REALIZATION OF FILTER PERFORMANCE SPECIFICATIONS FOR THE QUALIFICATION OF HIGHER-STRENGTH HEPA FILTER UNITS

C. I. Ricketts
Department of Engineering Technology
New Mexico State University
P. O. Box 30001 MSC 3566
Las Cruces, NM 88003-8001
U. S. A.

W. H. Cambo
Lydall, Inc
Chestnut Hill Rd
Rochester, NH 03867
U. S. A.

A. Stillo
Camfil Farr
One North Corporate Dr
Riverdale, NJ 07457-1715
U. S. A.

Abstract

The confinement of radioactive and toxic airborne particles within controlled areas of US nuclear facilities is accomplished by High Efficiency Particulate Air (HEPA) filter units. These filters typically contain a filter medium consisting of a 0.5-mm thick mat of submicron diameter glass fibers. Several eras characterize the history of filter development since the early 1940's. In contrast to both the early years and the last major phase of filter development that concluded in the early 1980's, current priorities focus upon consolidation of filter performance characteristics into qualification-test specifications delineated in US national codes and standards. Units having a glass-fiber filter medium are qualified to be of nuclear grade according to Sections FC (*HEPA Filters*) and FK (*Special HEPA Filters*) of ASME's AG-1(1) Code. The performance criteria of these two code sections presently serve to specify the minimum performance levels of what can be referred to as conventional filter designs, *i. e.*, those which incorporate a filter medium of non-reinforced glass fibers.

A number of disadvantages characteristic of conventional units make them less well suited for several particularly crucial applications. These include nuclear facilities where plutonium or explosive chemicals are processed, or ones in which contact of filters with airborne water droplets, or with air at greater than 80% relative humidity, can not be ruled out. The Achille's heel of conventional glass-fiber filter designs is the filter medium itself. By one to three orders of magnitude, conventional, non-reinforced glass-fiber filter media remain the weakest construction material in US HEPA filter units (2). Moreover, during normal filter service, the detrimental effects of filter medium aging and fatigue - or even more adversely, moisture exposure - can result in increasing fragility of the filter medium and correspondingly significant decreases in filter reliability. Filter functional failure - via unacceptable decreases in filter removal efficiency - can result from only slight physical damage to the inherently brittle and fragile glass-fiber medium, in the form of small tears.

One prospective remedy is represented by nuclear-grade HEPA filters of higher strength, which have been available in Europe for some twenty years (3). One improvement characteristic to them consists of a filter medium reinforced by a cloth of glass fibers (4, 5). Another is a special separator configuration (3) aimed at preventing filter pack loosening that can occur gradually with service time, or quite rapidly, as a result of exposure to moisture, high air velocities, or shock waves. The use of higher strength filters in select, critical applications in the US has been precluded by a lack of sufficiently stringent, code-based test standards that are prerequisite to filter qualification for nuclear service. This is expected to change in the foreseeable future, with the ongoing development of a proposed AG-1 code Section, designated as FM (HEPA Filters of Enhanced Strength and of High Strength).

The principal technical challenges addressed by proposed code section FM are discussed, including setting performance standards, both for reinforced filter media and for filters of higher strength. Also discussed are prospective test-rig concepts for conducting a proof-strength test for new filters: analogous in function to the "resistance-to-pressure" test utilized for qualification of conventional filters under Sections FC and FK. Performance characteristics of a prospective test rig are summarized, together with preliminary results from laboratory tests on specimens of filter media and on model filter packs.

Introduction

The need for higher strength, moisture-resistant HEPA filter units was again formally recognized in the early 1980's [6, 7]. Almost no other air-cleaning system component is fabricated from weaker materials than are they; or can degrade, during service, to the point of functional failure under some of the possible operating conditions of nuclear air-cleaning systems, as can they. The primary deficiency of conventional, non-reinforced units is the inherent fragility of glass-fiber filter media. With increasing service time, this can become compounded by the susceptibility of the filter medium to cumulative degradations in strength properties resulting from aging, from fatigue at locations of highest stress, and from the effects of any exposure to moisture . Also over time, airflow-induced mechanical interactions between the filter medium and the separators (typically aluminum) can further lower filter-unit burst strength and thus performance reliability. In essence, the reliability of an already inherently fragile component can be significantly and adversely affected during service by numerous factors of influence that may lie outside the direct oversight and control of the filter end-user.

High-strength filter units introduced to the European market in the late 1980's [3] represented a combination of technical solutions that addressed several major characteristic weakness of filter designs that incorporate both deep pleats and separators. Under both dry and wet conditions, proof strengths of the European high-strength filters have been demonstrated to be high enough to permit meaningful factors of safety to be quantitatively specified for filter units in their service locations within nuclear air-cleaning systems [3].

Implications of the Realization of High-Strength Filters

In the context of nuclear-grade HEPA filters, higher proof strengths permit an advancement to be made in both the philosophy and practice of nuclear safety. One based upon first recognizing filter units in their service locations as structural elements. And then, acknowledging their functional reliability to be contingent upon their physical integrity being sustained under a broad spectrum of operating conditions. This rationale and higher-strength filters allow performance qualification specifications to be increased and expectations upon the reliability of these critical components to be raised. In both cases to approach levels similar to those of permanently installed air-cleaning system components, such as fans and blowers, dampers and louvers, ductwork, housings, and mounting frames.

Air-cleaning system ductwork, as one example of a permanent component, is presently recognized as a structural element for which code performance characteristics correspondingly include suggested factors of safety [1]. And more illustrative of a double standard: filter mounting frames are required to sustain, without permanent deformation, a pressure impulse loading of 20.7 kPa (3 psi) [1] corresponding to a tornado-induced pressure pulse, while the filter units they hold in place currently are not.

This reflects the historical perception of HEPA filters as one of replaceable cartridge-like components characterized by intrinsically low proof strengths for new units and uncertain burst strengths for aged ones in service. As such, they have been allowed a pass on demonstrable reliability and quantifiable safety factors in performance specifications, in both those of end users and those of codes and standards, even under benign operating conditions. This can be primarily attributed to economics dictating that the cost of replacing expendable components be kept to a minimum.

Codes and Standards in Nuclear Air and Gas Cleaning

The function of a code or standard is to specify minimum performance requirements - covering aspects from design through maintenance - toward ensuring the reliability of safety-related components during their service lifetimes. A number of fundamental HEPA filter unit performance characteristics are typically delineated in codes and standards: particle removal efficiency, pressure drop at rated flow, and some measure of minimum burst strength, usually in the form of a proof test [1]. Also in this group are nonflammability and resistance to the effects of moisture. Requirements relate solely to new filter units in a clean state. Also covered are performance requirements for HEPA filter media. Code sections are completely silent, however, on safety factors for HEPA filters.

The case can be made that - at a bare minimum - safety factors for filters should be based upon the maximum pressure drop of the air-cleaning system blower and a proof strength for filter units in a wet condition [8] . It can be further argued that filter proof strength should be demonstrated after extended exposure of filter units to elevated temperature, as part of a multi-step test sequence that comprises a qualification test process for nuclear-grade units [9]. In contemporary nuclear air-cleaning systems, peak blower pressure drops can exceed 25 kPa (100 in w. g.) [10].

High-Strength Filter Media and Qualification Test Standards

One of the challenges in developing a set of performance qualification requirements for higher strength filters is specifying performance requirements for the high-strength filter media required. Such media have been available since the early 1980's [4] and are typically characterized by a reinforcing cloth, or scrim of glass fibers. Shown in Fig. 1 is a summary of recent test results carried out by one filter media manufacturer toward quantifying the differences between a qualified, nuclear-grade HEPA filter medium and its reinforced equivalent which has not been submitted for nuclear service qualification. Also included are the current filter medium performance specifications of Section FC and tentatively proposed ones for Section FM that is in development. Data upon which Fig. 1 is based are summarized in Table AI.

It is clear from Fig. 1, that folding and wetness significantly reduce tensile strength, not only individually, but also cumulatively. Folding simulates the process of pleating the filter medium during actual filter unit manufacture, which causes breakage of the submicron glass fibers and tearing of the binder. Testing of wet specimens quantifies how severely the second greatest adverse factor of influence (after elevated temperature) reduces filter medium strength. It is noted that mandatory appendix, FC-I, of Section FC does not currently specify minimum tensile strength values for wet, folded specimens tested in the cross direction. Perhaps, because typical values are so low as to be almost meaningless. Results for the reinforced filter medium of Fig. 1 suggest that such a test could quite definitively separate a high-strength filter medium from a conventional one.

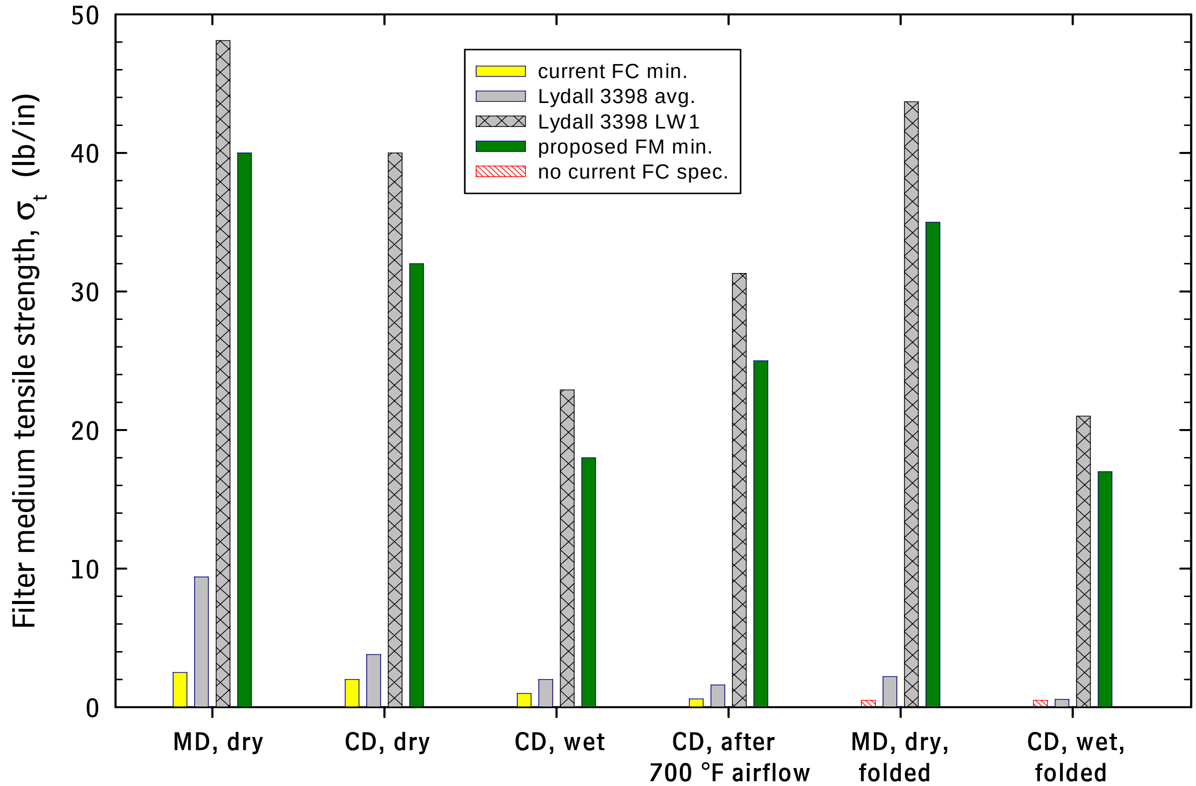

Figure 1: Filter medium strength comparisons to Section FC and proposed Section FM specifications.

Prospective Test Apparatus for Qualification Testing of High-Strength Filter Media and Filter Units

Another challenge encountered in developing code specifications for higher strength filters is the higher performance requirements of the test apparatus for qualifying the structural capabilities of more robust filters. A number of concepts have been proposed for proof testing high-strength HEPA filter units (11). As of yet, only one formal procedure has been implemented (12). However, it can no longer be performed due to the dismantling of two large-scale test facilities upon which it depended. This has left end-users of the German high-strength filter design without a means of qualification testing. This is one contributing factor in the lack of more widespread utilization of this filter design (13).

A number of prospective test rig concepts have been evaluated toward selecting a suitable one for qualifying HEPA filter units of higher strength in the proposed Section FM. A prototype of the water-loop test rig (see Table I) was built and found to be less suitable than anticipated, primarily due to the low flow resistance of high-strength filters. The idea of the falling water column was first proposed for consideration by one of the authors, A. Stillo, during a sidebar at the CONAGT (Committee on Nuclear Air and Gas Treatment) Standards Committee meeting in Summer 2007.

Table I: Prospective test rig concepts for qualification testing of higher-strength filter units.

Test Standard	Principle	Advantages	Disadvantages
FC-5140 of AG-1 (1)	1-h duration of $\Delta p = 2.5$ kPa, via recirculating loop of airflow with water spray	proven apparatus and procedures available text rig	insufficient mechanical loading mechanically complex high power consumption
TLA No. 22 (12)	20-h duration of $\Delta p \leq 8$ kPa, via recirculating loop of airflow with water spray	sufficient mechanical loading proven procedures	mechanically complex high power consumption expensive no available text rig
DIN EN *xxxx* (11), *prospective*	4-h duration of $\Delta p = 5$ kPa, via recirculating loop of airflow with water spray	proven apparatus and procedures	insufficient mechanical loading mechanically complex high power consumption expensive no available text rig
FM-*xxxx* of AG-1 (1), *prospective*	1-h duration of $\Delta p = 15$ kPa, via recirculating loop of water flow	prototype text rig available compact moderate power consumption	marginal mechanical loading mechanically complex expensive
FM-*xxxx* of AG-1 (1), *prospective*	0.25-s impulse of $\Delta p < 100$ kPa, via a falling water column	mechanically simple low power consumption inexpensive proven on small-scale	unproven on full-scale overall height may prove to be problematic
FM-*xxxx* of AG-1 (1), *prospective*	50-ms impulse of $\Delta p < 50$ kPa, via expansion wave moving through air within a shock tube	air instead of water for working fluid	need for diaphragm replacement expensive not fully proven on any scale

Concept of Falling Water Column for Proof-Test Qualification of Higher Strength Filters

As shown in the schematic for the falling water column of Fig. 2., the test filter is located at the bottom of a vertically oriented, sealed duct. The column of water (the working fluid) is initially supported at rest by a quick-opening valve located above the test filter at fall distance, l_a. Above the water column of length, l_w, is an optional air chamber of length, h_1. This chamber can either be open to the atmosphere for driving-air pressure, $p_1 = p_{atm} = 0$ gage pressure, or alternatively sealed and pressurized to $p_1 \geq p_{atm}$. The test is initiated by opening the valve, at which time the mass of the water column is accelerated by gravity and any $p_1 \geq p_{atm}$ toward impact with the test filter below, at velocity, v. For certain assumptions, the peak pressure at the upstream face of the test filter can be estimated by

$$p_2 = (l_w + \frac{v^2}{g})\gamma_w \quad , \tag{1}$$

where the hydrostatic pressure term is represented by l_w, the impulse pressure term by v^2/g, the specific weight of the working fluid by γ_w, and gravitational acceleration by g. The underlying assumptions include negligible air and water flow resistance in the duct, negligible airflow resistance through the filter, and the vertical component of the water velocity upon impact with the upstream face of the filter becomes zero.

Using equations of particle motion, an equation was developed for h(t), the position of the top surface of the water in terms of fall time (t), g, h_1, p_1, l_w, and working fluid density, ρ_w. Setting h(t) equal to ($h_1 + l_a$) and solving iteratively, the time (t_{la}) for the water column to fall distance, l_a, can be determined. By differentiating h(t) with respect to time, an equation for the velocity v(t) was obtained. Use of the fall time value in the velocity equation, allowed the water velocity at impact with the upstream face of the test filter to be explicitly determined.

Illustrated in Fig. 3 is a rendering of a proposed design for a full-scale, prototype water-column test rig having an overall height of 10 m (33 ft). Represented is the 24 x 24-in (0.610 x 0.610-m) filter cross-section. The metal duct to contain the water column is 4.88 m (16 ft) long to accommodate $l_a \leq$ 3.81 m (150 in), partly based upon a maximum blower Δp = 2.54 m (100-in) w.c. This, toward being able to ensure a minimum filter safety factor of 1.5, based upon a maximum hydrostatic pressure component of l_w = 3.81 m (150 in) in a proof test. Values in the range of 0.91 $\geq l_a \leq$ 3.05 m (3 $\geq l_a \leq$ 10 ft) are foreseen for the distance between the horizontal centerline of the valve body and the test filter, made up by the valve body itself and the duct section between valve and test filter. The quick-acting valve, 1.22 m (4 ft) in overall height, is a pinch type, consisting of a sleeve body of vinyl-impregnated fiber-glass cloth and an externally mounted pneumatic-cylinder-actuated clamping device.

The layout of the prototype rig was in part determined by the information compiled in Fig.s 4 and 5 which are based upon Eq. (1), as well as the equations for h(t) and v(t) described above. By selecting, for example, a peak pressure of approx. 100 kPa gage (14.5 psig) and the closest integer value of fall distance, l_a = 3 m, needed to

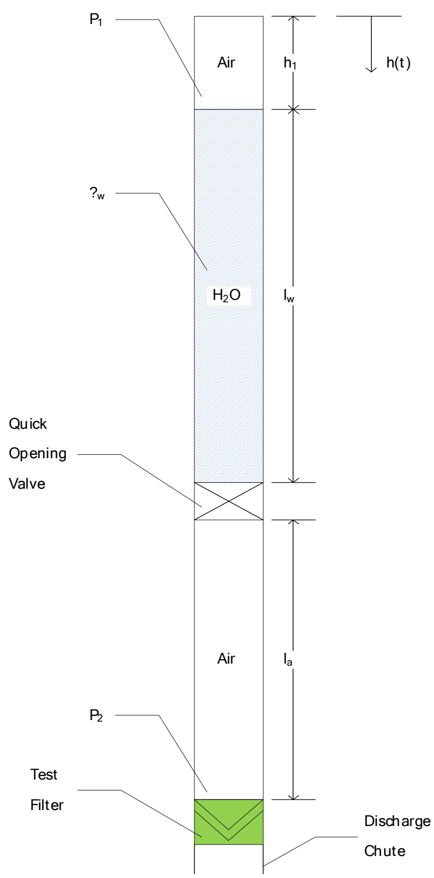

Figure 2: Schematic of falling water column for qualification testing of higher-strength nuclear-grade HEPA filters.

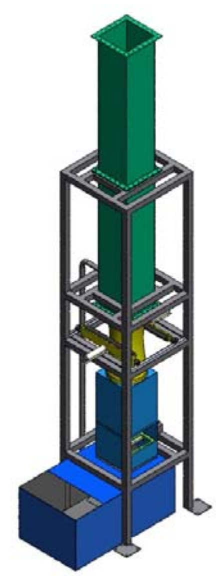

Figure 3: Rendering of full-scale filter qualification test rig based upon concept of falling column.

obtain it, Fig. 4 reveals that v = 7.66 m/s (25 ft/s) and p_2 = 92.7 kPa gage (13.4 psig). This represents a value of 2.6 times the hydrostatic pressure value at the bottom of the water column for the maximum water column height selected above, l_w = 3.81 m (150 in). The effect of the hydrostatic pressure alone on the filter is

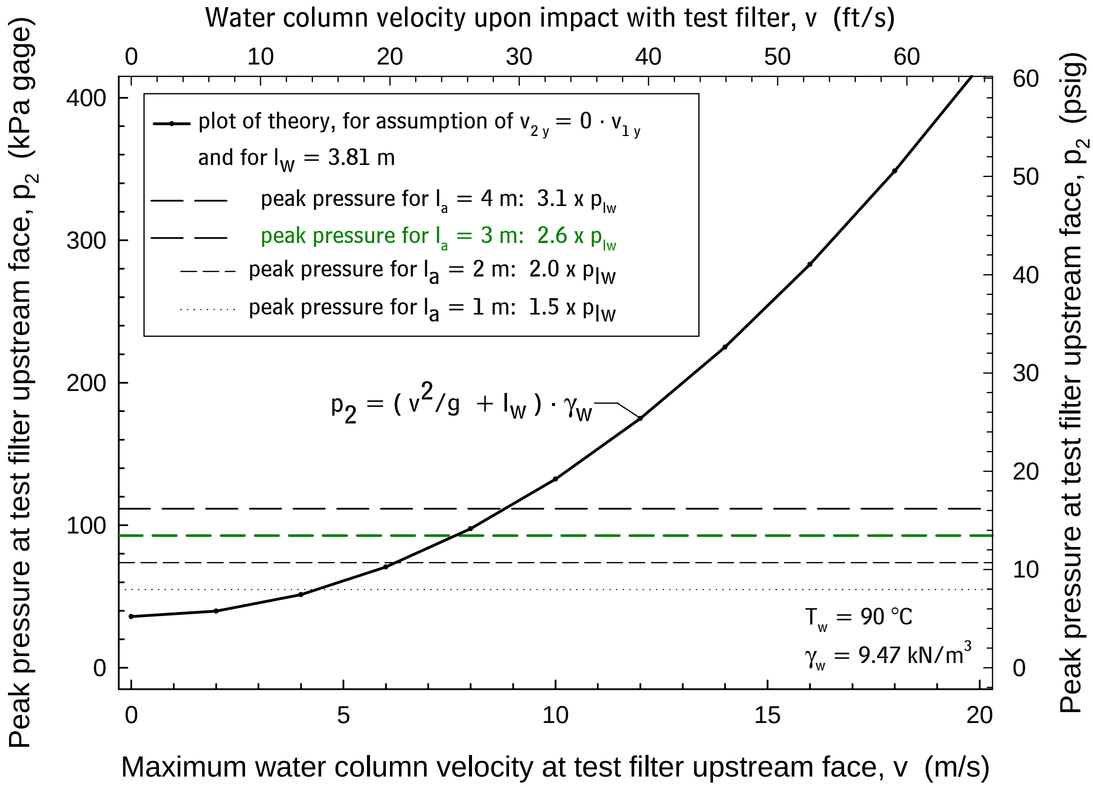

Figure 4: Peak water pressure at test filter upstream face with maximum fall velocity of water column.

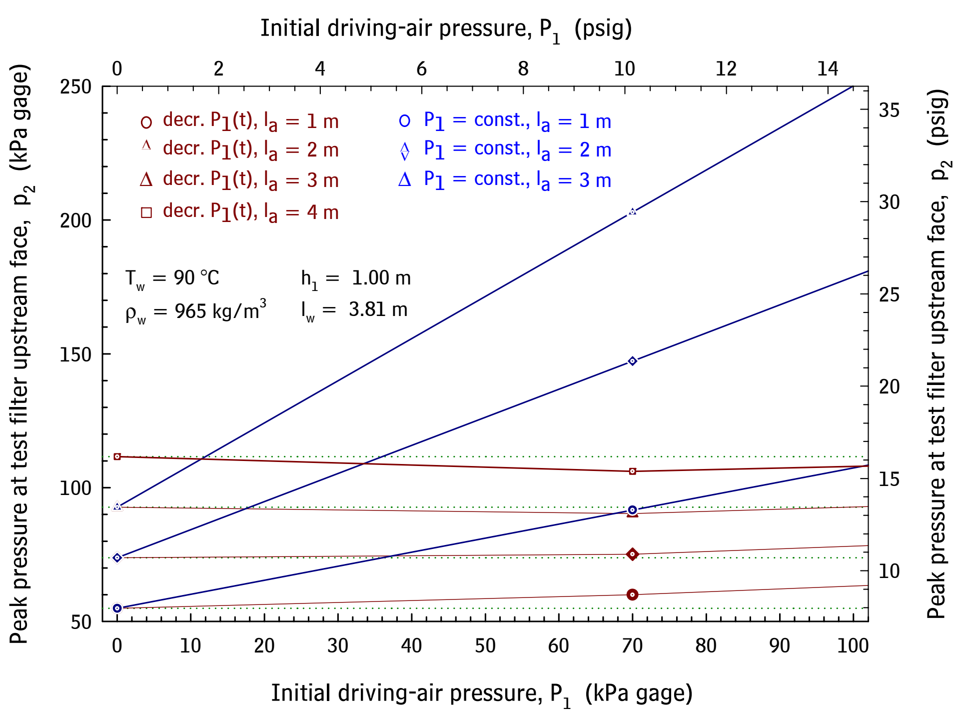

Figure 5: Peak pressure at test filter upstream face with decreasing and with constant pressure of driving air.

effectively multiplied by this factor; via the added impulse pressure of the falling water column. Figure 5 can be used to determine how best to generate a target peak pressure value, p_2, using the test rig. One way is via fall distance alone for $p_1 = 0$. Or alternatively, with $p_1 > 0$ and either p_1 = constant, or p_1 decreasing, as the water column falls (or flows, in the limiting case of $l_a = 0$).

An example for $p_2 = 92.7$ kPa gage (13.4 psig) is as follows. Figure 5 reveals that the target p_2 value can be generated by $p_1 = 0$ and $l_a = 3$ m, representing an open-top configuration. Or alternatively, by $p_1 = 18$ kPa and $l_a = 2$ m, or by $p_1 = 70$ kPa and $l_a = 1$ m, using a closed system and a constant pressure supply. Also in a closed system, an initial driving-air pressure that is decreasing with the falling water requires $p_1 = 100$ kPa and $l_a = 3$ m, the least economical choice. For overall economic rig operation, the first option listed above appears best, *i. e.*, no pressurization. The sole advantage of pressurization lies in reducing the overall height of the rig.

Results of Preliminary Test on Filter Media Specimens and Model Filter Packs

To evaluate the feasibility of the falling water column concept, as well as to check the mathematical models developed to evaluate it, a laboratory-scale test apparatus was constructed. It consisted of 3-in, standard-wall PVC pipe, a standard brass gate valve actuated by an electric motor, and a test section for clamping and supporting specimens of filter media having diameters of 92 mm (3.6 in). The test apparatus was laid out in the configuration of Fig. 2, had the specific dimensions noted in Fig. 6, and was used under the test conditions specified in Fig.6. Results of some preliminary tests are shown in Fig.s 6 - 8.

The transient pressure traces of Fig. 6 were obtained by recording the output of a variable-reluctance pressure transducer using a digital storage oscilloscope. A small-diameter, stainless steel tube with a side-on total-pressure tap was connected to the transducer via a short flexible plastic tube. Great care was taken to ensure that only water as a pressure transmitting medium was present from the upward facing pressure tap hole through the tube and into transducer cavities, all the way to its bleed-off port. The pressure probe was mounted in the test section a only few millimeters above each filter medium test specimen which was supported by a plate with grill-like opening to simulate the presence of an aluminum separator on the downstream side of the filter medium.

The two specimens of filter media represented in Fig. 6 are shown in Fig. 7. The conventional filter medium exhibited two lengthy tears which help explain its peak p_2 value lying below that of the reinforced medium which actually was pulled loose from the outer annular ring clamp during the test. Both the resulting wrinkles around the edge and the parallel indentations from the support grill are evident for it in Fig. 7. But for coming loose from the sealing clamp, the peak p_2 value would have exceeded the theoretical peak by more than the 18% recorded. A test conducted (trace not shown) with an aluminum plate in place of a specimen, has a peak value 49% higher than the theoretical peak. This may be related to nonuniform velocity profiles in the water flow or some another violation of the simplifying assumptions made for the mathematical models.

In a filter pack of pleated medium and separators, the horizontal fluid flow moves parallel to the vertically oriented filter medium as the flow travels down the triangular channels between filter medium and separators, before entering the filter medium at some angle less than 90°. In the test apparatus, however, the specimens were oriented horizontally, that is, perpendicular to the vertical flow of water. This is one of several dissimilar-ities that could compromise direct scale-up of results from specimens in the lab-scale apparatus to filter units in a full-scale rig. Others may include the filter pack depth and the spring-like give to the separators.

The post-test photographs of the model filter packs in Fig. 8 show catastrophic damage to the conventional filter medium ($p_2 = 9.96$ psig) and damage to one pleat end of the pack of reinforced filter medium ($p_2 = 14.0$ psig).

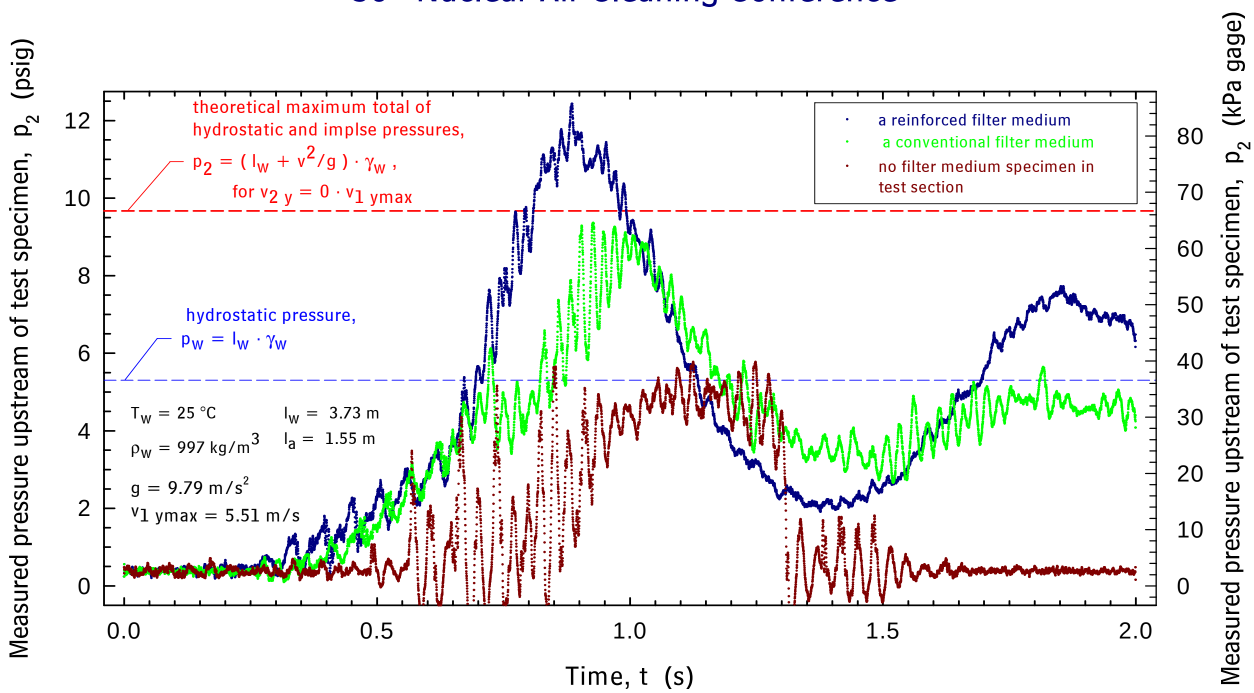

Figure 6: Measured pressures upstream of filter media specimens in laboratory-scale test apparatus.

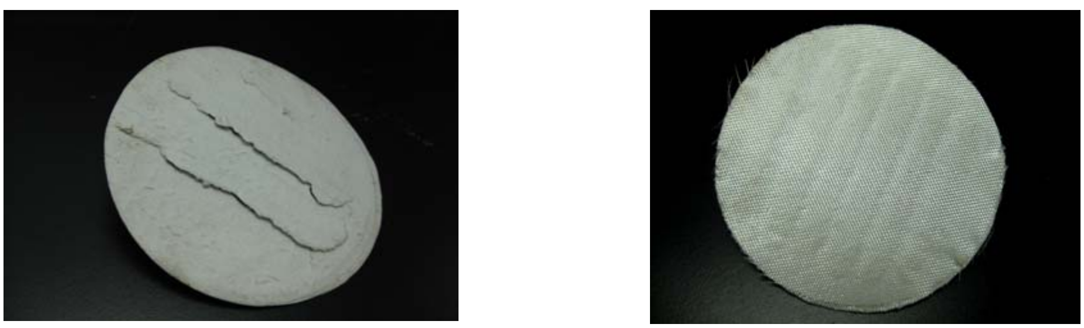

Figure 7: Specimen of conventional (l) and high-strength (r) filter medium after lab-scale falling-water-column test.

Figure 8: Model filter pack of conventional (l) and high-strength (r) filter medium after falling-water-column test.

Conclusions

The availability of higher strength filters alone, is not sufficient to provide filter end-users with the option of utilizing such filters for which meaningful in-service safety factors can be calculated. Also necessary is the delineation of filter performance specifications in a universally accepted code. Any code that addresses nuclear HEPA filters of higher strength will need to specify performance criteria not only for the filters, but also for the filter media utilized in their fabrication. Results presented here suggest that particular consideration should be given to specifying a minimum tensile strength for folded, wet samples of filter media in the cross direction.

Based upon both mathematical models and results of preliminary laboratory-scale tests on samples of filter media and model filter packs, the falling water column concept shows viable promise as a proof-test method for qualifying filters of higher strength. No other known concept appears suitable for qualification testing of higher strength filte units. Therefore, it is recommended that focus now be directed toward fabrication and construction of a full-scale prototype test rig based upon the water column principle. The primary functions of the prototype rige would be two-fold. One is to confirm the suitability of the method on full-scale filter units.
The other is establish detailed filter performance qualification criteria, based upon testing of both conventional and higher strength filter units.

Acknowledgments

The efforts of the mechanical engineering technology students who explored alternative test-rig concepts and numerous designs are also appreciatively recognized for their preliminary laboratory-scale testing. Their project-related accomplishments were achieved toward fulfillment of academic requirements for graduating seniors. This team of recent NMSU graduates included: Efren Chavez, Reginald McCoy, Juan Carlos Molina, and Matthew Steele (team leader). Thanks are also extended to Garett Jordan for assistance with many of the figures.

References

1. ASME AG-1-2003
   Code on Nuclear Air and Gas Treatment
   ASME, New York 10017-2392, 2003.

2. Ricketts, C. I. and P. R. Smith, *The Case for Improved HEPA-Filter Mechanical Performance Revisited*; CONF 960715 (1997),
   Proceedings of 24th DOE/NRC Nuclear Air Cleaning and Treatment Conference, p. 829 ff.

3. Rüdinger, V., C. I. Ricketts, and J. G. Wilhelm,
   High-Strength High-Efficiency Particulate Air Filters for Nuclear Applications;
   Nuclear Technology 92 (1) (1990) p. 11 ff.

4. Pratt, R.P. and Green, B.L.
Performance Testing of HEPA Filters Under Hot Dynamic Conditions;
CONF 840 806 (1985), p. 1107 ff.

5. Gilbert, H., W. Bergman, and J. K. Fretthold
Development and Evaluation of a HEPA Filter for Increased Strength and Resistance to Elevated Temperature;
CONF 9020823 (1993), p. 617 ff.

6. Carbaugh, E. H.
A *Survey of HEPA Filter Experience*;
CONF-820 833 (1983) p. 790 ff.

7. Carbaugh, E. H.
Survey of HEPA Filter Applications and Experience at Department of Energy Sites;
NTIS, UC-70, PNL-4020,
Pacific Northwest Laboratories, Richland, WA, 1981

8. Ricketts, C. I. and P. R. Smith, *A Model for the Stresses in the Filter Medium of Deep-Pleat HEPA-Filter Packs: Implications and Applications in Review*,
28th Nuclear Air Cleaning Conference, Albuquerque, NM, September 2004.

9. Ricketts C. I., P. H. Ricketts, and P. R. Smith,
Specifications and a Prototype Test Apparatus for Qualification of High-Strength HEPA Filter Designs ,
29th Nuclear Air Cleaning Conference, Cincinnati, OH, July, 2006.

10. Gerard Garcia, verbal communication, Section FM task group meeting, February 2008.

11. Kuhn, W., M. Fronhoefer, M. Neuberger, and J. G. Wilhelm, *Design and Construction of an Apparatus for Qualification and Production Lot Testing of HEPA Filters to be installed in Ventilation Systems of German Nuclear Power Plants* , (in German); KfK 5149, ISSN 0303-4003, Forschungszentrum Karlsruhe,
D-76021 Karlsruhe, Fed. Rep. of Germany, 1993.

12. TLA No. 22 *Technical Specifications for the Delivery and the Acceptance of Nuclear Grade HEPA Filter Units*, 1st Ed. (in German)
Karlsruhe Nuclear Research Centre, Karlsruhe, Fed. Rep. of Germany, June 1988.

13. Dr.-Ing. M. Neuberger, PM, Forschungszentrum Karlruhe, Germany, private communication, 29 June 2006.

Appendix

Table AI: Average properties for grade 3398 ASME AG-1 HEPA medium for higher strength HEPA filters, 3398-LW1, differences, and tentative FM specifications.

		current FC Spec.	Average. Properties 3398	3398-LW1	3398 / 3398-LW1 Comparison Difference	(units)	tentative FM Spec.
BASIS WEIGHT (LBS./3MSQ.FT.)		none	55.0	117.0	2.1	(x greater)	none
7.3 PSI CALIPER (IN.)		0.015 ≥ t; t ≤ 0.040	0.0177	0.021	19	(% higher)	0.015 ≥ t; t ≤ 0.040
TENSILE (LBS./IN.)	MD	≥ 2.5	9.4	48.1	5.1	(x greater)	≥ 40
	CD	≥ 2.0	3.8	40.0	10.5	(x greater)	≥ 32
ELONGATION (%)	MD	≥ 0.5	1.4	1.8	29	(% higher)	≥ 1
	CD	≥ 0.5	2.1	2.1	0	(% higher)	≥ 1
WET TENSILE (LBS./IN.)	CD	≥ 1.0	2.0	22.9	11.5	(x greater)	≥ 18
HEATED AIR TENSILE @ 700 °F (LB./IN.)	CD	≥ 0.6	1.6	31.3	19.6	(x greater)	≥ 25
WATER REPELLENCY (IN.)		≥ 20	30	28	7	(% lower)	≥ 20
DOP (%)		≤ 0.03	0.011	0.015	36	(% higher)	≤ 0.03
RESISTANCE (MM)		≤ 40	35.5	37	4	(% higher)	≤ 40
COMBUSTIBLES (%)		≤ 7	5.9	6.5	10	(% higher)	≤ 7.5
FOLDED TENSILE STRENGTH (LBS/IN)	MD	*none*	2.2	43.7	19.9	(x greater)	≥ 35
FOLDED TENSILE STRENGTH, WET (LBS/IN)	CD	*none*	0.56	21.0	37.5	(x greater)	≥ 17