DEVELOPMENT OF A LOW FLOW RATE AXIAL HEPA FILTER FOR RADIOLOGICAL APPLICATIONS

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ABSTRACT

When servicing nuclear systems, glovebag containments and portable collection tanks are often used to perform work. Currently, the American Society of Mechanical Engineers (ASME) AG-1 Code on Nuclear Air and Gas Treatment [1] covers HEPA filters with rated capacity in excess of 20 cfm. No code currently exists to provide requirements for nuclear grade filters rated below 20 cfm. The American Glovebox Society (AGS) provides a standard of practice [2] for the design and fabrication of glovebag containments and the standard includes a recommendation for the use of small 2 cubic feet per minute respirator filters for low flow applications. The AGS standard is not specific to nuclear applications and there are differences in the applications of respirator filters used for nuclear work verses respirators.

In an effort to address the gap in requirements for HEPA filters used for servicing nuclear and radiological systems, a new HEPA filter has been developed. The new filter is designed for use on glovebag containments and collection tanks used for servicing nuclear systems. The filter utilizes nuclear grade filter media with proposed testing similar to ASME AG-1 nuclear grade filters. The current ASME AG-1 code is also evaluated for applicability to a low flow filter used for radiological applications.

INTRODUCTION

During the performance of work on nuclear systems or any system which includes the potential generation of hazardous particulate, HEPA filtered active and passive ventilation systems are of vital importance for the protection of personnel and the environment. When servicing systems that require higher air changes per hour, the use of HEPA filters qualified in accordance with the American Society of Mechanical Engineers (ASME) AG-1 Code on Nuclear Air and Gas Treatment are commonly used. When servicing nuclear systems in which the required ventilation flow rates are less than 20 acfm, a gap exists in the requirements and guidelines for HEPA filter design and qualification. A common application that is often used in servicing nuclear systems involves the use of flexible radiological containments. When systems and components are serviced, glovebag containments are often used. When a glovebag is used it can get compressed when workers hands and arms move around inside the glovebag. A filter is installed on the glovebag to prevent pressure build-up inside the bag and protect the worker from outflow. Figure 1 shows a simplified diagram of a glovebag containment with a filter installed.

Another application that requires filtration at lower flow rates is venting radiological collection tanks and bottles. Figure 2 is a simplified diagram of a collection bottle with a filter used for venting. Fluids are often pumped into collection tanks when nuclear fluid systems are serviced. Radiological collection tanks and bottles are also used to collect moisture when air is pushed through a nuclear system. Lower flow filters are also directly attached to some radiological systems that require venting at low flow rates.

The American Glovebox Society (AGS) provides a standard of practice for the design and fabrication of glovebag containments and the standard includes a recommendation for the use of small 2 cubic feet per minute respirator filters for low flow applications. The AGS standard is not specific to nuclear applications and there are limitations associated with the use of respirator filters for nuclear work. Respirator filter requirements and their associated limitations are discussed in more detail in the NIOSH respirator filter section of this paper.

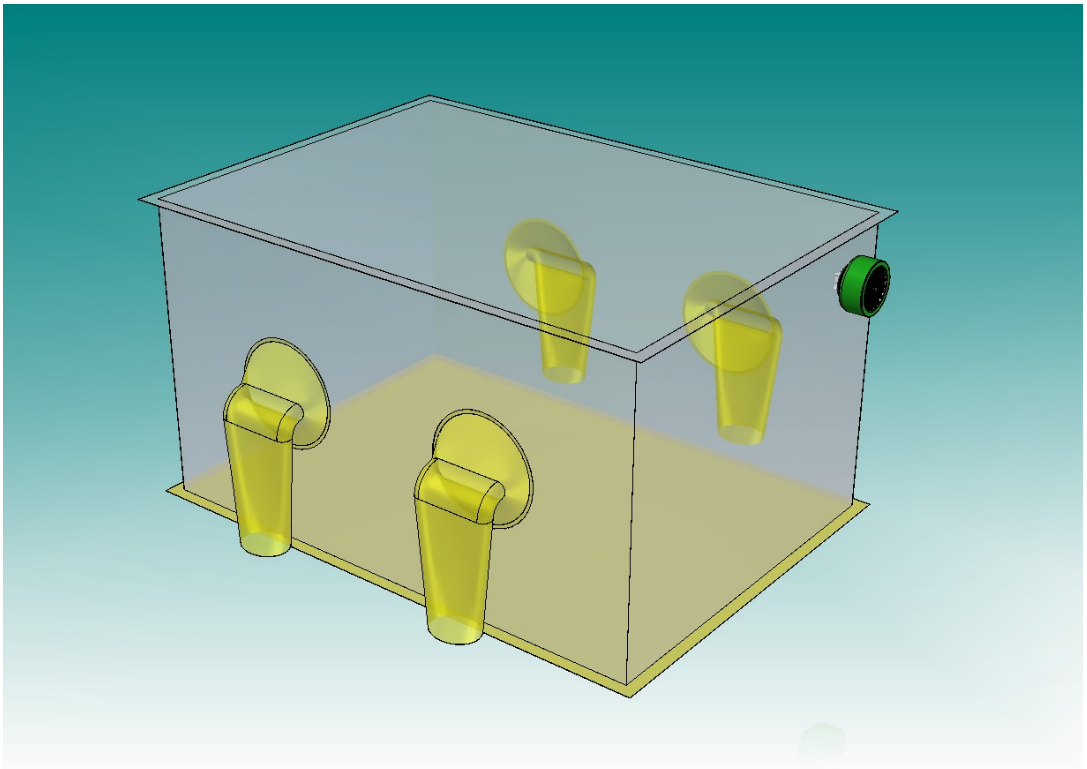


Figure 1, Diagram of a Typical Glovebag with Filter Attached

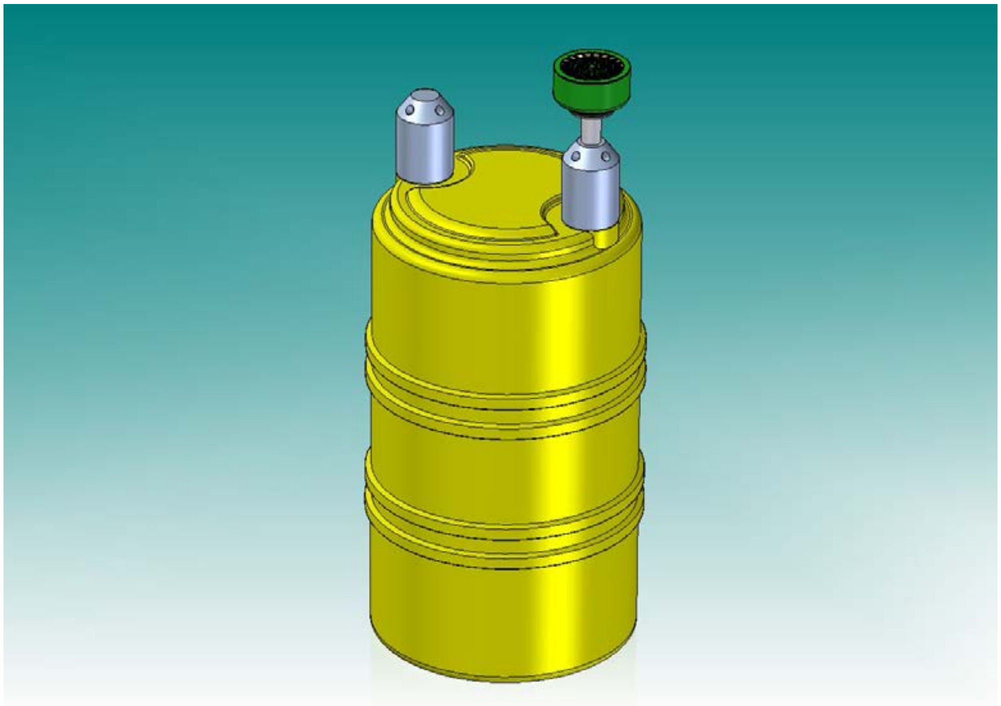


Figure 2, Diagram of a Collection Bottle with a Filter for Venting

NIOSH FILTERS

As stated above, respirator filters are commonly used on glovebags when required flow rates in the glovebag are low or when the filter is needed only for venting. An example of a respirator filter used in radiological glovebag applications is shown in Figure 3. An example of a respirator filter used for venting collection bottles is shown in Figure 4. Requirements for small respirator filters fall under the Code of Federal Regulations 42 CFR part 84 standard [3]. The National Institute for Occupational Safety and Health (NIOSH) publishes recommendations for respirator filters and test procedures [4] for respirator filters. The Occupational Safety and Health Administration (OSHA) require the respirators used by personnel to be certified by NIOSH. Testing of NIOSH respirator filters includes flow resistance and particulate filter efficiency. Respirator filters are not tested to the same level as nuclear qualified filters. In addition, the AGS standard is not specific to nuclear applications and there are limitations associated with the use of respirator filters for nuclear work.

Figure 3, A typical NIOSH P100 Filter with a 2 cfm capacity

Figure 4, A typical NIOSH P100 filter with a 3 cfm capacity

Structurally, respirator filters are not as robust as nuclear qualified filters. They are not subjected to the ASME AG-1 rough handling test to which nuclear grade filters are qualified. They are also not designed to operate on positive pressure systems. Respirators filter air when air is drawn into a respirator mask by the user. When the user exhales, the air is expelled through a check valve. The respirator filter does not normally experience airflow into the smaller opening and often there is not a baffle provided near the small opening. If a respirator filter is attached to a positive pressure system through the threaded small opening, the airflow would be inlet airflow (vs. outlet airflow for which the filter is designed). Since the airflow is more concentrated through the small opening, a pressure and velocity gradient would exist across the face of the filter media. These pressure and velocity gradients may not be accounted for when the filters are tested to NIOSH test procedures. Another complication with the use respirator filters is they often have custom threads or attachment methods. This is intentional, in that respirator filters are matched with respirator face masks such that they cannot be interchangeable with other face masks. This is a CFR requirement for respirators.

Another potentially important feature of nuclear qualified filters that is not present in respirator filters is the more extensive testing that is performed on nuclear qualified filter media. The various strength tests that are performed on nuclear qualified media per Appendix FC-I of ASME AG-1 would be useful for low flow radiological filtration applications. For example, the testing regarding strength and water repellency after gamma irradiation would be useful in a radiological environment.

New Low Flow HEPA Filter for Radiological Applications

In response to the need for a more robust filter design for radiological applications, a new filter design has been developed. Several types and material options were considered including the following:

1. Stainless Steel Cylindrical Radial Flow Filter.
2. Stainless Steel Cylindrical Axial Flow Filter
3. Stainless Steel Square Axial Flow Filter
4. Injection Molded Plastic Cylindrical Axial Flow Filter
5. Injection Molded Plastic Square Axial Flow Filter.

The filter design selected is the option 4 axial flow filter with a cylindrical injection molded case. This option was selected because it is a structurally sound, cost effective option that provides good flow characteristics in both directions. The design uses Type B minipleat filter medium and a rated airflow of 4 acfm. The filter design is depicted in Figure 5 through Figure 7.

The filter case selected is injection molded and made of ABS plastic with a small threaded inlet/outlet and perforated cap on the opposite end of the inlet/outlet of the filter. The filter case includes an integrated baffle on the threaded side of the case that is designed to distribute the airflow radially outward to provide more uniform airflow across the filter medium. The integrated baffle allows the filter to be used in both positive and negative pressure environments. The baffle also protects the medium from inadvertent damage that may be caused by a sharp object or finger protruding through the threaded side of the filter case. The filter case also includes a perforated cap that presses into the inlet/outlet of the filter after installation of the filter media. After the media and the cap are in place, the potting material is injected into the threaded end of the filter assembly during a spinning process. The potting material seals the filter media in the case and glues the perforated cap to the case in one step.

The filter media is nuclear grade filter medium manufactured and tested to the requirements of ASME AG-1, Mandatory Appendix FC-I. The filter pack is designed to provide an exposed medium area such that the medium velocity is 2.5 cm/s maximum at the design volumetric flow rate of 4 acfm. The adhesive (or potting material) used to bond and seal the filter pack to the case is a self-extinguishing urethane adhesive and it complies with the requirements of section FC of ASME AG-1. The filter assembly also includes rubber gaskets compressed by a nut that threads into the inlet/outlet of the filter. The gaskets seal the filter assembly to the glovebag walls (see Figure 7) and may also be used with an adapter to make a sealed connection to collection bottles (see Figure 2).

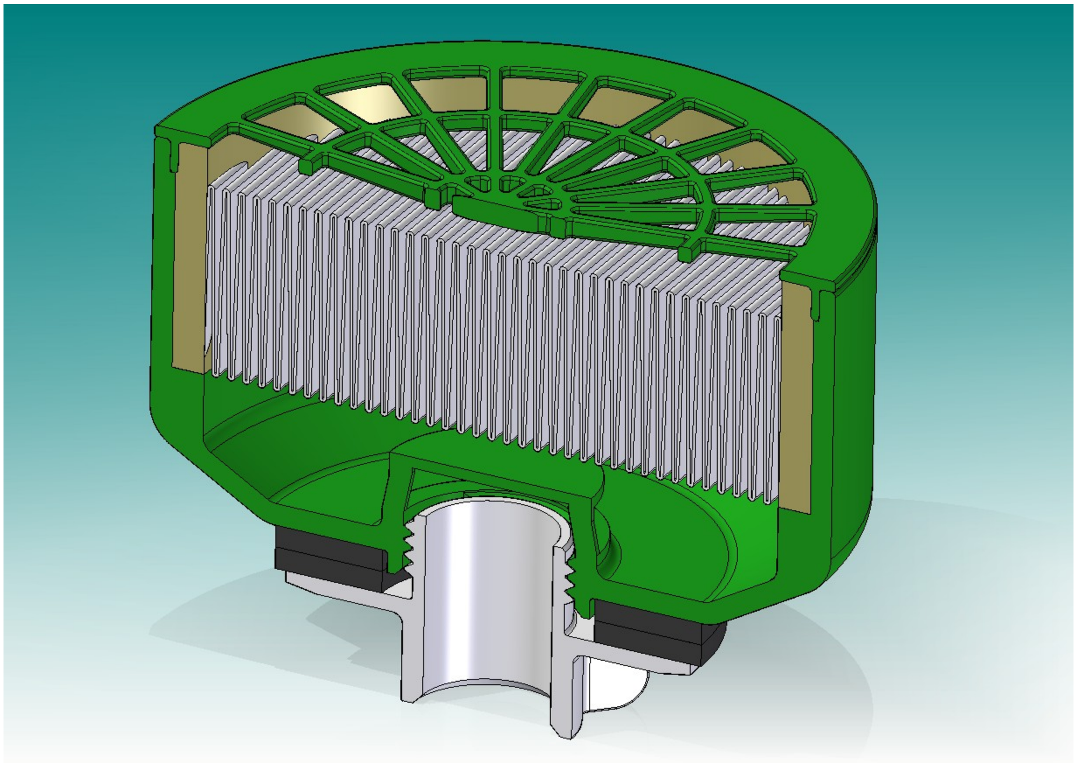


Figure 5, Cross Sectional View of the New Filter Concept

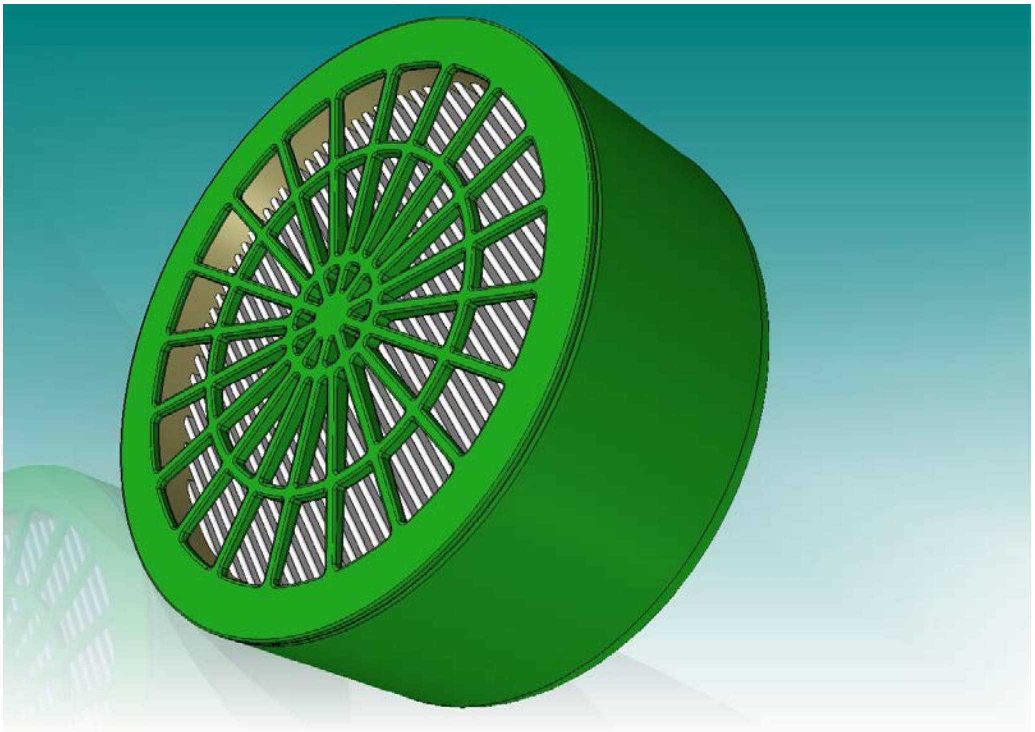


Figure 6, Top View of the New Filter Concept

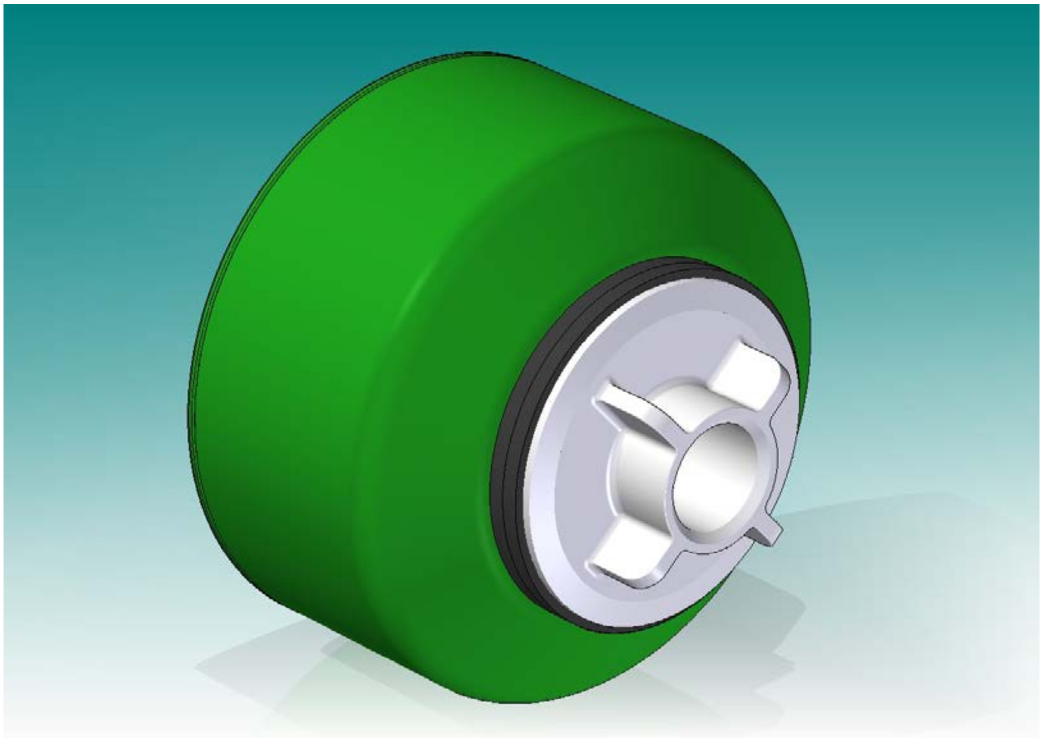


Figure 7, Bottom View of the New Filter Concept

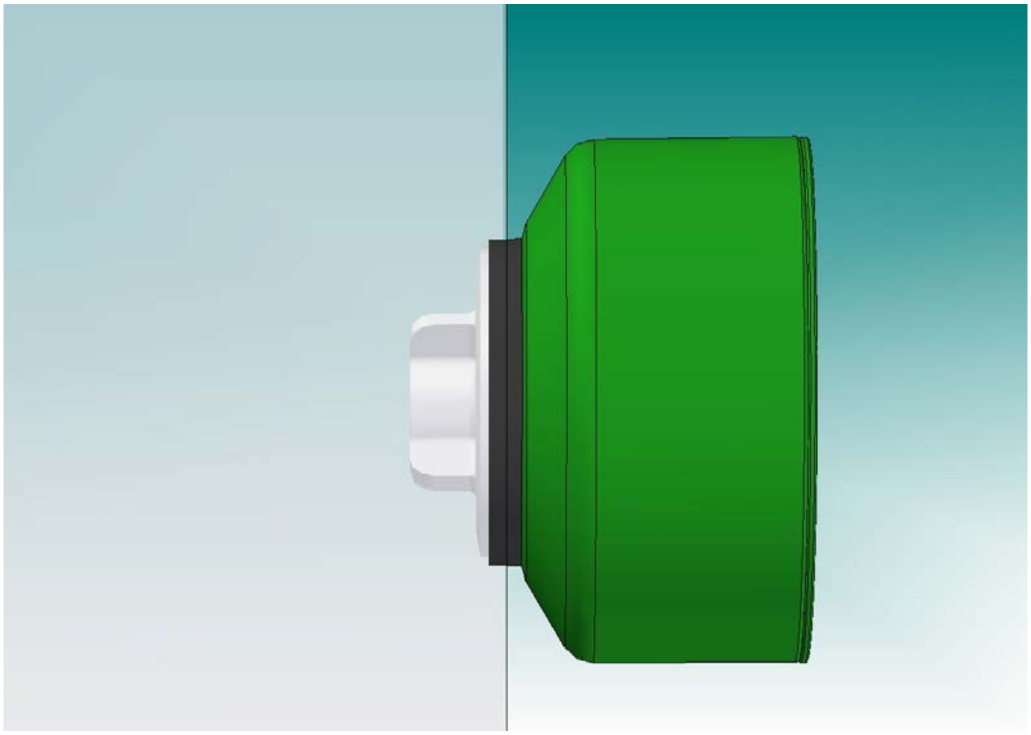


Figure 8, Side View of Filter Attached to Glovebag Wall

Analysis of Airflow Inside of HEPA Filter Using Computational Fluid Dynamics (CFD)

Due to concerns that the small opening at the inlet of the filter would create unacceptable velocity and pressure gradients at the filter pack, the air and filter media inside the new filter was modeled and analyzed using ANSYS Fluent CFD software. The filter was modeled both with and without a baffle at the small inlet. The air was modeled at standard conditions and the filter media was modeled as a porous medium with linear flow resistance defined using a Darcy Formulation shown in Equation 1 below:

$$\Delta P = \left(\frac{\mu}{\alpha} v\right) t \qquad \text{Eq. 1}$$

Where

ΔP is the pressure loss [Pa] = 348 Pa
μ is the viscosity [Pa s] = 1.789 x 10^{-5} Pa s
v is the superficial velocity [m/s] = .0533 m/s
t is the porous media thickness [m] = .00043 m
α is permeability [m^2]
$1/\alpha$ is the viscous resistance coefficient [$1/m^2$] = 8.485 x 10^{11} m^{-2}

The viscous resistance coefficient was required in Fluent to define the porous media domain. Rearranging equation 1, the viscous resistance coefficient was determined using Equation 2 below:

$$\frac{1}{\alpha} = \frac{\Delta P}{\mu v t} \qquad \text{Eq. 2}$$

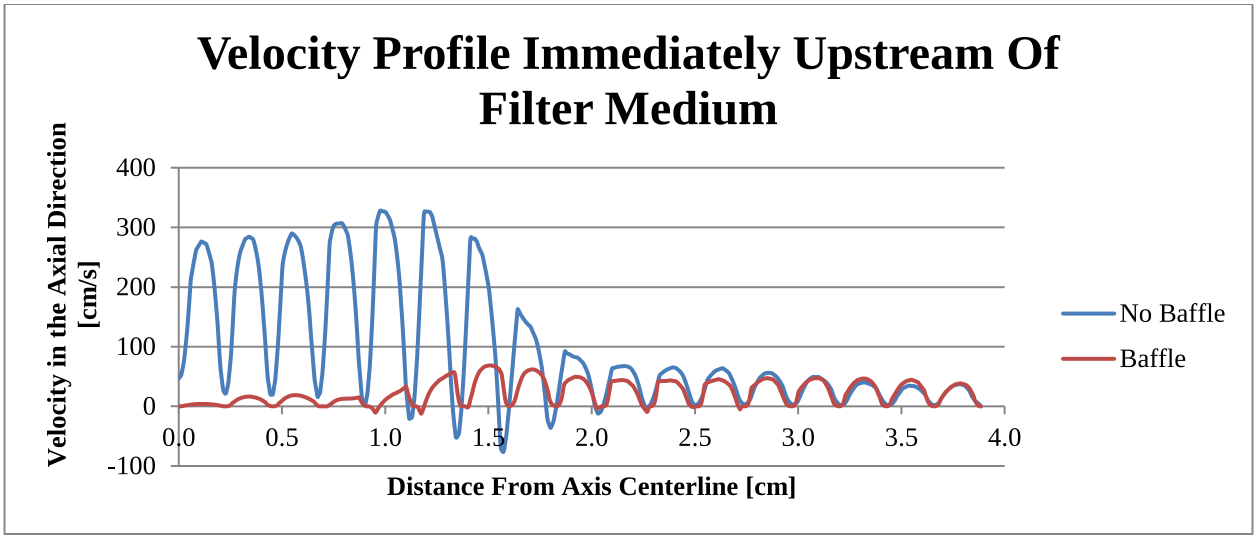
The viscosity used was determined based on air at standard conditions (1.789 x 10^{-5} Pa s), the velocity was defined using the AG-1 qualification test velocity (5.33 cm/s) and the pressure loss and thickness terms were determined using filter media data sheets from the manufacturer.

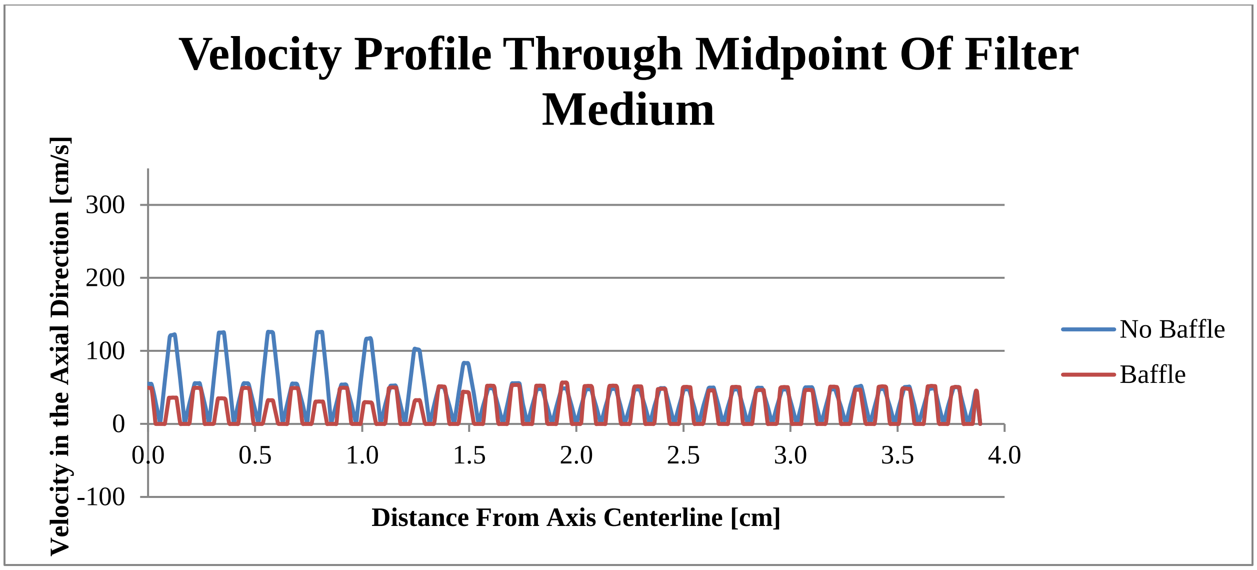
The fluid domain in the CFD model contained two symmetry boundary conditions on perpendicular planes passing through the axis of the filter making a ¼ symmetry model. The inlet of the filter was the small opening in the filter where a velocity boundary condition was defined based on the rated flow of the filter. The outlet of the filter was defined at the large opening where a pressure boundary condition was defined at zero gage pressure. The fluid domain was meshed with a fine grid that comprised of approximately 3.5 million grids. Grid refinement was performed near the folds in the filter pleats and a minimum of two grids through the thickness of the filter media. The solver used for the analysis was a pressure based coupled solver and the turbulence model used was a k-ε realizable model with standard wall functions.

Results of the Analysis

The results of the analysis indicate that the airflow is reasonable through the filter media. The results of the analysis of the filter without a baffle showed a fairly large velocity gradient on the inlet face of the filter media. Based on this, a baffle was added on the inlet side of the filter and the analysis of the filter with the baffle showed a more uniform velocity profile. The analysis also showed that the velocity profile tended to become more uniform as the air passed through the media pack. Figure 9 shows the velocity profile at the three locations as the air passes through the filter pack. The velocity reported in the graphs is the velocity parallel to the filter axis. The velocity profiles were taken along lines perpendicular to the filter axis and in plane with the filter centerline. Figure 10 and Figure 11 show contour plots of the velocity at the centerline of the filter looking down at the filter pleats. One can see the higher velocities at the face of the filter media on the filter with no baffle. The filter with the baffle shows a more uniform velocity at the filter media face.

The pressure is more uniform in the media pack when the baffle is included as shown in F igure 12. The blue curves on the graph depict the pressure at the front (upstream) face of the filter media. The peaks in the curve occur at the tip of the media folds. The red curves depict the pressure at the middle of the media pack. The peaks in the curve are the zones between the pleats where the air hasn't yet passed through the media. The green curves depict the pressure on the back face of the media pack immediately downstream of the pack, just as the air is exiting the pack. One can see that the pressure drop is lower through the media on the filter with the baffle (approx. 90 Pa [0.36 in w.g.] vs 120 Pa [0.48 in-w.g.]). The overall pressure drop through the filter; however, is higher on the filter with the baffle as shown in Figure 13. This is expected due to losses associated with a baffle. The pressure drop seen across the inlet/outlet of the filter with no baffle is approximately 95 Pa [0.38 in-w.g.]. The pressure drop seen across the inlet/outlet of the filter with the baffle is approximately 140 Pa [0.48 in-w.g.].


Velocity Profile Immediately Upstream Of Filter Medium
Velocity in the Axial Direction [cm/s]
400
300
200
100
0
-100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Distance From Axis Centerline [cm]
No Baffle
Baffle


Velocity Profile Through Midpoint Of Filter Medium
Velocity in the Axial Direction [cm/s]
300
200
100
0
-100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Distance From Axis Centerline [cm]
No Baffle
Baffle

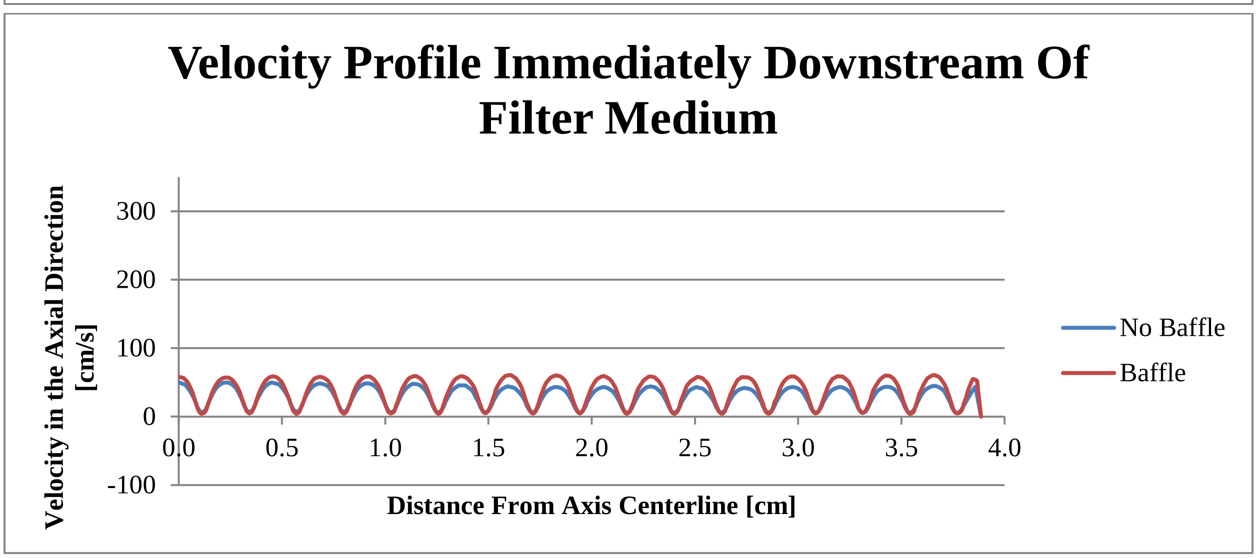

Velocity Profile Immediately Downstream Of Filter Medium
Velocity in the Axial Direction [cm/s]
300
200
100
0
-100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Distance From Axis Centerline [cm]
No Baffle
Baffle

Figure 9

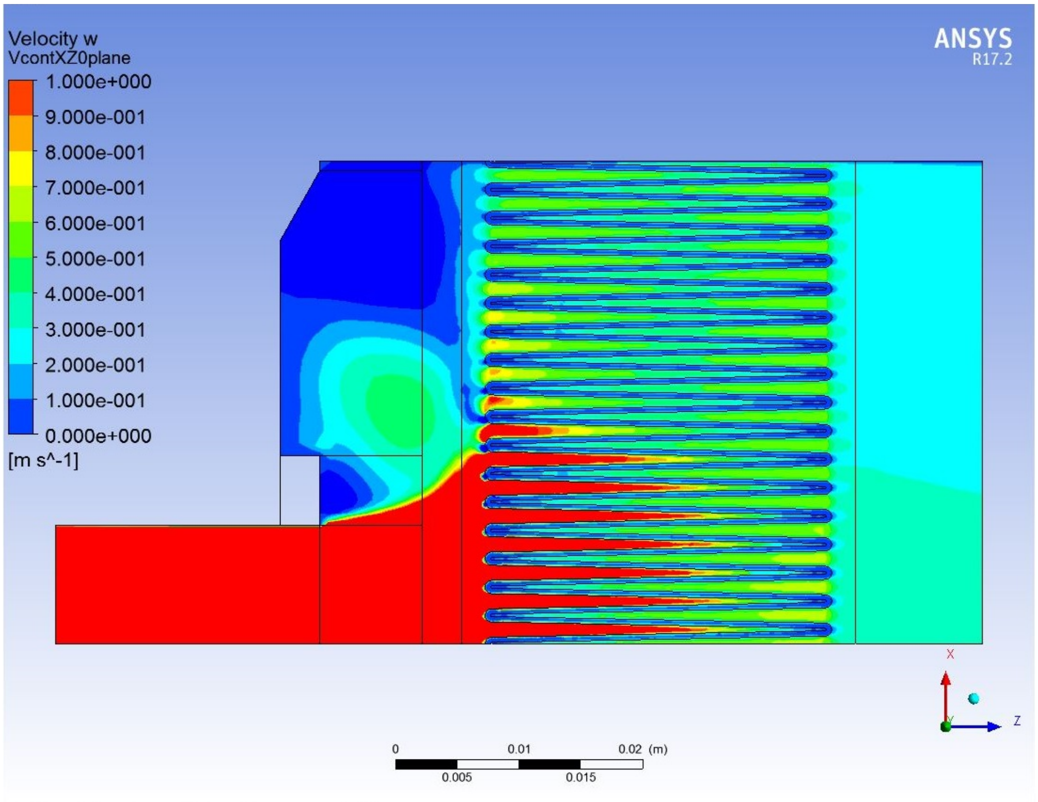


Figure 10, Velocity Contours at Centerline – No Baffle

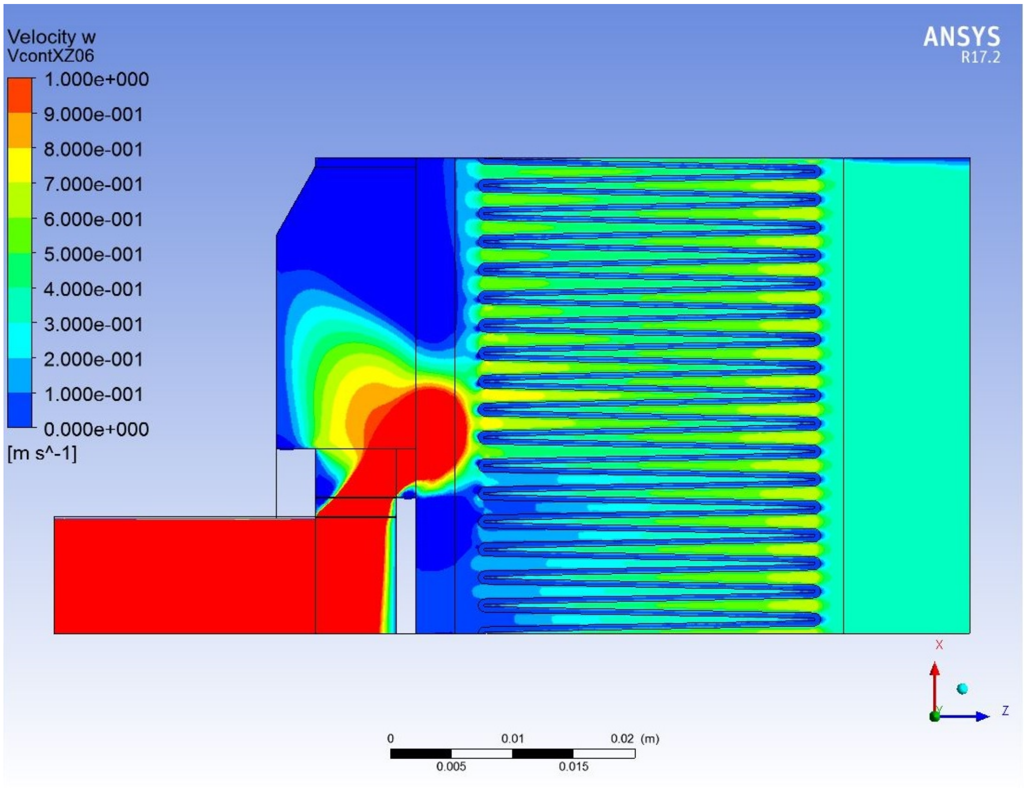
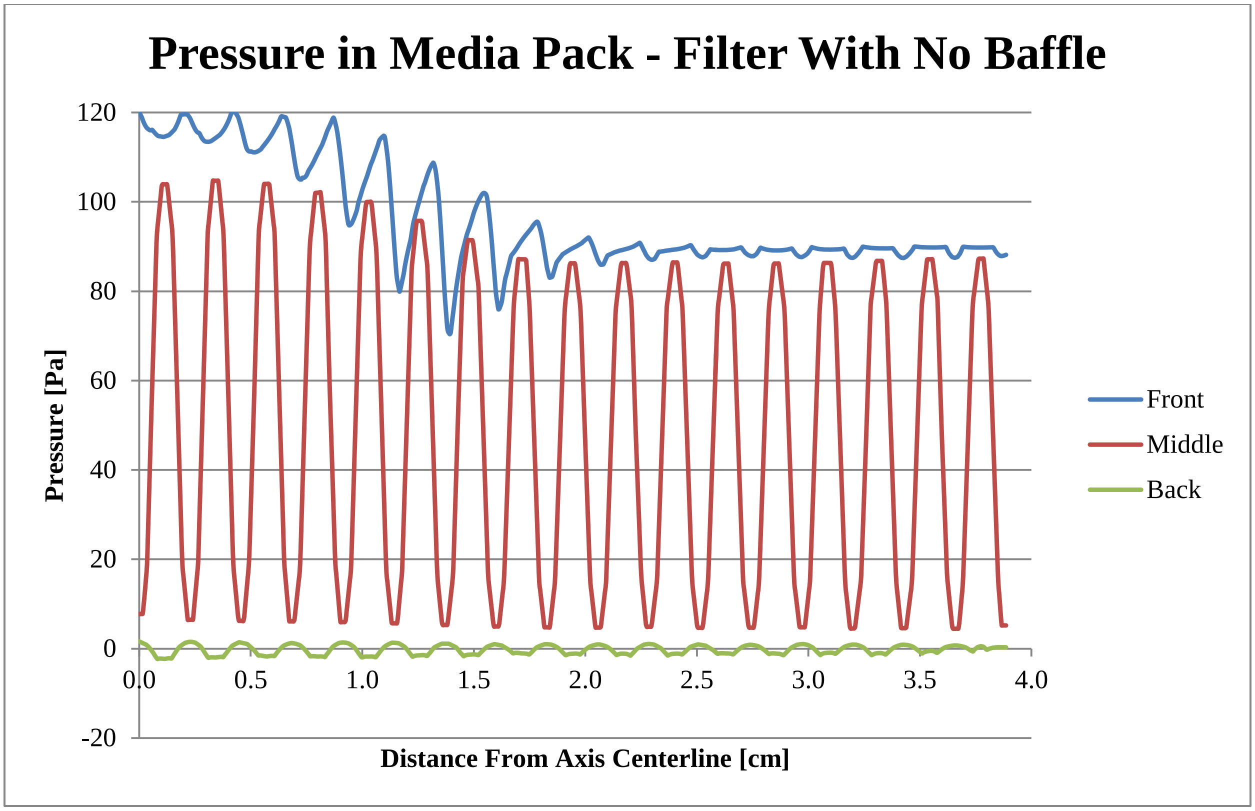


Figure 11, Velocity Contours at Centerline – Baffle


Pressure in Media Pack - Filter With No Baffle
120
100
80
60
40
20
0
-20
Pressure [Pa]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Distance From Axis Centerline [cm]
Front
Middle
Back

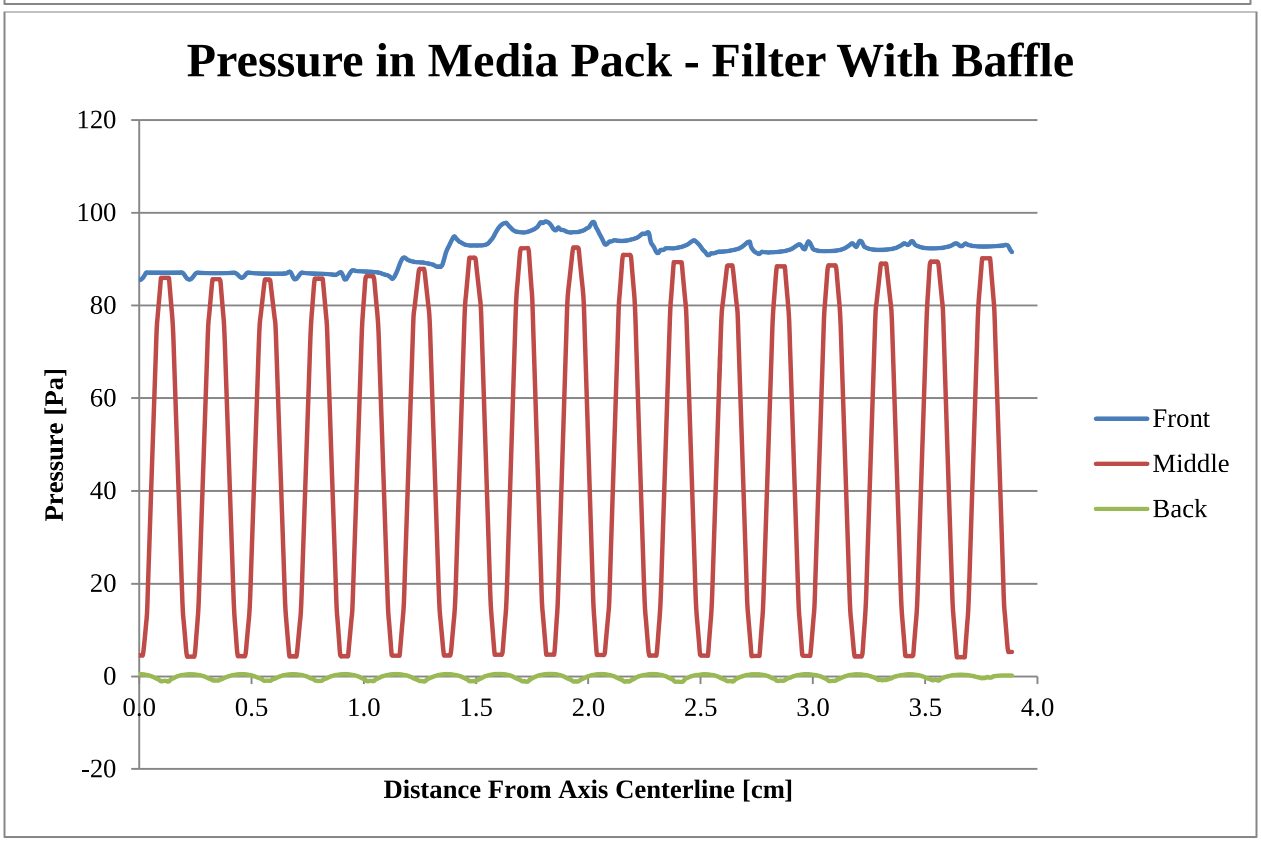
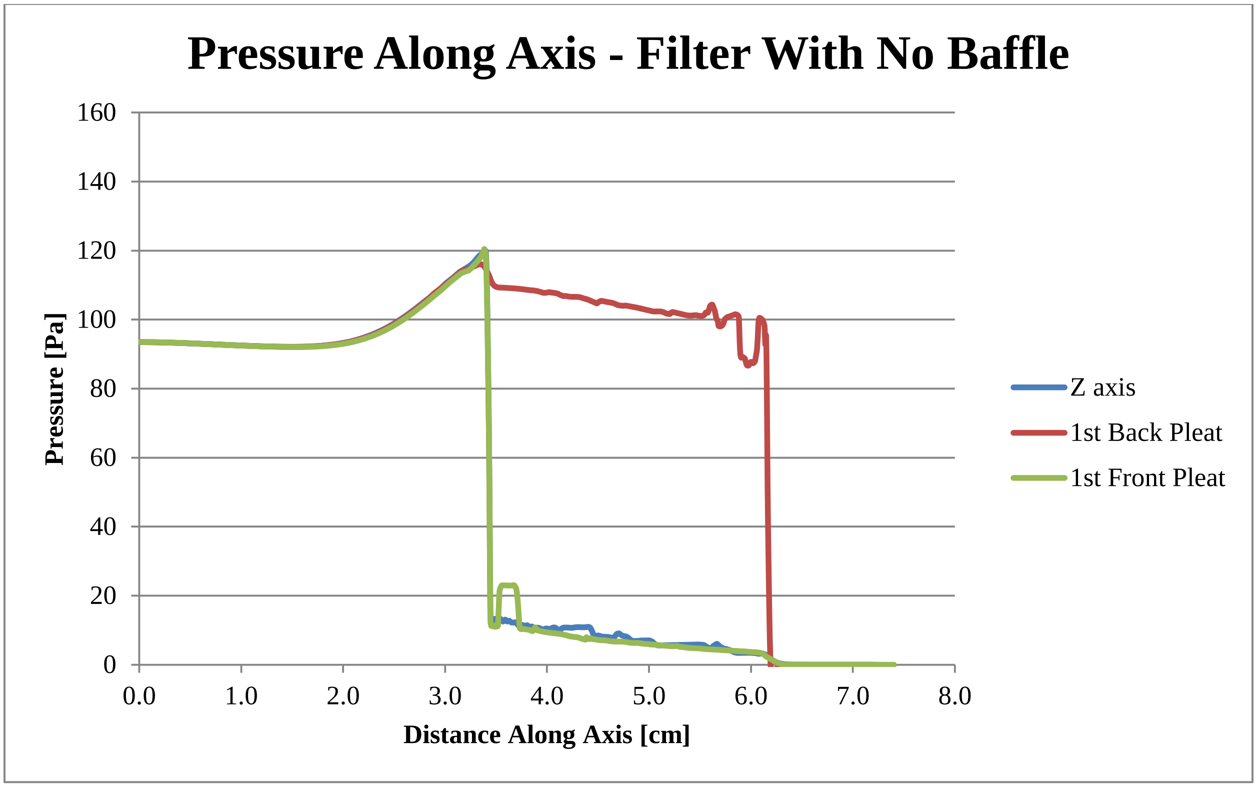

Pressure in Media Pack - Filter With Baffle
120
100
80
60
40
20
0
-20
Pressure [Pa]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Distance From Axis Centerline [cm]
Front
Middle
Back

Figure 12


Pressure Along Axis - Filter With No Baffle
160
140
120
100
80
60
40
20
0
Pressure [Pa]
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Distance Along Axis [cm]
Z axis
1st Back Pleat
1st Front Pleat

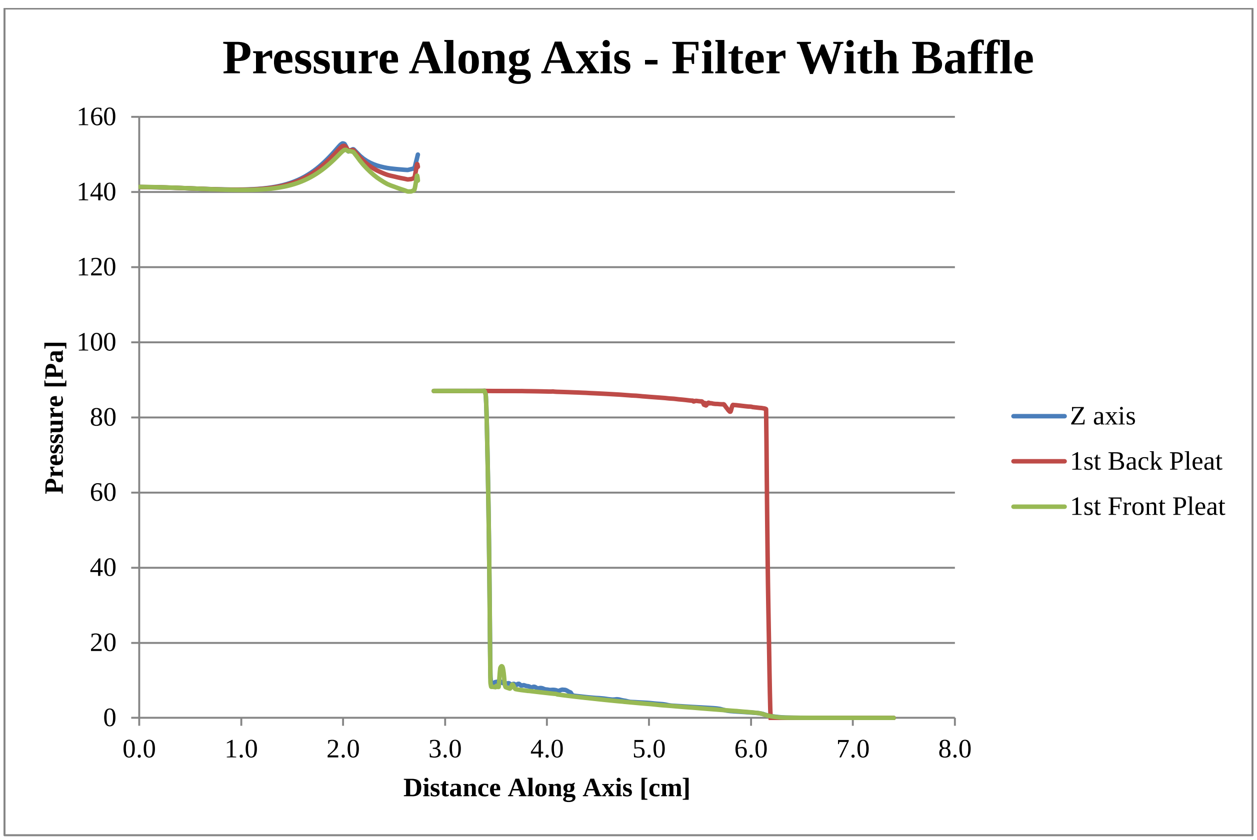

Pressure Along Axis - Filter With Baffle
160
140
120
100
80
60
40
20
0
Pressure [Pa]
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Distance Along Axis [cm]
Z axis
1st Back Pleat
1st Front Pleat

Figure 13

Evaluation of Existing ASME AG-1 Code Sections for Applicability to a Low Flow Rate Radiological HEPA Filter.

If a new low flow HEPA filter is added to the AG-1 code, an evaluation needs to conducted to determine which section of the code is applicable or if a new section would be required. Currently the AG-1 code is being reorganized such that Section FK will pertain only to radial flow HEPA filters, so this filter design would not fit into Section FK. The following is an evaluation of ASME Section FC for applicability to a low flow HEPA filter used for servicing applications.

Article FC-1000 Introduction:

Paragraph FC-1100 Scope covers HEPA filters used in air and gas treatment systems in nuclear facilities. An addition to the FC-1100 scope or a new code section for low flow HEPA filters would cover temporary systems used for servicing nuclear systems and components at nuclear facilities. Section FC-1300 states Section FC applies to extended media dry-type filters for use in systems operating up to 250º F (120ºC). Filters used for servicing generally are not used at temperatures this high. A lower maximum temperature is recommended (perhaps 150º F).

Article FC-3000 Materials:

Paragraph FC-3100 covers allowable materials and would need to be adjusted. Although paragraph FC-3210 allows alternate materials, the inclusion of injection molded materials may be beneficial. In addition, the inclusion of plywood material for filter cases in this size range may not be appropriate. The other material paragraphs could be applied to HEPA filters in the low flow servicing category. Paragraphs FC-3200 and FC-3210 (Special Limitations and Alternate Materials respectively) should be included as well.

Article FC-4000 Design:

The current article covers nine very specific square shaped axial flow designs. Article FC-4000 would have to be modified to include cylindrical and other special designs. Other diagrams would need to be added to the article to include the cylindrical designs. The types of filter packs described in paragraph FC-4130 would be applicable but would need to be modified to allow for fit within a non-rectangular case. The design that this paper describes uses a Type B minipleat slab that is cut into a cylinder. Another likely candidate for smaller low flow filters would be the Type D filter pack that would be cut to a cylindrical shape after folding. Paragraph FC-4140 (Gaskets) would need a subparagraph that would allow the existence of loose gaskets for the compression joint in the threaded nut connection. The FC-4150 paragraph would not need to be modified but probably would not be utilized in the smaller low flow filters. The Faceguard paragraph (FC-4160) would not need to be modified for the case where a wire faceguard is used. For the case where an injection molded faceguard is used, the spacing requirement would be the same, but the material used would be different and would not be needed on both faces of the filter pack when a threaded connection is used similar to design presented in this paper.

The paragraph FC-4200 Performance Requirements would not need to be changed. The Test Aerosol Particle Penetration and Resistance to Airflow paragraphs (FC-4210 and FC-4220 respectively) could remain unchanged. If a new code section was created for low flow filters and/or servicing filters, the sentence regarding testing at 20% rated flow would not be necessary. Paragraph FC-4300 Seismic Qualification would not be necessary for the servicing filters since they are used on temporary systems.

Article FC-5000 Inspection and Testing:

The inspection and testing requirements for a low flow radiological servicing HEPA filter would be similar to a standard nuclear grade filter qualified to ASME AG-1 with three omissions and one addition. The tests for Resistance to Airflow and Test Aerosol Particle Penetration could remain the same but an evaluation needs to be done of the existing equipment (Q-76 and Q-107 penetrometers) for suitability to testing at low flow rates. Metering airflow at low flow rates and low differential pressures is more difficult so this would need to be evaluated. The rate of aerosol dilution would need to be evaluated for low flow testing such that detection instruments are not saturated due to the higher concentrations at low flow rates.

The rough handling testing per FC-5130 would be required for the low flow HEPA filter. The Resistance to Pressure test (FC-5140) needs to be evaluated for feasibility at low flow rates. Although the low flow HEPA filter is not intended for protection during accident or upset conditions, there is a possibility for overpressure when used on positive pressure applications on collection tanks and bottles. The Resistance to Heated Air and Spot Flame Resistance Test (FC-5150 and FC-5160 respectively) would not be required because the filters are used on temporary systems that are not intended for protection during upset conditions. The Structural Requirements and Inspection paragraphs (FC-5170 and FC-5200 respectively) required for the current FC filters are also applicable to the low flow filter.

Recommended Additional Test

One additional test that would be beneficial relates to how a low flow filter would be installed. The filter is installed by hand and involves gripping the case while threading the filter nut and compressing the gasket. A test that applies a load commensurate with the grip strength of an adult human may be appropriate when the filter is qualified. After application of the test load, the Structural Requirements of paragraph FC-5170 would be applied including the paragraph (b) airflow resistance and aerosol particle penetration requirements. The load applied would be based on research on Grip and Pinch strength for adults [5].

Article FC-6000, FC-7000, FC-8000, and FC-9000 Fabrication, Packaging, Quality Assurance and Nameplates:

The requirements for fabrication, packaging, quality assurance, and nameplates would be similar for the low flow filter designs. The parameters would have to be adjusted to include filters with cases that are not rectangular and have different dimensions from the current FC type filters.

Mandatory Appendix FC-I, Filter Media:

The requirements for the filter media used in the low flow filters used in servicing of nuclear systems would be the same as other nuclear grade filters qualified to ASME AG-1 requirements.

Conclusions and Recommendation:

A new low flow HEPA filter design has been developed for use on temporary systems used to service nuclear components and systems. An evaluation of the current code governing nuclear grade filters has been conducted to address a gap in requirements for nuclear filters with rated capacities below 20 acfm. The evaluation indicates that the current code section covering axial flow filters (Section FC in ASME AG-1) differs in significant ways from requirements applicable to a low flow HEPA filter used for temporary nuclear servicing work.

For this reason, a new code section is recommended that would cover requirements for special filters used in temporary nuclear systems. Since these HEPA filters would not be used for protection during accident or upset conditions, the requirements for such filters would be different than the current requirements for nuclear grade filters qualified per ASME AG-1, Section FC. This new code section could also cover requirements for other temporary systems used for nuclear work such as vacuum cleaners used in radiological environments.

References:

1. ASME AG-1-2017 "Code on Nuclear Air and Gas Treatment", Section FC
2. American Glovebox Society, AGS-G002-1998 "Standard Practice for the Design and Fabrication of Glovebags", pg. 9
3. Code of Federal Regulations 42 CFR part 84, "Respiratory Protective Devices"
4. National Institute for Occupational Safety and Health, Procedure No. TEB-APR-STP-0051, "Determination of Particulate Filter Efficiency Level for P100 Series Filters Against Liquid Particulates for Non-Powered, Air-Purifying Respirators Standard Testing Procedure (STP)"
5. Virgil Mathiowetz, MS, OTR, Nancy Kashman, OTR, Gloria Volland, OTR, Karen Weber, OTR, Mary Dowe, OTS, Sandra Rogers OTS, "Grip and Pinch Strength: Normative Data for Adults", Occupational Therapy Program, University of Wisconsin-Milwaukee.