114.4	114.4	114.4	114.4	114.4	114.4	114.4	114.4	114.4	0.0
2	312.8	311.3	312.8	311.3	311.3	311.3	311.3	311.3	311.3	311.3	0.6
3	602.7	602.7	602.7	602.7	602.7	602.7	602.7	602.7	602.7	602.7	0.0
4	973.5	973.5	973.5	973.5	972.0	973.5	973.5	973.5	973.5	973.5	0.5
5	1413.0	1413.0	1413.0	1413.0	1413.0	1413.0	1413.0	1413.0	1413.0	1413.0	0.0
6	1907.3	1907.3	1907.3	1907.3	1907.3	1907.3	1907.3	1907.3	1907.3	1907.3	0.0
7	2461.2	2459.7	2461.2	2459.7	2461.2	2461.2	2461.2	2461.2	2461.2	2461.2	0.6
8	3035.0	3035.0	3035.0	3035.0	3035.0	3035.0	3035.0	3035.0	3035.0	3035.0	0.0

Table B.4 Filter KC016

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	112.9	112.9	112.9	112.9	112.9	112.9	112.9	112.9	112.9	112.9	0.0
2	306.7	306.7	306.7	306.7	306.7	306.7	306.7	306.7	306.7	306.7	0.0
3	590.5	590.5	590.5	590.5	590.5	590.5	590.5	590.5	590.5	590.5	0.0
4	958.3	958.3	958.3	958.3	958.3	958.3	958.3	958.3	958.3	958.3	0.0
5	1391.6	1391.6	1391.6	1391.6	1391.6	1391.6	1391.6	1391.6	1391.6	1391.6	0.0
6	1876.8	1876.8	1876.8	1876.8	1876.8	1876.8	1876.8	1876.8	1876.8	1876.8	0.0
7	2420.0	2420.0	2420.0	2420.0	2420.0	2420.0	2420.0	2420.0	2420.0	2420.0	0.0
8	2986.1	2986.1	2986.1	2986.1	2986.1	2987.7	2986.1	2986.1	2986.1	2986.1	0.5

Table B.5 Filter KC025

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	111.4	111.4	111.4	111.4	111.4	111.4	111.4	111.4	111.4	111.4	0.0
2	302.1	302.1	302.1	302.1	300.6	302.1	302.1	302.1	302.1	302.1	0.5
3	582.9	584.4	584.4	584.4	584.4	584.4	584.4	584.4	584.4	584.4	0.5
4	943.0	943.0	943.0	943.0	943.0	943.0	943.0	943.0	943.0	943.0	0.0
5	1371.8	1371.8	1371.8	1371.8	1371.8	1371.8	1371.8	1371.8	1371.8	1371.8	0.0
6	1847.8	1847.8	1847.8	1847.8	1847.8	1847.8	1847.8	1847.8	1847.8	1847.8	0.0
7	2383.4	2383.4	2383.4	2383.4	2383.4	2383.4	2384.9	2383.4	2381.9	2383.4	0.7
8	2944.9	2944.9	2944.9	2944.9	2944.9	2944.9	2946.5	2944.9	2946.5	2944.9	0.6

Table B.6 Filter KC026

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	109.9	111.4	109.9	109.9	109.9	109.9	109.9	109.9	109.9	109.9	0.5
2	300.6	300.6	300.6	300.6	300.6	300.6	300.6	300.6	300.6	300.6	0.0
3	573.7	573.7	573.7	573.7	573.7	573.7	573.7	573.7	573.7	575.3	0.5
4	930.8	930.8	930.8	930.8	930.8	930.8	930.8	930.8	930.8	930.8	0.0
5	1351.9	1351.9	1351.9	1353.5	1351.9	1351.9	1351.9	1351.9	1351.9	1351.9	0.5
6	1828.0	1828.0	1828.0	1828.0	1828.0	1828.0	1828.0	1828.0	1828.0	1828.0	0.0
7	2365.1	2365.1	2365.1	2365.1	2365.1	2365.1	2366.6	2365.1	2365.1	2365.1	0.5
8	2916.0	2917.0	2916.0	2916.0	2916.0	2916.0	2916.0	2916.0	2916.0	2916.0	0.3

Table B.7 Filter KC028

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	112.9	112.9	112.9	112.9	112.9	112.9	112.9	112.9	112.9	112.9	0.0
2	306.7	306.7	306.7	306.7	303.6	306.7	306.7	306.7	306.7	306.7	0.9
3	592.0	592.0	592.0	592.0	592.0	592.0	592.0	592.0	593.6	592.0	0.6
4	958.3	958.3	958.3	958.3	958.3	958.3	958.3	958.3	958.3	958.3	0.0
5	1391.6	1391.6	1391.6	1391.6	1391.6	1391.6	1391.6	1391.6	1391.6	1391.6	0.0
6	1873.8	1875.3	1875.3	1875.3	1875.3	1875.3	1875.3	1875.3	1876.8	1876.8	0.9
7	2429.2	2429.2	2429.2	2429.2	2429.2	2429.2	2430.7	2430.7	2430.7	2430.7	0.8
8	2966.3	2966.3	2966.3	2966.3	2966.3	2966.3	2966.3	2966.3	2966.3	2966.3	0

Table B.8 Filter KC029

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	112.9	112.9	112.9	112.9	112.9	112.9	112.9	112.9	112.9	112.9	0.0
2	308.2	306.7	306.7	308.2	308.2	306.7	306.7	306.7	306.7	306.7	0.7
3	593.6	593.6	593.6	593.6	593.6	593.6	593.6	593.6	593.6	593.6	0.0
4	959.3	959.3	959.3	959.3	959.3	959.3	959.3	959.3	959.3	959.3	0.0
5	1390.1	1390.1	1390.1	1390.1	1390.1	1390.1	1390.1	1390.1	1390.1	1390.1	0.0
6	1878.4	1878.4	1878.4	1878.4	1878.4	1879.9	1879.9	1878.4	1878.4	1878.4	0.6
7	2433.8	2433.8	2432.3	2432.3	2432.3	2432.3	2432.3	2432.3	2432.3	2432.3	0.6
8	2998.4	2996.8	2996.8	2996.8	2998.4	2996.8	2998.4	2996.8	2996.8	2996.8	0.7

Table B.9 Filter KC030

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	114.4	114.4	114.4	114.4	114.4	114.4	114.4	114.4	114.4	114.4	0.0
2	311.3	311.3	311.3	311.3	311.3	311.3	311.3	311.3	311.3	311.3	0.0
3	602.7	602.7	602.7	602.7	602.7	602.7	602.7	602.7	602.7	602.7	0.0
4	970.5	970.5	970.5	970.5	970.5	970.5	970.5	970.5	970.5	970.5	0.0
5	1406.9	1406.9	1406.9	1406.9	1406.9	1406.9	1406.9	1406.9	1406.9	1406.9	0.0
6	1901.2	1901.2	1901.2	1901.2	1901.2	1901.2	1901.2	1901.2	1901.2	1901.2	0.0
7	2449.0	2449.0	2449.0	2449.0	2449.0	2449.0	2449.0	2449.0	2449.0	2449.0	0.0
8	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	3021.2	3021.2	3022.8	3022.8	0.6

Table B.10 Filter KC031

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	111.4	109.9	111.4	111.4	111.4	111.4	111.4	111.4	111.4	111.4	0.5
2	303.6	303.6	303.6	303.6	303.6	303.6	303.6	303.6	303.6	303.6	0.0
3	585.9	585.9	585.9	585.9	585.9	585.9	585.9	585.9	585.9	585.9	0.0
4	944.5	944.5	944.5	944.5	946.0	944.5	944.5	944.5	944.5	944.5	0.5
5	1371.8	1371.8	1371.8	1371.8	1371.8	1371.8	1371.8	1371.8	1371.8	1371.8	0.0
6	1852.4	1852.4	1852.4	1852.4	1852.4	1852.4	1852.4	1852.4	1852.4	1852.4	0.0
7	2386.5	2386.5	2386.5	2386.5	2386.5	2386.5	2386.5	2386.5	2386.5	2388.0	0.5
8	2954.1	2954.1	2954.1	2954.1	2954.1	2954.1	2954.1	2954.1	2954.1	2954.1	0.0

Table B.11 Filter KC032

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	109.9	109.9	109.9	109.9	109.9	109.9	109.9	109.9	109.9	109.9	0.0
2	300.6	300.6	300.6	300.6	300.6	300.6	300.6	300.6	300.6	300.6	0.0
3	581.4	581.4	581.4	581.4	581.4	581.4	581.4	581.4	581.4	581.4	0.0
4	936.9	936.9	936.9	936.9	936.9	936.9	936.9	936.9	936.9	936.9	0.0
5	1364.1	1364.1	1364.1	1364.1	1364.1	1364.1	1364.1	1364.1	1364.1	1364.1	0.0
6	1838.7	1838.7	1838.7	1838.7	1838.7	1838.7	1838.7	1838.7	1838.7	1838.7	0.0
7	2369.7	2369.7	2369.7	2369.7	2369.7	2369.7	2368.2	2369.7	2369.7	2369.7	0.5
8	2925.1	2925.1	2925.1	2925.1	2925.1	2925.1	2925.1	2925.1	2925.1	2925.1	0.0

Table B.12 Filter LC023

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	114.4	114.4	114.4	112.9	112.9	112.9	114.4	112.9	112.9	114.4	0.8
2	312.8	311.3	311.3	311.3	311.3	311.3	311.3	311.3	311.3	311.3	0.5
3	599.7	599.7	599.7	599.7	599.7	599.7	599.7	599.7	599.7	599.7	0.0
4	967.4	967.4	967.4	967.4	967.4	967.4	967.4	967.4	967.4	967.4	0.0
5	1408.4	1408.4	1408.4	1408.4	1408.4	1408.4	1408.4	1408.4	1408.4	1408.4	0.0
6	1895.1	1895.1	1895.1	1895.1	1895.1	1895.1	1895.1	1895.1	1895.1	1895.1	0.0
7	2447.5	2447.5	2447.5	2447.5	2447.5	2445.5	2447.5	2445.5	2445.5	2447.5	1.0
8	3027.3	3027.3	3027.3	3027.3	3027.3	3027.3	3027.3	3027.3	3027.3	3027.3	0.0

B.2 Frequency Results for 24 New Schumacher TF-20

The frequencies from the tests conducted on the new Schumacher TF-20 filters are tabulated in Tables B.13 to B.36. Frequencies obtained at different impact locations are shown on these tables for each one of the specimens.

Table B.13 Filter 324H01

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	119.0	119.0	119.0	119.0	119.0	119.0	119.0	119.0	119.0	119.0	0.0
2	326.5	326.5	326.5	326.5	326.5	326.5	326.5	326.5	326.5	326.5	0.0
3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	634.8	0.5
4	1031.5	1031.5	1031.5	1031.5	1031.5	1031.5	1031.5	1031.5	1031.5	1031.5	0.0
5	1506.0	1506.0	1506.0	1506.0	1506.0	1506.0	1506.0	1506.0	1506.0	1506.0	0.0
6	2043.2	2043.2	2043.2	2043.2	2043.2	2043.2	2043.2	2043.2	2043.2	2041.6	0.5
7	2647.5	2648.9	2648.9	2647.5	2647.5	2647.5	2647.5	2647.5	2647.5	2647.5	0.6
8	3289.8	3288.3	3288.3	3288.3	3288.3	3289.8	3288.3	3288.3	3288.3	3288.3	0.6

Table B.14 Filter 324H03

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	0.0
2	332.6	332.6	332.6	332.6	332.6	332.6	332.6	332.6	332.6	332.6	0.0
3	647.0	647.0	647.0	647.0	647.0	647.0	647.0	647.0	647.0	647.0	0.0
4	1052.9	1052.9	1052.9	1052.9	1052.9	1052.9	1052.9	1052.9	1052.9	1052.9	0.0
5	1536.6	1536.6	1536.6	1536.6	1536.6	1536.6	1536.6	1536.6	1536.6	1536.6	0.0
6	2085.9	2085.9	2085.9	2085.9	2085.9	2085.9	2085.9	2085.9	2085.9	2085.9	0.0
7	2705.4	2705.4	2705.4	2705.4	2705.4	2706.9	2705.4	2706.9	2705.4	2706.9	0.7
8	3344.7	3344.7	3344.7	3344.7	3344.7	3344.7	3344.7	3344.7	3344.7	3344.7	0.0

Table B.15 Filter 324H04

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	0.0
2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	0.0
3	654.6	654.6	654.6	654.6	654.6	654.6	654.6	654.6	654.6	654.6	0.0
4	1063.5	1063.5	1063.5	1063.5	1063.5	1063.5	1063.5	1063.5	1063.5	1063.5	0.0
5	1551.8	1551.8	1551.8	1551.8	1551.8	1551.8	1551.8	1551.8	1551.8	1551.8	0.0
6	2104.2	2104.2	2104.2	2104.2	2104.2	2104.2	2104.2	2104.2	2104.2	2104.2	0.0
7	2725.2	2725.2	2725.2	2723.7	2725.2	2725.2	2725.2	2725.2	2725.2	2725.2	0.5
8	3375.2	3375.2	3375.2	3376.8	3375.2	3375.2	3375.2	3376.8	3375.2	3375.2	0.6

Table B.16 Filter 324H05

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	120.5	120.5	120.5	120.5	120.5	120.5	120.5	120.5	120.5	120.5	0.0
2	328.1	328.1	328.1	328.1	328.1	328.1	328.1	328.1	328.1	328.1	0.0
3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	0.0
4	1034.5	1034.5	1034.5	1034.5	1034.5	1034.5	1034.5	1034.5	1034.5	1034.5	0.0
5	1510.6	1510.6	1510.6	1509.7	1510.6	1510.6	1510.6	1510.6	1510.6	1510.6	0.3
6	2049.3	2049.3	2049.3	2049.3	2049.3	2049.3	2049.3	2049.3	2049.3	2049.3	0.0
7	2661.1	2659.6	2659.6	2661.1	2661.1	2661.1	2662.7	2661.1	2661.1	2661.1	0.9
8	3291.3	3291.3	3291.3	3291.3	3292.8	3291.3	3291.3	3291.3	3291.3	3291.3	0.5

Table B.17 Filter 324H06

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	0.0
2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	0.0
3	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	0.0
4	1055.9	1055.9	1055.9	1055.9	1055.9	1055.9	1055.9	1055.9	1055.9	1055.9	0.0
5	1535.0	1535.0	1535.0	1535.0	1535.0	1535.0	1535.0	1535.0	1535.0	1535.0	0.0
6	2081.3	2082.8	2081.3	2081.3	2082.8	2081.3	2082.8	2082.8	2082.8	2082.8	0.8
7	2696.2	2696.2	2696.2	2696.2	2696.2	2696.2	2696.2	2696.2	2696.2	2696.2	0.0
8	3344.7	3344.7	3344.7	3344.7	3344.7	3344.7	3344.7	3344.7	3344.7	3344.7	0.0

Table B.18 Filter 324H07

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	0.0
2	320.4	320.4	320.4	320.4	320.4	320.4	320.4	320.4	320.4	320.4	0.0
3	624.1	624.1	624.1	624.1	624.1	624.1	624.1	624.1	624.1	624.1	0.0
4	1016.2	1016.2	1016.2	1016.2	1016.2	1016.2	1016.2	1016.2	1016.2	1016.2	0.0
5	1484.7	1484.7	1484.7	1484.7	1484.7	1484.7	1484.7	1484.7	1484.7	1484.7	0.0
6	2015.7	2015.7	2015.7	2015.7	2015.7	2015.7	2015.7	2015.7	2015.7	2015.7	0.0
7	2615.4	2615.4	2615.4	2615.4	2615.4	2615.4	2615.4	2615.4	2615.4	2615.4	0.0
8	3241.0	3241.0	3241.0	3241.0	3241.0	3241.0	3241.0	3241.0	3241.0	3241.0	0.0

Table B.19 Filter 324H08

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	116.0	116.0	116.0	116.0	116.0	116.0	116.0	116.0	116.0	116.0	0.0
2	320.4	320.4	320.4	320.4	320.4	320.4	320.4	320.4	320.4	320.4	0.0
3	624.1	624.1	624.1	624.1	624.1	624.1	624.1	624.1	624.1	624.1	0.0
4	1014.7	1014.7	1014.7	1014.7	1014.7	1014.7	1014.7	1014.7	1014.7	1014.7	0.0
5	1477.1	1477.1	1477.1	1477.1	1477.1	1477.1	1477.1	1477.1	1477.1	1477.1	0.0
6	2006.5	2006.5	2006.5	2006.5	2006.5	2006.5	2006.5	2006.5	2006.5	2006.5	0.0
7	2598.6	2598.6	2598.6	2598.6	2598.6	2598.6	2600.1	2598.6	2598.6	2598.6	0.5
8	3222.7	3222.7	3222.7	3222.7	3222.7	3222.7	3222.7	3222.7	3222.7	3222.7	0.0

Table B.20 Filter 324H09

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	0.0
2	323.5	323.5	323.5	323.5	323.5	323.5	323.5	323.5	323.5	323.5	0.0
3	630.2	630.2	630.2	630.2	630.2	630.2	630.2	630.2	630.2	630.2	0.0
4	1023.9	1023.9	1023.9	1023.9	1023.9	1023.9	1023.9	1023.9	1023.9	1023.9	0.0
5	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	1493.8	0.0
6	2027.9	2027.9	2027.9	2027.9	2027.9	2027.9	2027.9	2027.9	2027.9	2027.9	0.0
7	2619.9	2619.9	2619.9	2619.9	2619.9	2619.9	2619.9	2619.9	2619.9	2619.9	0.0
8	3253.2	3253.2	3253.2	3253.2	3253.2	3253.2	3253.2	3253.2	3253.2	3253.2	0.0

Table B.21 Filter 324H10

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	0.0
2	332.6	332.6	332.6	332.6	332.6	332.6	332.6	332.6	332.6	332.6	0.0
3	648.5	648.5	648.5	648.5	648.5	648.5	648.5	648.5	648.5	648.5	0.0
4	1055.9	1055.9	1055.9	1055.9	1055.9	1055.9	1055.9	1055.9	1055.9	1055.9	0.0
5	1541.1	1541.1	1541.1	1541.1	1541.1	1541.1	1541.1	1541.1	1541.1	1541.1	0.0
6	2087.4	2087.4	2087.4	2087.4	2087.4	2087.4	2087.4	2087.4	2087.4	2087.4	0.0
7	2702.3	2703.9	2706.9	2703.9	2705.4	2703.9	2703.9	2703.9	2703.9	2703.9	0.9
8	3341.7	3341.7	3341.7	3341.7	3341.7	3341.7	3341.7	3341.7	3341.7	3341.7	0.0

Table B.22 Filter 324H11

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	0.0
2	322.0	322.0	322.0	322.0	322.0	322.0	322.0	322.0	322.0	322.0	0.0
3	625.6	625.6	625.6	625.6	625.6	625.6	625.6	625.6	625.6	625.6	0.0
4	1019.3	1019.3	1019.3	1019.3	1019.3	1019.3	1019.3	1019.3	1019.3	1019.3	0.0
5	1486.2	1486.2	1486.2	1486.2	1486.2	1486.2	1486.2	1486.2	1486.2	1486.2	0.0
6	2015.7	2015.7	2015.7	2015.7	2015.7	2015.7	2015.7	2015.7	2015.7	2015.7	0.0
7	2615.4	2613.8	2613.8	2613.8	2615.4	2615.4	2615.4	2615.4	2615.4	2615.4	0.7
8	3231.8	3231.8	3231.8	3231.8	3231.8	3231.8	3231.8	3231.8	3231.8	3231.8	0.0

Table B.23 Filter 324H21

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	125.1	125.1	125.1	125.1	125.1	125.1	125.1	125.1	125.1	125.1	0.0
2	341.8	341.8	341.8	341.8	341.8	341.8	341.8	341.8	341.8	341.8	0.0
3	665.3	666.8	666.8	666.8	666.8	666.8	666.8	666.8	666.8	666.8	0.5
4	1081.8	1081.8	1081.8	1081.8	1081.8	1081.8	1081.8	1081.8	1081.8	1081.8	0.0
5	1574.7	1574.7	1574.7	1574.7	1574.7	1574.7	1574.7	1574.7	1574.7	1574.7	0.0
6	2134.7	2134.7	2134.7	2134.7	2134.7	2134.7	2134.7	2134.7	2134.7	2134.7	0.0
7	2769.5	2769.5	2769.5	2769.5	2771.0	2771.0	2769.5	2771.0	2771.0	2771.0	0.8
8	3418.0	3418.0	3418.0	3418.0	3418.0	3419.5	3418.0	3418.0	3419.5	3418.0	0.6

Table B.24 Filter 324E232

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	119.0	119.0	119.0	119.0	119.0	119.0	119.0	119.0	119.0	119.0	0.0
2	322.0	322.0	322.0	322.0	322.0	322.0	322.0	322.0	322.0	322.0	0.0
3	627.1	627.1	627.1	627.1	627.1	627.1	627.1	627.1	627.1	627.1	0.0
4	1019.3	1019.3	1019.3	1019.3	1019.3	1019.3	1019.3	1019.3	1019.3	1019.3	0.0
5	1486.2	1486.2	1486.2	1486.2	1486.2	1486.2	1486.2	1486.2	1486.2	1486.2	0.0
6	2020.3	2020.3	2020.3	2020.3	2021.8	2020.3	2020.3	2020.3	2020.3	2020.3	0.5
7	2610.8	2610.8	2610.8	2610.8	2610.8	2610.8	2610.8	2610.8	2610.8	2610.8	0.0
8	3250.1	3250.1	3250.1	3250.1	3250.1	3250.1	3248.6	3250.1	3248.6	3248.6	0.7

Table B.25 Filter 379H145

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	0.0
2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	0.0
3	657.7	657.7	657.7	657.7	657.7	657.7	657.7	657.7	657.7	657.7	0.0
4	1071.2	1071.2	1071.2	1071.2	1071.2	1071.2	1071.2	1071.2	1071.2	1071.2	0.0
5	1561.0	1561.0	1561.0	1561.0	1561.0	1561.0	1561.0	1561.0	1561.0	1561.0	0.0
6	2122.5	2122.5	2122.5	2122.5	2122.5	2122.5	2122.5	2122.5	2122.5	2122.5	0.0
7	2745.1	2743.5	2743.5	2743.5	2743.5	2743.5	2743.5	2743.5	2743.5	2743.5	0.5
8	3407.3	3407.3	3407.3	3407.3	3407.3	3407.3	3407.3	3407.3	3407.3	3407.3	0.0

Table B.26 Filter 379H146

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	0.0
2	325.0	323.5	323.5	323.5	323.5	323.5	323.5	323.5	323.5	323.5	0.5
3	634.8	634.8	634.8	634.8	634.8	634.8	634.8	634.8	634.8	634.8	0.0
4	1033.0	1033.0	1033.0	1033.0	1033.0	1033.0	1033.0	1033.0	1033.0	1033.0	0.0
5	1507.6	1507.6	1507.6	1507.6	1507.6	1507.6	1507.6	1507.6	1507.6	1507.6	0.0
6	2050.8	2052.1	2050.8	2050.8	2050.8	2050.8	2050.8	2050.8	2050.8	2050.8	0.4
7	2652.0	2652.0	2652.0	2652.0	2652.0	2652.0	2652.0	2652.0	2652.0	2652.0	0.0
8	3300.5	3300.5	3300.5	3300.5	3300.5	3300.5	3300.5	3300.5	3300.5	3300.5	0.0

Table B.27 Filter 379H147

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	0.0
2	335.7	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	0.5
3	656.1	654.6	654.6	654.6	654.6	654.6	654.6	654.6	654.6	654.6	0.5
4	1062.0	1062.0	1062.0	1062.0	1062.0	1062.0	1062.0	1062.0	1062.0	1062.0	0.0
5	1548.8	1547.1	1547.1	1547.1	1547.1	1547.1	1547.1	1547.1	1547.1	1547.1	0.5
6	2105.7	2105.7	2105.7	2105.7	2105.7	2105.7	2105.7	2105.7	2105.7	2105.7	0.0
7	2722.2	2720.6	2720.6	2720.6	2720.6	2720.6	2720.6	2720.6	2720.6	2720.6	0.5
8	3382.9	3381.1	3381.1	3381.1	3381.1	3381.1	3381.1	3381.1	3381.1	3381.1	0.6

Table B.28 Filter 379H148

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	120.5	120.5	120.5	120.5	120.5	120.5	120.5	120.5	120.5	120.5	0.0
2	329.6	329.6	329.6	329.6	329.6	329.6	329.6	329.6	329.6	329.6	0.0
3	643.9	643.9	643.9	643.9	643.9	643.9	643.9	643.9	643.9	643.9	0.0
4	1045.2	1045.2	1045.2	1045.2	1045.2	1045.2	1045.2	1045.2	1045.2	1045.2	0.0
5	1524.9	1524.9	1524.9	1524.9	1524.9	1524.9	1524.9	1524.9	1524.9	1524.9	0.0
6	2073.7	2073.7	2073.7	2073.7	2073.7	2073.7	2073.7	2073.7	2073.7	2073.7	0.0
7	2677.9	2677.9	2677.9	2677.9	2677.9	2677.9	2677.9	2677.9	2677.9	2677.9	0.0
8	3332.5	3332.5	3332.5	3332.5	3332.5	3332.5	3332.5	3332.5	3332.5	3332.5	0.0

Table B.29 Filter 379H149

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	122.1	120.5	120.5	120.5	120.5	120.5	120.5	120.5	120.5	120.5	0.5
2	331.1	331.1	331.1	331.1	331.1	331.1	331.1	331.1	331.1	331.1	0.0
3	643.9	643.9	643.9	643.9	643.9	643.9	643.9	643.9	643.9	643.9	0.0
4	1048.3	1048.3	1048.3	1048.3	1048.3	1048.3	1048.3	1048.3	1048.3	1048.3	0.0
5	1528.9	1528.9	1528.9	1528.9	1528.9	1528.9	1528.9	1528.9	1528.9	1528.9	0.0
6	2078.2	2078.2	2078.2	2078.2	2078.2	2078.2	2078.2	2078.2	2078.2	2078.2	0.0
7	2685.5	2685.5	2685.5	2685.5	2685.5	2685.5	2685.5	2685.5	2685.5	2685.5	0.0
8	3340.1	3340.1	3340.1	3340.1	3340.1	3340.1	3340.1	3340.1	3340.1	3340.1	0.0

Table B.30 Filter 379H150

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	122.1	0.0
2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	334.2	0.0
3	653.1	653.1	653.1	653.1	653.1	653.1	653.1	653.1	653.1	653.1	0.0
4	1062.0	1062.0	1062.0	1062.0	1062.0	1062.0	1062.0	1062.0	1062.0	1062.0	0.0
5	1550.3	1550.3	1550.3	1550.3	1550.3	1550.3	1550.3	1550.3	1550.3	1550.3	0.0
6	2105.7	2105.7	2105.7	2105.7	2105.7	2105.7	2105.7	2105.7	2105.7	2105.7	0.0
7	2722.2	2722.2	2722.2	2722.2	2722.2	2722.2	2722.2	2722.2	2722.2	2722.2	0.0
8	3382.9	3382.9	3382.9	3382.9	3382.9	3382.9	3382.9	3382.9	3382.9	3382.9	0.0

Table B.31 Filter 379H151

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	0.0
2	340.3	338.7	338.7	338.7	338.7	338.7	338.7	338.7	338.7	338.7	0.5
3	663.8	663.8	663.8	663.8	663.8	663.8	663.8	663.8	663.8	663.8	0.0
4	1077.3	1077.3	1077.3	1077.3	1077.3	1077.3	1077.3	1077.3	1077.3	1077.3	0.0
5	1571.7	1571.7	1571.7	1571.7	1571.7	1571.7	1571.7	1571.7	1571.7	1571.7	0.0
6	2137.8	2137.8	2137.8	2137.8	2137.8	2137.8	2137.8	2137.8	2137.8	2137.8	0.0
7	2763.4	2763.4	2761.8	2761.8	2761.8	2761.8	2761.8	2761.8	2761.8	2761.8	0.6
8	3434.8	3434.8	3434.8	3433.2	3433.2	3433.2	3433.2	3433.2	3433.2	3433.2	0.7

Table B.32 Filter 379H160

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	0.0
2	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	0.0
3	637.8	639.3	637.8	637.8	637.8	637.8	637.8	637.8	637.8	637.8	0.5
4	1039.1	1039.1	1039.1	1039.1	1039.1	1039.1	1039.1	1039.1	1039.1	1039.1	0.0
5	1515.2	1515.2	1515.2	1515.2	1515.2	1515.2	1515.2	1515.2	1515.2	1515.2	0.0
6	2061.5	2061.5	2061.5	2061.5	2061.5	2061.5	2061.5	2061.5	2061.5	2061.5	0.0
7	2662.7	2662.7	2662.7	2662.7	2662.7	2662.7	2662.7	2662.7	2662.7	2662.7	0.0
8	3314.2	3314.2	3314.2	3312.7	3312.7	3312.7	3314.2	3312.7	3314.2	3312.7	0.8

Table B.33 Filter 379H161

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	0.0
2	338.7	338.7	338.7	338.7	338.7	338.7	338.7	338.7	338.7	338.7	0.0
3	660.7	660.7	660.7	660.7	660.7	660.7	660.7	660.7	660.7	660.7	0.0
4	1072.7	1072.7	1072.7	1072.7	1072.7	1072.7	1072.7	1072.7	1072.7	1072.7	0.0
5	1564.0	1564.0	1564.0	1564.0	1564.0	1564.0	1564.0	1564.0	1564.0	1564.0	0.0
6	2128.6	2128.6	2127.1	2127.1	2127.1	2127.1	2127.1	2127.1	2127.1	2127.1	0.6
7	2749.6	2749.6	2749.6	2749.6	2749.6	2749.6	2749.6	2749.6	2749.6	2749.6	0.0
8	3418.0	3418.0	3418.0	3418.0	3418.0	3418.0	3418.0	3418.0	3418.0	3418.0	0.0

Table B.34 Filter 379H162

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	128.2	128.2	128.2	128.2	128.2	128.2	128.2	128.2	128.2	128.2	0.0
2	354.0	354.0	354.0	354.0	354.0	354.0	354.0	354.0	354.0	354.0	0.0
3	686.6	686.6	686.6	686.6	686.6	686.6	686.6	686.6	686.6	686.6	0.0
4	1115.4	1115.4	1115.4	1115.4	1115.4	1115.4	1115.4	1115.4	1115.4	1115.4	0.0
5	1625.5	1625.5	1625.5	1625.5	1625.5	1625.5	1625.5	1625.5	1625.5	1625.5	0.0
6	2203.4	2203.4	2203.4	2203.4	2203.4	2203.4	2203.4	2203.4	2203.4	2203.4	0.0
7	2844.2	2844.2	2844.2	2844.2	2844.2	2844.2	2844.2	2844.2	2844.2	2844.2	0.0
8	3533.9	3533.9	3533.9	3533.9	3533.9	3533.9	3533.9	3533.9	3533.9	3533.9	0.0

Table B.35 Filter 379H163

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	123.6	0.0
2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	337.2	0.0
3	657.7	657.7	657.7	657.7	657.7	657.7	657.7	657.7	657.7	657.7	0.0
4	1068.1	1068.1	1068.1	1068.1	1068.1	1068.1	1068.1	1068.1	1068.1	1068.1	0.0
5	1557.9	1557.9	1557.9	1557.9	1557.9	1557.9	1557.9	1557.9	1557.9	1557.9	0.0
6	2117.4	2117.9	2117.9	2117.9	2117.9	2117.9	2117.9	2117.9	2117.9	2117.9	0.5
7	2737.5	2737.5	2737.5	2737.5	2737.5	2737.5	2737.5	2737.5	2737.5	2737.5	0.0
8	3404.2	3404.2	3404.2	3404.2	3404.2	3404.2	3404.2	3404.2	3404.2	3404.2	0.0

Table B.36 Filter 379H164

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	119.0	117.5	119.0	119.0	119.0	119.0	119.0	119.0	119.0	119.0	0.5
2	326.5	326.5	326.5	326.5	326.5	326.5	326.5	326.5	326.5	326.5	0.0
3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	636.3	0.0
4	1036.1	1036.1	1036.1	1036.1	1036.1	1036.1	1036.1	1036.1	1036.1	1036.1	0.0
5	1510.6	1510.6	1509.1	1509.1	1509.1	1509.1	1509.1	1509.1	1509.1	1509.1	0.6
6	2053.8	2053.8	2053.8	2053.8	2053.8	2053.8	2053.8	2053.8	2053.8	2053.8	0.0
7	2653.5	2653.5	2653.5	2653.5	2653.5	2653.5	2653.5	2653.5	2653.5	2653.5	0.0
8	3302.0	3300.5	3300.5	3300.5	3300.5	3300.5	3300.5	3300.5	3300.5	3300.5	0.5

B.3 Frequency Results for 25 New Refractron 326

The frequencies from the tests conducted on the Refractron 326 (A series) filters have been tabulated in Tables B.37 to B.59. Tables B.60 and B.61 show the frequencies from the tests conducted on the Refractron 326 (# series). Frequencies obtained at different impact locations are shown on these tables for each one of the specimens.

Table B.37 Filter 1-22A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	129.7	131.2	129.7	129.7	129.7	129.7	129.7	131.2	129.7	129.7	0.6
2	354.0	354.0	354.0	354.0	354.0	354.0	354.0	354.0	354.0	354.0	0.0
3	689.7	691.2	691.2	689.7	689.7	689.7	689.7	689.7	689.7	689.7	0.6
4	1118.5	1118.5	1118.5	1118.5	1118.5	1118.5	1118.5	1118.5	1118.5	1118.5	0.0
5	1628.1	1628.1	1628.1	1628.1	1628.1	1628.1	1628.1	1628.1	1628.1	1628.1	0.0
6	2204.9	2204.9	2204.9	2204.9	2204.9	2204.9	2204.9	2204.9	2204.9	2204.9	0.5
7	2847.3	2847.3	2847.3	2847.3	2847.3	2847.3	2847.3	2847.3	2847.3	2847.3	0.0
8	3530.9	3529.4	3529.4	3529.4	3529.4	3529.4	3529.4	3529.4	3529.4	3529.4	0.5

Table B.38 Filter 1-35A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	143.4	143.4	143.4	143.4	143.4	143.4	143.4	143.4	143.4	143.4	0.0
2	390.6	390.6	390.6	390.6	390.6	390.6	390.6	390.6	390.6	390.6	0.0
3	759.9	759.9	759.9	759.9	759.9	759.9	759.9	759.9	759.9	759.9	0.0
4	1226.8	1226.8	1226.8	1226.8	1226.8	1226.8	1226.8	1226.8	1226.8	1226.8	0.0
5	1783.8	1783.8	1783.8	1783.8	1783.8	1783.8	1783.8	1783.8	1783.8	1783.8	0.0
6	2415.5	2415.5	2415.5	2415.5	2415.5	2415.5	2415.5	2415.5	2415.5	2415.5	0.0
7	3118.9	3118.9	3118.9	3118.9	3118.9	3118.9	3118.9	3118.9	3118.9	3118.9	0.0
8	3865.1	3865.1	3863.5	3863.5	3863.5	3863.5	3863.5	3863.5	3863.5	3863.5	0.6

Table B.39 Filter 1-37A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	0.0
2	379.9	378.9	379.9	379.9	379.9	379.9	379.9	379.9	378.9	379.9	0.4
3	741.6	740.1	740.1	740.1	740.1	740.1	740.1	740.1	740.1	740.1	0.5
4	1194.8	1194.8	1194.8	1194.8	1194.8	1194.8	1194.8	1194.8	1194.8	1194.8	0.0
5	1738.0	1738.0	1738.0	1738.0	1738.0	1738.0	1738.0	1738.0	1738.0	1738.0	0.0
6	2357.5	2357.5	2356.0	2356.0	2356.0	2356.0	2356.0	2356.0	2356.0	2356.0	0.6
7	3042.6	3044.1	3042.6	3042.6	3042.6	3042.6	3042.6	3042.6	3042.6	3042.6	0.5
8	3770.4	3770.4	3770.4	3770.4	3770.4	3770.4	3770.4	3770.4	3770.4	3770.4	0.0

Table B.40 Filter 1-38A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	0.0
2	378.9	376.9	376.9	376.9	376.9	376.9	376.9	376.9	376.9	376.9	0.6
3	733.9	735.5	735.5	735.5	735.5	735.5	735.5	735.5	735.5	733.9	0.6
4	1187.1	1187.1	1187.1	1187.1	1187.1	1187.1	1187.1	1187.1	1187.1	1187.1	0.0
5	1725.8	1725.8	1725.8	1725.8	1725.8	1725.8	1725.8	1725.8	1725.8	1725.8	0.0
6	2337.6	2336.1	2337.6	2337.6	2337.6	2337.6	2336.1	2337.6	2337.6	2337.6	0.6
7	3018.2	3018.2	3018.2	3016.7	3016.7	3016.7	3018.2	3018.2	3016.7	3016.7	0.8
8	3738.4	3738.4	3738.4	3738.4	3738.4	3738.4	3738.4	3738.4	3738.4	3738.4	0.0

Table B.41 Filter 1-39A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	138.9	138.9	137.3	137.3	137.3	137.3	137.3	137.3	137.3	137.3	0.6
2	375.4	376.9	376.9	375.4	375.4	376.9	376.9	376.9	376.9	376.9	0.7
3	729.4	730.9	730.9	730.9	730.9	730.9	730.9	730.9	730.9	730.9	0.5
4	1179.5	1179.5	1179.5	1179.5	1179.5	1179.5	1179.5	1179.5	1179.5	1179.5	0.0
5	1715.1	1715.1	1715.1	1715.1	1715.1	1715.1	1715.1	1715.1	1715.1	1715.1	0.0
6	2323.9	2323.9	2323.9	2323.9	2323.9	2323.9	2323.9	2323.9	2323.9	2323.9	0.0
7	3001.4	3001.4	3001.4	3001.4	3001.4	3001.4	3001.4	3001.4	3001.4	3001.4	0.0
8	3715.5	3715.5	3715.5	3715.5	3715.5	3715.5	3715.5	3715.5	3715.5	3715.5	0.0

Table B.42 Filter 1-40A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	0.0
2	378.4	376.9	378.4	378.4	378.4	378.4	378.4	376.9	376.9	376.9	0.8
3	732.4	733.9	733.9	733.9	733.9	733.9	733.9	733.9	733.9	733.9	0.5
4	1184.1	1184.1	1184.1	1184.1	1184.1	1184.1	1184.1	1184.1	1184.1	1184.1	0.0
5	1724.2	1722.7	1724.2	1722.7	1722.7	1722.7	1722.7	1722.7	1722.7	1722.7	0.6
6	2333.1	2333.1	2333.1	2333.1	2333.1	2333.1	2333.1	2333.1	2333.1	2333.1	0.0
7	3018.2	3018.2	3018.2	3018.2	3018.2	3018.2	3018.2	3018.2	3018.2	3018.2	0.0
8	3743.0	3743.0	3743.0	3743.0	3743.0	3743.0	3743.0	3743.0	3743.0	3743.0	0.0

Table B.43 Filter 1-69A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	0.0
2	381.5	381.5	381.5	381.5	381.5	381.5	381.5	381.5	381.5	381.5	0.0
3	741.6	741.6	741.6	741.6	741.6	741.6	741.6	741.6	741.6	741.6	0.0
4	1196.3	1196.3	1196.3	1196.3	1196.3	1196.3	1196.3	1196.3	1196.3	1196.3	0.0
5	1741.0	1741.0	1741.0	1741.0	1741.0	1741.0	1741.0	1741.0	1741.0	1741.0	0.0
6	2357.5	2357.5	2357.5	2357.5	2357.5	2357.5	2357.5	2359.0	2357.5	2357.5	0.5
7	3044.1	3042.6	3044.1	3044.1	3044.1	3042.6	3044.1	3044.1	3044.1	3044.1	0.6
8	3770.4	3770.4	3770.4	3770.4	3770.4	3770.4	3770.4	3770.4	3770.4	3770.4	0.0

Table B.44 Filter 1-71A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	138.9	140.4	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	0.5
2	378.9	378.9	378.9	378.9	378.9	378.9	378.9	378.9	378.9	378.9	0.0
3	737.0	737.0	737.0	737.0	737.0	737.0	737.0	737.0	737.0	737.0	0.0
4	1188.7	1188.7	1188.7	1188.7	1188.7	1188.7	1188.7	1188.7	1188.7	1188.7	0.0
5	1730.3	1730.3	1730.3	1730.3	1730.3	1730.3	1730.3	1730.3	1730.3	1730.3	0.0
6	2345.3	2345.3	2345.3	2345.3	2345.3	2345.3	2345.3	2345.3	2345.3	2345.3	0.0
7	3030.4	3030.4	3030.4	3030.4	3030.4	3030.4	3030.4	3030.4	3030.4	3030.4	0.0
8	3753.7	3753.7	3753.7	3753.7	3753.7	3753.7	3753.7	3753.7	3753.7	3753.7	0.0

Table B.45 Filter 2-21A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	126.6	128.2	126.6	126.6	126.6	126.6	126.6	128.2	126.6	126.6	0.6
2	346.4	346.4	346.4	346.4	346.4	346.4	346.4	346.4	346.4	346.4	0.0
3	676.0	677.5	677.5	677.5	677.5	677.5	677.5	677.5	677.5	677.5	0.5
4	1095.6	1095.6	1095.6	1095.6	1095.6	1095.6	1097.1	1095.6	1095.6	1095.6	0.5
5	1594.5	1594.5	1594.5	1594.5	1594.5	1594.5	1594.5	1594.5	1594.5	1594.5	0.0
6	2160.6	2160.6	2160.6	2160.6	2160.6	2160.6	2160.6	2160.6	2160.6	2160.6	0.0
7	2789.3	2787.8	2787.8	2787.8	2787.8	2787.8	2787.8	2789.3	2787.8	2787.8	0.6
8	3459.2	3457.6	3457.6	3457.6	3457.6	3457.6	3457.6	3457.6	3457.6	3457.6	0.5

Table B.46 Filter 2-23A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	131.2	132.8	131.2	131.2	131.2	131.2	131.2	131.2	131.2	131.2	0.5
2	360.1	358.6	358.6	358.6	358.6	358.6	358.6	358.6	358.6	358.6	0.5
3	698.9	698.9	698.9	698.9	698.9	698.9	698.9	698.9	698.9	698.9	0.0
4	1129.2	1129.2	1129.2	1129.2	1129.2	1129.2	1129.2	1129.2	1129.2	1129.2	0.0
5	1640.9	1640.9	1640.9	1640.9	1640.9	1640.9	1640.9	1640.9	1640.9	1640.9	0.0
6	2224.7	2224.7	2224.7	2224.7	2224.7	2224.7	2224.7	2224.7	2224.7	2224.7	0.0
7	2870.2	2870.2	2870.2	2870.2	2868.7	2870.2	2870.2	2868.7	2870.2	2868.7	0.7
8	3556.8	3555.3	3555.3	3555.3	3555.3	3555.3	3556.8	3555.3	3556.8	3555.3	0.7

Table B.47 Filter 2-29A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	135.8	135.8	135.8	135.8	135.8	135.8	135.8	135.8	135.8	135.8	0.0
2	367.7	367.7	367.7	367.7	367.7	367.7	367.7	367.7	367.7	367.7	0.0
3	714.1	714.1	714.1	714.1	714.1	714.1	714.1	714.1	714.1	714.1	0.0
4	1153.6	1153.6	1153.6	1153.6	1153.6	1153.6	1153.6	1153.6	1153.6	1153.6	0.0
5	1675.4	1675.4	1675.4	1675.4	1675.4	1675.4	1675.4	1675.4	1675.4	1675.4	0.0
6	2269.0	2269.0	2269.0	2269.0	2269.0	2269.0	2269.0	2269.0	2269.0	2269.0	0.0
7	2926.6	2926.6	2926.6	2926.6	2926.6	2926.6	2926.6	2926.6	2926.6	2926.6	0.0
8	3627.0	3627.0	3627.0	3627.0	3627.0	3627.0	3627.0	3627.0	3627.0	3627.0	0.0

Table B.48 Filter 2-37A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	0.0
2	379.9	379.9	378.4	379.9	379.9	379.9	378.4	378.4	379.9	379.9	0.7
3	740.1	740.1	740.1	740.1	740.1	740.1	740.1	740.1	740.1	740.1	0.0
4	1194.8	1194.8	1194.8	1194.8	1194.8	1194.8	1194.8	1194.8	1194.8	1194.8	0.0
5	1738.0	1738.0	1739.5	1738.0	1739.5	1738.0	1739.5	1739.5	1738.0	1738.0	0.8
6	2357.5	2357.5	2357.5	2357.5	2357.5	2357.5	2357.5	2357.5	2357.5	2357.5	0.0
7	3044.1	3044.1	3044.1	3044.1	3044.1	3044.1	3044.1	3044.1	3044.1	3044.1	0.0
8	3773.5	3773.5	3773.5	3773.5	3773.5	3773.5	3773.5	3773.5	3773.5	3773.5	0.0

Table B.49 Filter 2-41A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	0.0
2	379.9	379.9	379.9	379.9	379.9	379.9	379.9	379.9	379.9	379.9	0.0
3	738.5	738.5	738.5	738.5	738.5	738.5	738.5	738.5	738.5	738.5	0.0
4	1185.6	1185.6	1185.6	1185.6	1185.6	1185.6	1185.6	1185.6	1185.6	1185.6	0.0
5	1725.8	1725.8	1725.8	1725.8	1725.8	1725.8	1725.8	1725.8	1725.8	1725.8	0.0
6	2337.6	2337.6	2337.6	2337.6	2337.6	2337.6	2337.6	2337.6	2337.6	2337.6	0.0
7	3018.2	3018.2	3018.2	3018.2	3018.2	3018.2	3018.2	3018.2	3018.2	3018.2	0.0
8	3741.5	3741.5	3741.5	3741.5	3741.5	3741.5	3741.5	3741.5	3741.5	3741.5	0.0

Table B.50 Filter 2-49A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	134.3	135.8	134.3	134.3	134.3	134.3	134.3	134.3	134.3	134.3	0.5
2	367.7	366.2	366.2	366.2	366.2	366.2	366.2	366.2	366.2	366.2	0.5
3	712.6	712.6	712.6	712.6	712.6	712.6	712.6	712.6	712.6	712.6	0.0
4	1150.5	1150.5	1150.5	1150.5	1150.5	1150.5	1150.5	1150.5	1150.5	1150.5	0.0
5	1670.8	1670.8	1670.8	1670.8	1670.8	1670.8	1670.8	1670.8	1670.8	1670.8	0.0
6	2265.9	2265.9	2265.9	2265.9	2265.9	2265.9	2265.9	2265.9	2265.9	2265.9	0.0
7	2923.6	2923.6	2923.6	2923.6	2923.6	2923.6	2923.6	2923.6	2923.6	2923.6	0.0
8	3624.0	3625.8	3625.8	3625.8	3625.8	3625.8	3625.8	3625.8	3624.0	3624.0	0.9

Table B.51 Filter 3-25A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	129.7	131.2	129.7	129.7	129.7	129.7	131.2	129.7	129.7	129.7	0.6
2	355.5	354.0	354.0	354.0	354.0	354.0	354.0	354.0	354.0	354.0	0.5
3	688.2	688.2	689.7	688.2	688.2	688.2	688.2	688.2	688.2	688.2	0.5
4	1115.4	1115.4	1115.4	1115.4	1115.4	1115.4	1115.4	1115.4	1115.4	1115.4	0.0
5	1622.0	1622.0	1622.0	1622.0	1622.0	1622.0	1622.0	1622.0	1622.0	1622.0	0.0
6	2197.3	2195.7	2195.7	2195.7	2195.7	2195.7	2195.7	2195.7	2195.7	2195.7	0.5
7	2835.1	2833.6	2833.6	2835.1	2835.1	2835.1	2835.1	2835.1	2835.1	2835.1	0.6
8	3511.0	3511.0	3511.0	3511.0	3511.0	3511.0	3511.0	3511.0	3511.0	3511.0	0.0

Table B.52 Filter 3-29A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	135.1	134.3	135.1	135.1	135.1	135.1	135.1	135.1	135.1	135.1	0.3
2	367.4	366.2	366.2	366.2	366.2	366.2	366.2	366.2	366.2	366.2	0.4
3	714.1	714.1	714.1	714.1	714.1	714.1	714.1	714.1	714.1	714.1	0.0
4	1153.6	1153.6	1153.6	1153.6	1153.6	1153.6	1153.6	1153.6	1153.6	1153.6	0.0
5	1680.0	1680.0	1678.5	1678.5	1678.5	1678.5	1678.5	1678.5	1678.5	1678.5	0.6
6	2272.0	2272.0	2272.0	2272.0	2272.0	2272.0	2272.0	2272.0	2272.0	2272.0	0.0
7	2931.2	2932.8	2931.2	2931.2	2931.2	2931.2	2931.2	2931.2	2931.2	2931.2	0.5
8	3633.6	3633.6	3633.6	3633.6	3633.6	3633.6	3633.6	3633.6	3633.6	3633.6	0.0

Table B.53 Filter 3-35A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	141.9	141.9	141.9	141.9	141.9	141.9	141.9	141.9	141.9	141.9	0.0
2	387.6	387.6	387.6	387.6	387.6	387.6	387.6	387.6	387.6	387.6	0.0
3	755.3	755.3	755.3	755.3	755.3	755.3	755.3	755.3	755.3	755.3	0.0
4	1219.2	1219.2	1219.2	1219.2	1219.2	1219.2	1219.2	1219.2	1219.2	1219.2	0.0
5	1774.6	1774.6	1774.6	1774.6	1774.6	1774.6	1774.6	1774.6	1774.6	1774.6	0.0
6	2403.3	2403.3	2403.3	2403.3	2403.3	2403.3	2403.3	2403.3	2403.3	2403.3	0.0
7	3102.1	3102.1	3102.1	3103.6	3103.6	3103.6	3103.6	3103.6	3103.6	3103.6	0.7
8	3843.7	3843.7	3843.7	3843.7	3843.7	3843.7	3843.7	3843.7	3843.7	3843.7	0.0

Table B.54 Filter 3-38A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	0.0
2	381.5	378.4	379.9	379.9	379.9	379.9	379.9	379.9	379.9	379.9	0.7
3	735.5	738.5	738.5	738.5	737.0	737.0	737.0	737.0	737.0	737.0	1.0
4	1190.2	1190.2	1190.2	1190.2	1190.2	1190.2	1190.2	1190.2	1190.2	1190.2	0.0
5	1731.9	1731.9	1731.9	1731.9	1731.9	1731.9	1731.9	1731.9	1731.9	1731.9	0.0
6	2343.8	2345.3	2345.3	2345.3	2345.3	2345.3	2345.3	2345.3	2345.3	2345.3	0.5
7	3028.9	3028.9	3028.9	3028.9	3028.9	3028.9	3028.9	3028.9	3028.9	3028.9	0.0
8	3750.6	3749.1	3750.6	3750.6	3749.1	3750.6	3750.6	3750.6	3750.6	3750.6	0.6

Table B.55 Filter 3-68A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	0.0
2	376.9	376.9	376.9	376.9	376.9	376.9	376.9	376.9	376.9	376.9	0.0
3	730.9	732.4	732.4	732.4	732.4	732.4	732.4	732.4	732.4	732.4	0.5
4	1182.6	1182.6	1182.6	1182.6	1182.6	1182.6	1182.6	1182.6	1182.6	1182.6	0.0
5	1721.2	1721.2	1721.2	1721.2	1721.2	1721.2	1721.2	1721.2	1721.2	1721.2	0.0
6	2331.5	2331.5	2331.5	2331.5	2331.5	2331.5	2331.5	2331.5	2331.5	2331.5	0.0
7	3010.6	3010.6	3010.6	3010.6	3010.6	3010.6	3010.6	3010.6	3010.6	3010.6	0.0
8	3782.3	3782.3	3782.3	3782.3	3782.3	3782.3	3782.3	3782.3	3782.3	3782.3	0.0

Table B.56 Filter 4-27A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	137.3	137.3	137.3	137.3	137.3	137.3	137.3	137.3	137.3	137.3	0.0
2	370.8	370.8	369.3	369.3	369.3	369.3	370.8	370.8	370.8	370.8	0.8
3	720.2	720.2	720.2	720.2	720.2	720.2	720.2	720.2	720.2	720.2	0.0
4	1162.7	1162.7	1162.7	1162.7	1162.7	1162.7	1162.7	1162.7	1162.7	1162.7	0.0
5	1689.1	1689.1	1689.1	1689.1	1689.1	1689.1	1689.1	1689.1	1689.1	1689.1	0.0
6	2288.8	2288.8	2288.8	2288.8	2288.8	2288.8	2288.8	2288.8	2288.8	2288.8	0.0
7	2952.6	2952.6	2952.6	2952.6	2952.6	2952.6	2952.6	2952.6	2952.6	2952.6	0.0
8	3660.6	3660.6	3660.6	3660.6	3660.6	3660.6	3660.6	3660.6	3660.6	3660.6	0.0

Table B.57 Filter 4-31A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	145.0	145.0	145.0	145.0	145.0	145.0	145.0	145.0	145.0	145.0	0.0
2	395.2	395.2	395.2	395.2	395.2	395.2	395.2	395.2	395.2	395.2	0.0
3	762.9	762.9	762.9	762.9	762.9	762.9	762.9	762.9	762.9	762.9	0.0
4	1231.4	1231.4	1231.4	1231.4	1231.4	1231.4	1231.4	1231.4	1231.4	1231.4	0.0
5	1791.4	1791.4	1791.4	1791.4	1791.4	1791.4	1791.4	1791.4	1791.4	1791.4	0.0
6	2426.1	2426.1	2426.1	2426.1	2426.1	2426.1	2426.1	2426.1	2426.1	2426.1	0.0
7	3131.1	3131.1	3131.1	3131.1	3131.1	3131.1	3131.1	3131.1	3131.1	3131.1	0.0
8	3878.8	3878.8	3878.8	3878.8	3878.8	3878.8	3878.8	3878.8	3878.8	3878.8	0.0

Table B.58 Filter 4-71A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	138.9	0.0
2	378.9	378.9	378.9	378.9	378.9	378.9	378.9	378.9	378.9	378.9	0.0
3	735.5	735.5	737.0	737.0	737.0	737.0	737.0	737.0	737.0	737.0	0.6
4	1188.7	1188.7	1188.7	1188.7	1188.7	1188.7	1188.7	1188.7	1188.7	1188.7	0.0
5	1727.3	1727.3	1727.3	1727.3	1727.3	1727.3	1727.3	1727.3	1727.3	1727.3	0.0
6	2340.7	2340.7	2340.7	2340.7	2340.7	2340.7	2340.7	2340.7	2340.7	2340.7	0.0
7	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	0.0
8	3747.6	3749.1	3747.6	3747.6	3747.6	3747.6	3747.6	3747.6	3747.6	3747.6	0.5

Table B.59 Filter 4-87A

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	141.9	141.9	141.9	141.9	141.9	141.9	141.9	141.9	141.9	141.9	0.0
2	387.6	387.6	387.6	387.6	387.6	387.6	387.6	387.6	387.6	387.6	0.0
3	752.3	753.8	753.8	753.8	753.8	753.8	752.3	753.8	753.8	752.3	0.7
4	1214.6	1214.6	1214.6	1214.6	1214.6	1214.6	1214.6	1214.6	1214.6	1214.6	0.0
5	1768.5	1768.5	1768.5	1768.5	1768.5	1768.5	1768.5	1768.5	1768.5	1768.5	0.0
6	2394.1	2394.1	2394.1	2394.1	2394.1	2394.1	2394.1	2394.1	2394.1	2394.1	0.0
7	3091.4	3091.4	3091.4	3091.4	3091.4	3091.4	3091.4	3091.4	3091.4	3091.4	0.0
8	3831.5	3831.5	3831.5	3831.5	3831.5	3831.5	3831.5	3831.5	3831.5	3831.5	0.0

Table B.60 Filter 3-1290

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	139.2	139.2	139.2	139.2	139.2	139.2	139.2	139.2	139.2	139.2	0.0
2	379.0	379.0	379.0	379.0	379.0	379.0	379.0	379.0	379.0	379.0	0.0
3	734.3	734.3	734.3	734.3	734.3	734.3	734.3	734.3	734.3	734.3	0.6
4	1185.3	1185.3	1185.3	1185.3	1185.3	1185.3	1185.3	1185.3	1185.3	1185.3	0.0
5	1725.5	1725.5	1725.5	1725.5	1725.5	1725.5	1725.5	1725.5	1725.5	1725.5	0.0
6	2337.6	2337.6	2337.6	2337.6	2337.6	2337.6	2337.6	2337.6	2337.6	2337.6	0.0
7	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	3022.8	0.0
8	3747.6	3749.1	3747.6	3747.6	3747.6	3747.6	3747.6	3747.6	3747.6	3747.6	0.5

Table B.61 Filter 7-1289

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	141.0	141.0	141.0	141.0	141.0	141.0	141.0	141.0	141.0	141.0	0.0
2	383.9	383.9	383.9	383.9	383.9	383.9	383.9	383.9	383.9	383.9	0.0
3	743.4	743.4	743.4	743.4	743.4	743.4	743.4	743.4	743.4	743.4	0.7
4	1200.6	1200.6	1200.6	1200.6	1200.6	1200.6	1200.6	1200.6	1200.6	1200.6	0.0
5	1749.3	1749.3	1749.3	1749.3	1749.3	1749.3	1749.3	1749.3	1749.3	1749.3	0.0
6	2367.6	2367.6	2367.6	2367.6	2367.6	2367.6	2367.6	2367.6	2367.6	2367.6	0.0
7											
8											

B.4 FREQUENCY RESULTS OF 8 NEW REFRACTRON 442T

The frequencies from the tests conducted on the Refractron 4442T filters have been tabulated in Tables B.62 to B.69. Frequencies obtained at different impact locations are shown on these tables for each one of the specimens.

Table B.62 Filter 1-830

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	142.8	142.8	142.8	142.8	142.8	142.8	142.8	142.8	142.8	142.8	0.0
2	394.9	394.9	394.9	394.9	394.9	394.9	394.9	394.9	394.9	394.9	0.0
3	757.4	757.4	757.4	757.4	757.4	757.4	757.4	757.4	757.4	757.4	0.0
4	1225.6	1225.6	1225.6	1225.6	1225.6	1225.6	1225.6	1225.6	1225.6	1225.6	0.0
5	1786.5	1786.5	1786.5	1786.5	1786.5	1786.5	1786.5	1786.5	1786.5	1786.5	0.0
6	2422.5	2422.5	2422.5	2422.5	2422.5	2422.5	2422.5	2422.5	2422.5	2422.5	0.0
7											
8											

Table B.63 Filter 1-854

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	0.0
2	384.5	384.5	384.5	384.5	384.5	384.5	384.5	384.5	384.5	384.5	0.0
3	749.2	749.2	749.2	749.2	749.2	749.2	749.2	749.2	749.2	749.2	0.0
4	1211.5	1211.5	1211.5	1211.5	1211.5	1211.5	1211.5	1211.5	1211.5	1211.5	0.0
5	1767.0	1767.0	1767.0	1767.0	1767.0	1767.0	1767.0	1767.0	1767.0	1767.0	0.0
6	2392.6	2392.6	2392.6	2392.6	2392.6	2392.6	2392.6	2392.6	2392.6	2392.6	0.0
7	3091.4	3091.4	3091.4	3091.4	3091.4	3091.4	3091.4	3091.4	3091.4	3091.4	0.0
8	3831.5	3831.5	3831.5	3831.5	3831.5	3831.5	3831.5	3831.5	3831.5	3831.5	0.0

Table B.64 Filter 2-752

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	139.2	139.2	139.2	139.2	139.2	139.2	139.2	139.2	139.2	139.2	0.0
2	378.6	378.6	378.6	378.6	378.6	378.6	378.6	378.6	378.6	378.6	0.0
3	739.1	739.1	739.1	739.1	739.1	739.1	739.1	739.1	739.1	739.1	0.0
4	1193.8	1193.8	1193.8	1193.8	1193.8	1193.8	1193.8	1193.8	1193.8	1193.8	0.0
5	1739.5	1739.5	1739.5	1739.5	1739.5	1739.5	1739.5	1739.5	1739.5	1739.5	0.0
6	2356.6	2356.6	2356.6	2356.6	2356.6	2356.6	2356.6	2356.6	2356.6	2356.6	0.0
7											
8											

Table B.65 Filter 2-850

[illegible]

Table B.66 Filter 4-869

[illegible]

Table B.67 Filter 4-878

[illegible]

Table B.68 Filter 5-879

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	0.0
2	407.4	405.9	405.9	405.9	405.9	405.9	405.9	405.9	405.9	405.9	0.5
3	784.3	784.3	785.8	785.8	785.8	785.8	784.3	784.3	784.3	784.3	0.8
4	1269.5	1269.5	1269.5	1269.5	1269.5	1269.5	1269.5	1269.5	1269.5	1269.5	0.0
5	1850.9	1850.9	1850.9	1850.9	1850.9	1850.9	1850.9	1850.9	1850.9	1850.9	0.0
6	2510.1	2510.1	2510.1	2510.1	2510.1	2510.1	2510.1	2510.1	2510.1	2510.1	0.0
7	3242.5	3242.5	3242.5	3242.5	3242.5	3242.5	3242.5	3242.5	3242.5	3242.5	0.0
8	4023.7	4023.7	4023.7	4023.7	4023.7	4023.7	4023.7	4023.7	4023.7	4023.7	0.0

Table B.69 Filter 6-737

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	142.8	142.8	142.8	142.8	142.8	142.8	142.8	142.8	142.8	142.8	0.0
2	391.8	391.8	391.8	391.8	391.8	391.8	391.8	391.8	391.8	391.8	0.0
3	756.2	756.2	756.2	756.2	756.2	756.2	756.2	756.2	756.2	756.2	0.0
4	1223.1	1223.1	1223.1	1223.1	1223.1	1223.1	1223.1	1223.1	1223.1	1223.1	0.0
5	1781.0	1781.0	1781.0	1781.0	1781.0	1781.0	1781.0	1781.0	1781.0	1781.0	0.0
6	2413.9	2413.9	2411.5	2411.5	2411.5	2411.5	2413.9	2413.9	2413.9	2413.9	0.0
7											
8											

APPENDIX – C

Appendix C includes natural frequency values and mode shapes for new ceramic composite filters tested nondestructively

Table C.1 Filter Dupont 641

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	30.52	30.52	30.52	30.52	30.52	30.52	30.52	30.52	30.52		0.0
2	85.45	85.45	85.45	85.45	85.45	85.45	85.45	85.45	85.45		0.0
3	170.9	169.4	169.4	169.4	169.4	170.9	170.9	170.9	170.9		0.0
4	280.8	279.2	279.2	279.2	279.2	280.8	280.8	280.8	280.8		0.0
5	422.7	422.7	422.7	422.7	422.7	422.7	422.7	422.7	422.7		0.0
6	587.5	584.4	584.4	584.4	584.4	587.5	584.4	584.4	587.5		0.0

Table C.2 McDermonitt 8-130-1

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	57.07	57.07	57.07	57.07	57.07	57.07	57.07	57.07	57.07	57.07	0.0
2	163.88	163.88	163.88	163.88	163.88	163.88	163.88	163.88	163.88	163.88	0.0
3	315.2	316.16	316.16	316.16	316.16	316.16	316.16	316.16	316.16	316.16	0.0
4	538.9	538.94	538.94	538.94	538.94	538.94	538.94	538.94	538.94	538.94	0.0
5	800.5	800.48	800.48	797.12	798.65	798.65	798.65	798.65	798.65	798.65	0.0

Table C.3 3M 8004

Mode #	L/10 Hz	2 L/10 Hz	3 L/10 Hz	4 L/10 Hz	L/2 Hz	6 L/10 Hz	7 L/10 Hz	8 L/10 Hz	9 L/10 Hz	L Hz	STDEV
1	94.6	94.6	94.6	94.60	94.60	94.6	94.60	94.60	94.60	94.60	0.0
2	270.4	270.4	270.4	270.4	270.4	270.4	270.4	270.4	270.4	270.4	0.0
3	535.3	535.3	535.3	535.3	535.3	535.3	535.3	535.3	535.3	535.3	0.0

Figure C1 First four mode shapes for DuPont 641 filter.

Figure C2 First four mode shapes for McDermott 8-130-1 641 filter.

Figure C3 First four mode shapes for 3M 8004 filter.

Appendix D

Ceramic Filter Specimens

Figure D.1 New Coors P-100A-1 Alumina Mullite Filters.

Figure D.2 New Pall Vitropore 326 Filter.

Figure D.3 Used Schumacher TF-20 Filters (500 hrs)

Figure D.4 Used Refractron Filters a) 400 hrs, b) April Fire.