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Abstract

Ventilation and air cleaning systems provide for the health safety and the thermal comfort of personnel in facilities that contain hazardous or toxic radioactive materials. The air cleaning systems also prevent the release of contaminated airborne particulate and gases to the surrounding environment. In such systems, the required high particle-removal efficiencies at relatively low pressure drops are made possible by the use of High Efficiency Particulate Air (HEPA) filter units. As part of the containment barrier between contaminated zones and the environment, HEPA filters must perform reliably not only during normal facility operations but also under possible abnormal or so-called accident conditions. Filter units may be called upon to withstand individual or combined challenges of elevated temperature, pressure drop, shock wave impingement, or high air humidity: ideally without performance decreases that would result in a loss of particle containment or confinement.

To meet these requirements, two filter pack designs find widespread use in the US: deep-pleat, separatorless, and deep-pleat with separators. The packs of all conventional HEPA filter designs can be characterized as fragile, the service reliability of which is dependent upon an inherently weak and brittle constituent; the glass-fiber filter medium. Packs with separators are recognized as being both of the most robust design and that with a high potential for raising filter burst strength, a measure of reliability.

To better understand the reliability limitations of current filter pack designs, selected references in the literature were reassessed in the context of reviewing the implications and applications of one stress model for the filter medium in deep-pleat configurations with separators. The model, derived from solid mechanics fundamentals, has been experimentally verified only for new filter units under steady or relatively slowly changing pressure drops. Plots of the stress distributions predicted by the model reveal locations of stress concentrations at which fatigue of the filter medium can be expected. An approx 50% deviation, of model-predicted results from actual results for used filters, indicates the possibility that fatigue - in combination with pleat-to-separator interactions - can degrade filter medium tensile strength much more than aging of the filter medium in normal benign service. The model also explains why the pack depth should never be less than one-half that of the pack height or diameter, for deep-pleat filters having a square or round cross-section and separators.

The model itself and the experimental data gathered to verify it have been used to analyze other aspects of bench-marking and improving filter pack reliability, particularly in humid airflows. Some of those summarized here include verification of failure modes, design of more robust packs, and revision of filter-unit performance specifications in US codes and standards. The overall review indicates that many, if not most, concerns about filter reliability in service could be addressed by the adoption of reinforced glass fiber media. Given the commercial availability of such media and current knowledge of the filter medium as the Achilles' heel of conventional units: it seems likely that reinforced media would be universally mandated in codes for qualification of nuclear-grade filters, were they to be invented today.

Introduction

Ventilation and air cleaning systems provide for the health safety and the thermal comfort of personnel in facilities that contain hazardous or toxic radioactive materials. The air cleaning systems also prevent the release of contaminated airborne particulate and gases to the surrounding environment. In such systems, the required high particle removal efficiencies at relatively low pressure drops are made possible by the use of High Efficiency Particulate Air (HEPA) filter units. Under benign operating conditions, HEPA filters serve as reliable and relatively economical components in air cleaning systems of nuclear facilities worldwide.

As part of the containment barrier between contaminated zones and the environment, HEPA filters must be relied upon not only during normal facility operations, but also under possible abnormal or so-called accident, or upset conditions. Filter units may be called upon to withstand individual or combined challenges of elevated temperature, pressure drop, or high air humidity: ideally without performance decreases that would result in unacceptable losses of particle containment or confinement.

To help meet these requirements, two basic filter pack designs find widespread use in the US: deep-pleat, separatorless and deep-pleat packs with separators. Two other designs, the mini-pleat and the radial flow are more common in Europe. Filter packs of all four designs can be characterized as fragile elements, whose reliability in service is dependent upon an inherently weak and brittle constituent; the glass-fiber filter medium. During manufacture of the deep-pleat design with separators, the flat, paper- like filter medium of glass fibers is pleated over corrugated separators of aluminum to form the filter pack as shown in Fig. 1. For handling, transport, and mounting purposes, the pack is then typically sealed into a rigid protective frame of plywood or metal with an elastomeric adhesive.

Conventional HEPA filter units meeting current US codes and standards represent not only the least robust components to be found in a nuclear air cleaning system, but also the most sensitive to the adverse effects of conditions deviating from those of normal operation. They correspondingly constitute the weakest link in a chain of crucial components forming the barriers between contaminated zones and the environment. Figure 2 illustrates the fragility of conventional glass fiber filter media, as compared to other typical filter-unit construction materials.

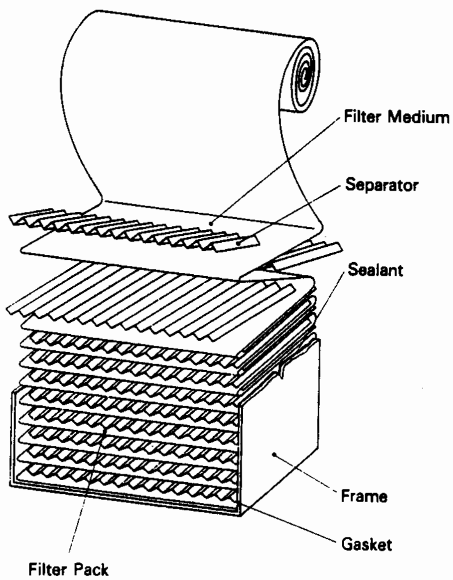

Figure 1: Conventional deep-pleat filter unit with aluminum separators during manufacture[1].

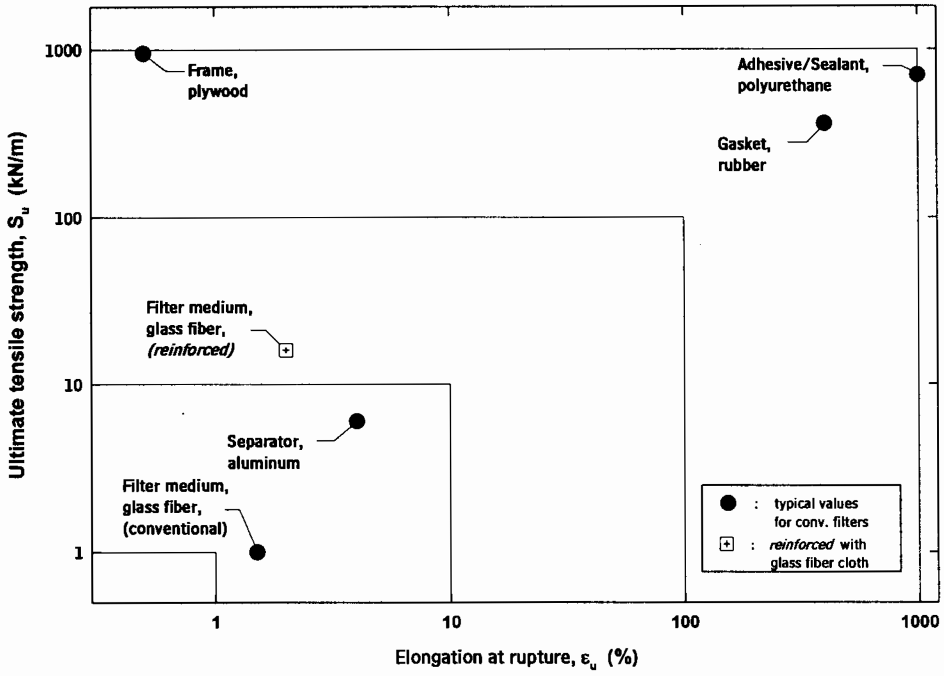

Figure 2: Strength characteristics for fabrication materials in nuclear grade HEPA filters[2].

The sensitivity of conventional, i. e., non-reinforced filter media to reductions in tensile strength caused by various factors, is illustrated in Fig. 3. Note the significant decreases for pleating and moisture exposure, in particular. Moreover, exposure of a filter medium to multiple attenuation factors - concurrently or sequentially - can be expected to result in cumulative reductions in tensile strength.

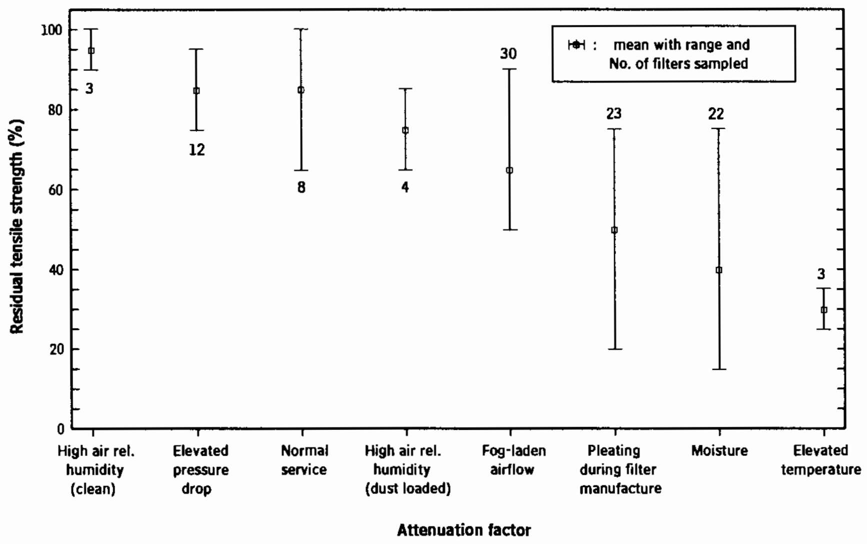

Figure 3: Residual tensile strength of HEPA filter media for eight strength-attenuating factors[2].

Filter unit burst strength as a measure of filter reliability

One measure used to quantify filter-unit reliability is burst strength. A breach of the physical integrity of the filter medium, or of any other fabrication component (e.g., frame, pack sealant, or gasket) that leads to an unacceptable, irreversible decrease in filtration efficiency, constitutes functional failure of the filter unit. The differential pressure (Δp) across the filter at which this failure occurs, is referred to as the filter-unit burst strength. It is a variable that can change with time, due to potentially significant degradations in the strength of non-reinforced glass-fiber filter media during service. It represents an upper limit of differential pressure across the filter that should not be exceeded at any time in service.

Both filter burst strengths and failure modes have been documented in the literature for numerous test conditions used to evaluate filter reliability during so-called accident, or upset conditions in nuclear air-cleaning systems. For example, failure pressures have been measured under test conditions simulating the high-velocity airflows induced by tornadoes (Table I) or the overpressures of explosive shock waves (Table III). Other test conditions have simulated the high temperatures in the combustion gases of fires, as well as the flows of high-humidity air that could result from a Loss-of-Coolant Accident (LOCA) in a power reactor (Table II) or from fire abatement measures. The burst strength statistics of two different investigative teams, one for filters from primarily American manufacturers (Table I) [3,4], the other for primarily European (Table II) [1], show good agreement for results that can be directly compared: those for deep-pleat and mini-pleat designs in dry air for service up to 120 °C. For the former, contrast 6.2 - 24.8 kPa and 10 - 23 kPa; and for the latter, 6.9 - 16.5 kPa and 6 - 19 kPa.

Of particular interest are values for deep-pleat filter units *with separators*. Given sufficient pack depth for a given pack height, they have been found not only to be of the most robust design, but also of that with the most potential for efficiently raising filter burst strength and hence reliability in service. A serious drawback of the separatorless and mini-pleat filter packs is their susceptibility to catastrophic failure at mechanical loads approx. 10 - 30% above that which first results in tearing of the filter medium. The entire separatorless pack and the edges of mini-pleat panels are prone to being torn from the filter frame, essentially resulting in a total loss of particle removal efficiency [5].

This is not typical for deep-pleat packs of the 292-mm depth for the square 610-x 610-mm cross-section, which are comparatively more robust and stable under loads up to approx. 50% above that at which initial failure of the filter medium occurs. Thus not only do deep-pleat filters fail at higher mechanical loads than those of the separatorless and mini-pleat designs, they also do not tend to fail catastrophically at loads that significantly exceed that of initial failure. For the above reasons, this design and size was judged most suitable and was subsequently modified to create commercially available high-strength filter units for the German market [1].

It is of interest to compare the data of Tables I and II to those of a German high-strength, glass-fiber, filter design developed during the 1980's [1]. The high-strength units showed no failure after Δp's of 56 kPa (8.1 psi) in dry air and 15 kPa (2.2 psi) under fog conditions. This as verified by post-test filtration efficiencies > 99.97%, against a monodisperse sodium fluoresceine aerosol with a mean diameter of approx. 0.15 μm.

Table I: Summary of burst strengths for conventional, new, clean 610- x 610- x 292-mm nuclear-grade, glass-fiber HEPA filter units for service ≤120 °C exposed to simulated tornado pulses with an average pressurization rate of 12.4 kPa/s (1.8 psig/s) to pressure drops of approx. 20.7 kPa [gage] (3 psig) using dry air.

Filter Unit Design	No. of Manufacturers (Ea.)	No. of Filter Units Tested (Ea.)	Range of Diff. Pressures at Failure [c] (kPa)	Average Diff. Pressure at Failure [d] (kPa)	Sample Standard Deviation (kPa)
Deep pleat † [a]	4	125	6.2 – 24.8	16.3	4.7
Mini-pleat [b]	3	7	6.9 – 16.5	11.8	3.9
Separatorless [b]	1	3	11 - 11	11	0

[a] excerpted from [3]. [c] numbers represent a result for an individual filter. † with separators.
[b] excerpted from [4]. [d] numbers represent an average of all results for a design.

Table II: Summary of burst strengths for conventional, new, clean 610- x 610- x 292-mm nuclear-grade, glass-fiber HEPA filter units exposed to dry air at high velocities, or humid air at design flow, representing a total of approx. 140 test filters from 8 manufacturers [1].

Filter Unit Design		Maximum Operating Temperature (°C)	Range of Average Differential Pressure at Failure [a] (kPa)	
Pack	Frame		Dry Air ($\varphi \leq 50\%$ RH)	Humid Air (100% RH ≤ *Air Humidity* ≤ 5 g H_2O/m^3 of saturated air)
Deep pleat †	Wood	120	10 - 23	3 - 9
Deep pleat †	Metal	240	4 - 11	2 - 3
Mini-pleat	Wood	120	6 - 19	1 - 2

[a] numbers represent an average for a test group by manufacturer. † with separators.

Model for Bending Stresses in the Filter Medium of Deep-Pleat Packs with Separators

The inherent fragility of conventional HEPA filter media and their sensitivity to degradations in strength characteristics during service, makes knowledge of how stresses are distributed in the filter medium relevant to failure analysis that underlie designs for improved filter reliability. The stress model addressed below is one of two developed during analyses of filter failure modes documented in the literature for numerous test conditions used to evaluate filter reliability during so-called accident, or upset conditions in nuclear air-cleaning systems.

Detailed descriptions of the relevant failure modes of deep-pleat packs with separators and the two related stress models - one for the bending stresses in the sides of the pleats; the other for the hoop stresses in the ends of the pleats - have been reported elsewhere [1]. The model for the bending stresses in the sides of the pleats is based upon applying principles of statics and of solid mechanics to the pleat geometry of Fig. 4. As seen here, the pleats are considered as a row of parallel beams with fixed ends, under the distributed loads q_u, q_d, and q_s that are created by the pressure drop across the filter pack.

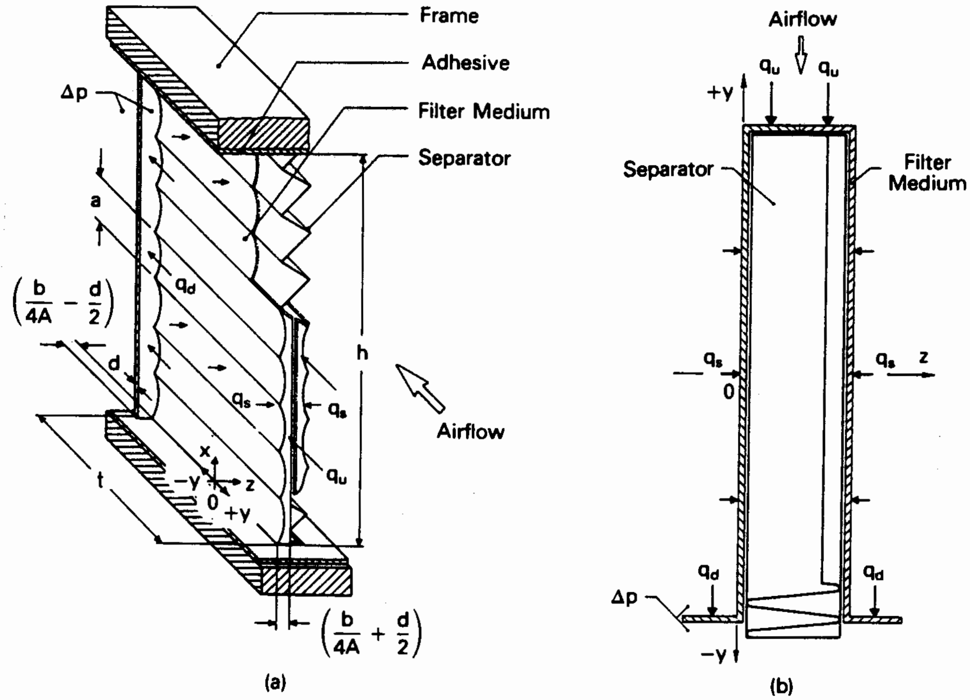

Figure 4: (a) Geometry and (b) beam profiles and loading underlying bending stress model for filter pleats[1].

The maximum (σ_1) and minimum (σ_2) principal stresses at any point within a beam under load can be obtained using *Mohr*'s circle or calculated from

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \left[\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2\right]^{\frac{1}{2}}, \tag{1}$$

where τ_{xy} is the shear stress and σ_x and σ_y are the stresses in the *x* and *y* directions, respectively. A plot of the distribution of σ_1 is shown in Fig. 5. For $\sigma_x > \sigma_y$, the case here, the highest value of maximum principal stress can be shown to be equal to the maximum value of stress in the *x*-direction, i.e.,

$$\sigma_{1max} = \sigma_{xmax} \approx \left(\frac{b \cdot h^2}{4A \cdot d \cdot t^2} + \frac{2a}{d\sqrt{\varepsilon}}\right) \cdot \Delta p, \tag{2}$$

where the dimensional variables *a*, *d*, *h*, and *t* are identified in Fig. 4, *b* is the pack width, *A* is the number of pleats in the pack, *Δp* is the pressure drop across the filter pack, and *ε* the elongation of the filter medium (in %) at the value of *Δp*. The highest value (6 N/cm^2 in Fig. 5) is seen to typically occur on the upstream side of the pack at two locations, the top and at the bottom of the pleat, with (*x*, *y*) coordinates of (0, +*t*/2) and (*h*, +*t*/2).

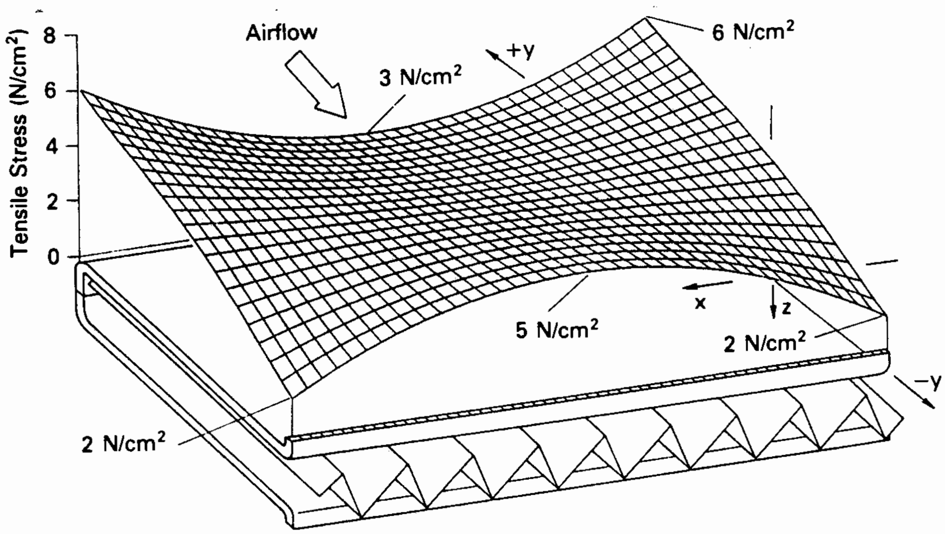

Figure 5: Distribution of the maximum principal stresses within the side of a filter medium pleat at a differential pressure of 1 kPa for a 610- x 610- x 292-mm unit ($A = 65$ pleats, $d = 0.5$ mm, $a = 10$ mm, and $\varepsilon = 1\%$)[1].

Verification of Stress Model

By rearranging Eq. (2), the relation

$$\Delta p_t \approx \frac{S_u}{\left(\frac{b \cdot h^2}{4A \cdot t^2} + \frac{2a}{\sqrt{e_u}}\right) \cdot w}, \tag{3}$$

can be used to calculate predicted values of burst strength in terms of pack geometry and the filter medium ultimate tensile strength, S_u, and elongation, ε_u, for filter medium samples of width, w. Samples of filter medium were removed from 80 filters tested to failure in humid air flow at between 0.5 and 4 times design flow, or in dry air at up to 25 times design flow. Measured values of ultimate tensile strength and elongation in the cross direction were used in Eq. (3) to calculate predicted burst strengths. By plotting the measured burst strength against the predicted value as shown in Fig. 6, the validity of the stress model can be evaluated. The filter numerical size designations are those of AG-1[6](s. Table V).

The slope of 1.004 for the linear regression curve fit represents a quantitative confirmation of Eq. (3) and thus the theoretical stress model. It is noted that only 6 data points (7.5%) lie outside the prediction interval for a 95% confidence level. The coefficient of determination for the curve fit, 0.61, indicates that 61% of the variation in the measured burst pressure values can be attributed to the combination of variables on the right hand side of Eq. (3). One particular factor not taken in account by the stress model, pack tightness, could explain both data points lying far above and far below the curve fit. In very tight packs, the filter medium would be reinforced by the separators and the sides of the frame, leading to measured burst strengths higher than those predicted. In very loose packs, the filter medium would be subjected to higher than predicted stresses due to the pleat sides not remaining parallel to the flow or even oscillating under the influence of aero-dynamic forces. This would lead to measured burst strengths lower than those predicted. Neither of the two cases is handled by the model, nor are factors such as fatigue, or mechanical interactions between the separators and the pleated filter medium. The latter two factors would lead to measured values lower than predicted.

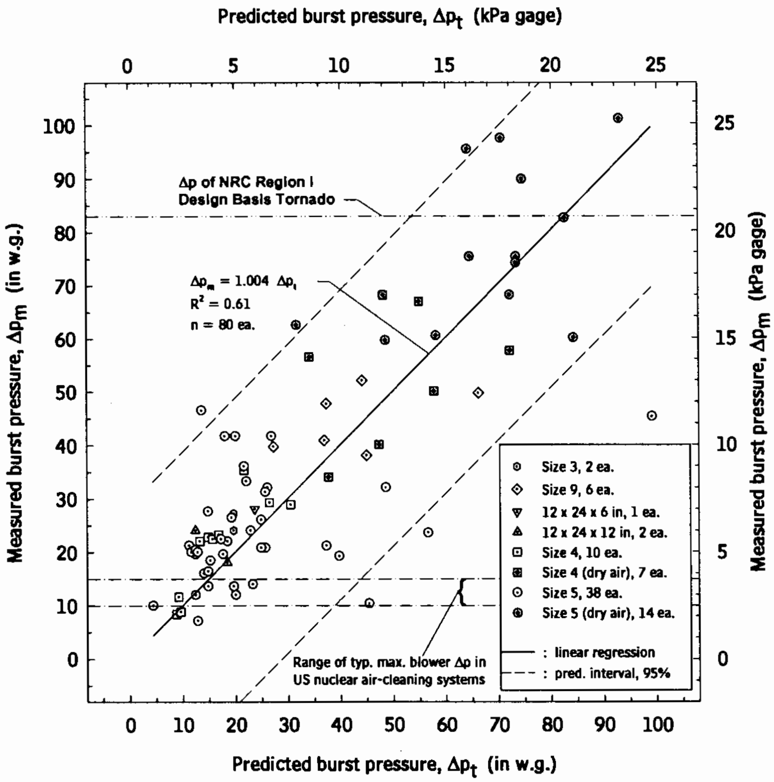

Figure 6: Verification of bending stress model for new, deep-pleat nuclear-grade HEPA filters in humid and dry airflow via comparison of measured to predicted burst pressures [7].

Practical Applications of Stress Model

Based upon confidence gained in the stress model from the verification data of Fig. 6, practical application can be made of conclusions to be drawn from it and the data used to verify it. These include insights related to filter failure modes, improved pack design, filter unit failures in service, filter medium fatigue, mechanical interactions between separators and the filter medium, and revision of filter performance codes and standards.

Explanation of Filter Failure Modes

The distribution of the maximum principal stress values in the side of a filter pleat illustrated in Fig. 5 show the highest maximum stress to closely coincide with the locations of tears observed in the sides of the pleats in 610- x 610- x 292-mm units after testing in dry and in humid airflows [7]. Figure 7 shows the predicted stress distribution for a 610- x 610- x 149-mm unit. Comparison of the maximum value of 12.7 N/cm^2 to the 6 N/cm^2 of Fig. 5, shows that in this case, a reduction in pack depth by a factor of 2.1 increases the maximum stress in the filter medium by 2.1 times. The greater highest stress in the Size 4 filter and the higher stress gradients in the x- and y-directions (x 4.2 and x 6.6, respectively), compared to the Size 5, explain the catastrophic failure of the filter pack in both wet and dry air, characteristic of this size. The two observed failure modes confirm the validity of the stress model, which in turn explains important underlying causes for both modes of failure, i. e., the distribution and gradients of the stresses.

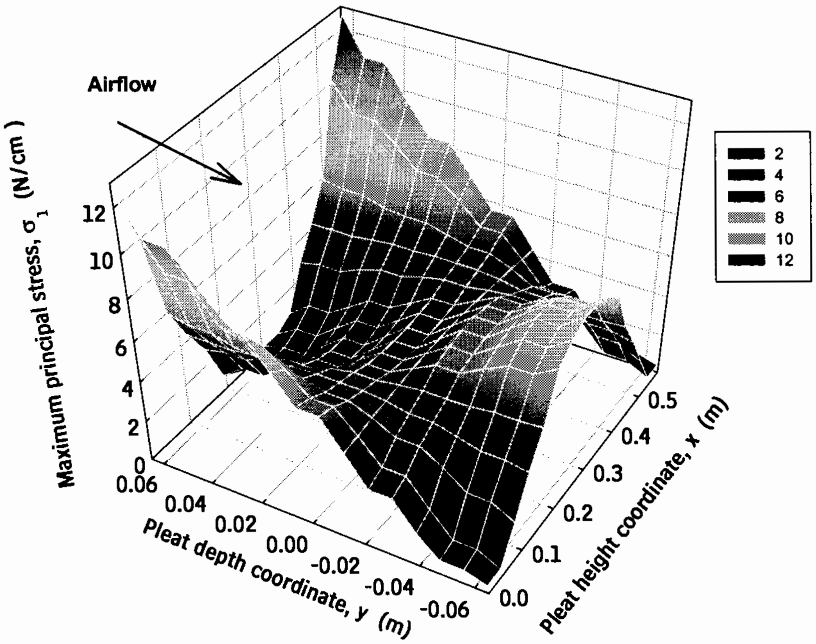

Figure 7: Distribution of the maximum principal stresses within the side of a filter medium pleat at a differential pressure of 1 kPa for a 610- x 610- x 149-mm unit (A = 65 pleats, d = 0.5 mm, a = 10 mm, and ε = 1%).

Filter Pack Designs for Increased Reliability

Once validated, an explicit analytical model for the stress level and distribution in the sides of the pleated filter medium can provide insights into how to change a filter design to reduce the stresses created by the pressure drop across the pack. For given filter pack cross section dimensions, b and h, and pressure drop, Δp, the remaining variables on the right-hand side of Eq. (2) can be selected so as to accomplish this. For example, increasing the values of t and a offer, respectively, an efficient and a practical means of reducing $\sigma_{1\,max}$. Another example is an insight used in the design of high-strength filter units to attain greater values of burst strength without changing pack geometry[1]. This was to significantly increase filter medium tensile strength, as suggested by Eq. (3).

Evidence for the Detrimental Effects of Filter Medium Aging and Fatigue

Aging of filter-unit construction materials, in particular the filter medium, is a process during which the performance characteristics of the medium change detrimentally with time. The relevant time intervals can include those of both filter medium storage and filter-unit service. One explanation for this is the large surface area per unit volume of the medium constituents (glass fibers, binder, and surface coating for water repellency) and therefore their enhanced susceptibility to chemical reactions with the gases of the surrounding atmosphere. Important media characteristics subject to aging effects include water repellency, ultimate tensile strength, and ultimate elongation. The only evidence presented here that possibly includes the effects of aging is that in Fig. 3, for the category of normal service. The decrease in filter medium tensile strength between 0 and 35% (mean of 15%), may result from combined effects of aging and fatigue of the filter medium during service. It should be noted that the specimens used to obtain this data did not include locations of highest stress in the filter medium, as discussed below.

Evidence for the Detrimental Effects of Filter Medium Fatigue and Mechanical Interactions between Separators and Filter Medium

Fatigue, another detrimental factor associated with filter media, is the process by which the ultimate tensile strength of a material decreases significantly at locations of highest stress under dynamic loading. Glass fiber media are quite brittle: the ultimate elongations at rupture typically lie between 1 and 2%. Compared to ductile ones, brittle materials characteristically exhibit short fatigue lives, i.e., they become susceptible to failure due to diminishing ultimate strength, after far fewer loading cycles. Pleated glass fiber media thus represent a brittle material configured in a geometry that induces concentrated stresses (see Fig.'s 5 and 7) which fluctuate under the dynamic loading of the airflow.

A comparison of the slope of the line fitted to data from used, dust-loaded filters shown in Fig. 8, to that of Fig. 6 for new, clean filter units, shows a significant difference. Whereas for new filters the measured burst strength was essentially equal to the predicted value; for used filters in humid airflow the measured value was, on average, only approx. one-half (52%) of the predicted one. This difference has been attributed to two prospective factors[7].

One is medium-damaging mechanical interactions between the ends of the pleats and the edges of the separators enclosed by the filter medium. Direct evidence for this could be established post-failure for approx. one-quarter of the filter units tested[7]. Any mechanical interaction of the much weaker filter medium with the much stiffer, stronger, and relatively sharp-edged separator (Fig. 2) can be expected to impair filter medium integrity long before the separator sustains damage. A facilitating factor in the mechanical interactions is a loosening of the filter pack, one of the major contributing failure mechanisms for filters in humid airflows, particularly for used, dust-loaded units, in which significant loosening can occur very quickly and at air relative humidities less than 100%.

The second proposed contributing factor was filter medium fatigue at the locations of highest stress (Fig. 5), which coincided consistently with the observed tears in the filter medium[7]. This hypothesis remains untested, due to the practical difficulty of determining filter medium tensile strength and elongation at these failure locations, close to the top and bottom of the filter pack, along the adhesive/sealant line at $(x, y) = (0, +t/2)$ and $(h, +t/2)$ (s. Fig.'s 4 and 5). Removing representative media samples from these locations of failure and presumed fatigue due to maximum stress is not possible. The stress model thus remains unvalidated for used filters; due to a lack of test results for filter medium specimens having strength properties characteristic of those at the failure locations.

Filter Failures in Service: Reported and Hypothetical

Filter unit failures in service have been reported to have occurred primarily - but not only - under operating conditions involving filter exposure to moisture (literature compilation in [7]). Understanding of how failure can occur in humid airflows, follows from viewing the burst strength data of Table II and Fig. 6; together with recognizing that the blower peak pressure drop - in US nuclear facilities, 10 - 15 in w.g. (2.5 - 3.7 kPa) - can appear across a HEPA filter stage in service. The lower limits of burst strength in humid airflow for all three designs (1, 2, and 3 kPa in the last column of Table II), lie below the upper limit of blower Δp.

Inferences can also be drawn from Fig. 6 about a less likely, yet not entirely negligible operating condition, the appearance of the full pressure drop of a NRC Region I Design Basis Tornado across a HEPA filter bank. The data show that few conventional filter units would be capable of withstanding the resultant mechanical load, without functional failure resulting from tearing of the filter medium.

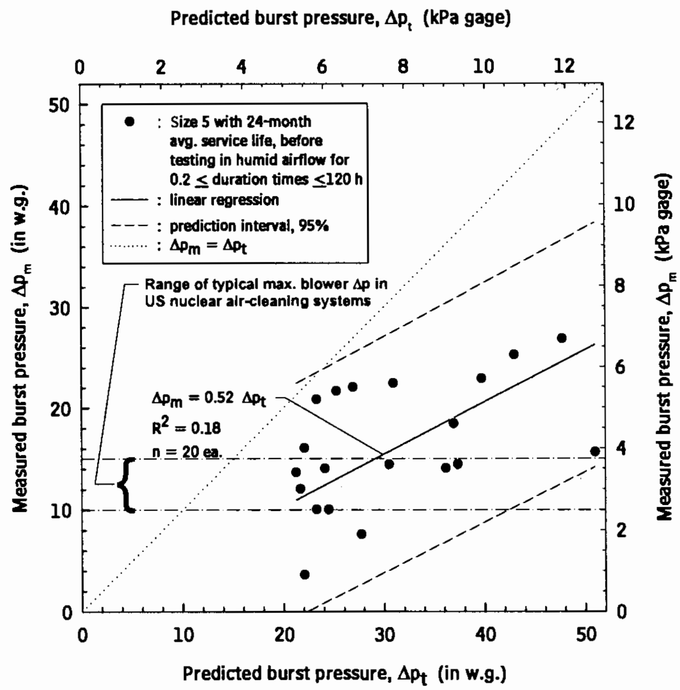

Figure 8: Verification of bending stress model for used, dust loaded, deep-pleat nuclear-grade HEPA filters in humid and dry airflow via comparison of measured to predicted burst pressures[7].

A third prospective challenge to filter reliability in some service applications is that of filter exposure to shock-wave impingement. This involves a shock overpressure and subsequent elevated pressure drop, due to the so-called particle flow of high velocity following behind the shock wave. Filter burst strength data for such conditions (Table III) have not been used to validate the stress model. To do so would require the ultimate tensile strength and elongation of filter medium specimens to be measured under the shock conditions corresponding to those experienced by the filter packs during testing with shock waves. Such strength characteristic values can be expected to be significantly lower than those typically measured under quasi-steady conditions. Thus Eq. (3), though validated to predict filter burst pressures for slow transients that simulate tornado pulses, remains yet to be verified for shock overpressures.

Comparing test results - of filter units from the same production lots and manufacturers - for shock overpressure and tornado pulses, shows lower burst strengths for shock wave exposure to be common to all three designs, i.e., -21.5, -42.4, and -50.9% (Table IV) . These data also underscore the inherent robustness of the deep-pleat design as compared to the mini-pleat and separatorless types.

It is relevant to also compare the data of Table III to those of the German high-strength filter design[1]. One high-strength filter withstood an overpressure of 22.2 kPa (3.2 psig) with a residual filtration efficiency > 99.97%, against a poly-disperse DEHS aerosol of unspecified mean diameter[8]. Exposure to an over-pressure of 94.4 kPa (13.7 psig) left the pack of a second test filter within the frame and a removal efficiency of 99.8%. In comparison, packs of conventional units at overpressures approaching 35 kPa (5 psig) can be expected to be fail catastrophically with the pack ejected completely from the frame, resulting in a 0% removal efficiency.

Table III: Summary of shock overpressures at failure for conventional, new, clean 610 x 610 x 292-mm nuclear-grade, glass-fiber HEPA filter units exposed to simulated explosive shock waves with a shock overpressure dwell of 47 ms[4].

Filter Unit Design	No. of Manufacturers (Ea.)	No. of Filter Units Tested (Ea.)	Range of Shock Overpressures at Failure [(a)] (kPa)	Average Shock Overpressure at Failure [(a)] (kPa)	Sample Standard Deviation (kPa)
Deep pleat †	4	18	7.2 - 17.4	12.8	5.3
Mini-pleat	3	15	5.4 - 9.2	6.8	2.1
Separatorless	1	2	5.4	5.4	-

(a) for all filters of each design building an individual test group. † with separators.

Table IV: Differential pressures at failure for conventional, new, clean 610 x 610 x 292-mm nuclear-grade, glass-fiber HEPA filter units exposed to simulated explosive shock waves as compared to those for simulated tornado pulses.

Filter Unit Design	Average Diff. Pressure at Failure for Tornado pulses [(a)] (kPa)	Average Overpressure at Failure for Shock Waves [(b)] (kPa)	Relative Difference in Pressure at Failure (%)
Deep pleat †	16.3	12.8	-21.5
Mini-pleat	11.8	6.8	-42.4
Separatorless	11	5.4	-50.9

(a) from Table I. (b) from Table III. † with separators.

Revision of Codes and Standards: Past

The validated stress model of Eq. (2) has provided insights to support revision of codes and standards that specify minimum requirements for HEPA-filter performance in nuclear air-cleaning systems. One example relates to the Size 4 filter (610- x 610- x 149-mm) in Section FC of the ASME standard AG-1[6]. Deep-pleat filter units of this size have long been recognized to have a structurally weak pack compared to other standard sizes. A caveat that Size 4 should be avoided is to be found in ERDA-76[9]. Though this warning was not incorporated into the superceding document[10], a restriction on Size 4 was recently added to Section FC of ASME AG-1, which was then quickly reflected in the online edition of the *Nuclear Air Cleaning Handbook*[10].

The change to Section FC was incorporated during a recent revision cycle. A proposal was made to continue allowing successful qualification of filter units of one size in a design family to automatically qualify all units of the same design having lower rated flows. The intent was to preclude requiring lower flow units of the same design to also be qualification tested every five years, thereby saving both filter manufacturers and users on testing expenses. The underlying assumption was that filters of lower rated flows would typically have smaller, geometrically-similar filter packs and would thus be stronger than larger ones under the same Δp. Successful test results for the largest, and presumed weakest size, were thus to be allowed to remain sufficient to qualify the entire family of a given design.

One flaw in this otherwise intuitively valid strategy resulted from an exception to the rule: an existing standard filter (Size 4) that is weaker than a larger (most commonly used) size, Size 5. The stress model of Eq. (2) provides insight into why this is so. The bending stress term within the parentheses on the right-hand side increases with $(h/t)^2$, the ratio of pack height to pack depth, squared. In Table V, the ratio of $h/t = 4.4$ is seen to be much larger for Size 4 than any other size. As noted above in comparing stress distributions for

Table V: Sizes[6], nominal ratings[6], and pack height-to-depth ratios of deep-pleat nuclear-grade HEPA filter units.

Number Designation	Frame Size (in)	Frame Size (mm)	Minimum Rated Air Flow (scfm)	Minimum Rated Air Flow (m^3/hr)	Maximum Resistance (in-wg)	Maximum Resistance (Pa)	Typical Pack Characteristics Height, h (mm)	Depth, t (mm)	h/t (-)
1	8 x 8 x 3 1/16	203 x 203 x 78	25	42	1.3	325	165	62	2.7
2	8 x 8 x 5 7/8	203 x 203 x 149	50	85	1.3	325	165	133	1.2
3	12 x 12 x 5 7/8	305 x 305 x 149	125	212	1.3	325	267	131	2.0
4	24 x 24 x 5 7/8	610 x 610 x 149	500	850	1.0	250	572	129	4.4
5	24 x 24 x 11 1/2	610 x 610 x 292	1000	1700	1.0	250	572	272	2.1
6	24 x 24 x 11 1/2	610 x 610 x 292	1250	2125	1.0	250	572	272	2.1
7	24 x 24 x 11 1/2	610 x 610 x 292	1500	2550	1.3	325	572	272	2.1
8	24 x 24 x 11 1/2	610 x 610 x 292	2000	3400	1.3	325	---- [a]	---	---
9	12 x 12 x 11 1/2	305 x 305 x 292	250	424	1.3	325	267	272	1.0

[a] not a deep-pleat pack.

Size 4 and 5 packs (Fig.'s 5 and 7), a reduction in pack depth by a factor of 2.1 increases the highest maximum normal stress in the filter medium by the same factor. The Size 4 filter pack is left weaker and correspondingly highly susceptible to catastrophic failure.

Based upon knowledge of the characteristic weakness of the Size 4 deep-pleat pack and the importance of restricting values of *h/t* to no more than approx. two (2) for sizes above Size 2, the initial proposal was modified to require Size 4 filter units to be tested for their qualification as nuclear grade. For example, only filter Sizes 1-3 and 5-9 can be certified as qualified based upon successful tests of Size 8 units. It should be noted that although the *h/t* value of 2.7 for the Size 1 pack appears relatively large, the stress model shows the highest maximum normal stress for the comparatively small *h* and *t* values to be < 83% of that for the Size 5, for the same Δp.

Revision of Codes and Standards: Ongoing

An ongoing example of an application of the stress model is that of setting specifications for deep-pleat axial-flow filters of circular cross-section covered by a new AG-1 section in development, Section FK (Special HEPA filters). The question to be addressed[11] relates to what limit should be set on the ratio of pack diameter to pack depth to avoid standardizing or qualifying a characteristically weak filter size, such as Size 4, in the square cross-section. In this case, the pack diameter, *D*, becomes the equivalent to both *h* and *b*, for $b = h$. By replacing both *h* and *b* with *D* in Eq. (2), the ratio equivalent to *h/t* becomes *D/t*. The maximum allowable value of *D/t* is chosen to equal two (2) for filters of circular cross-section, based upon the square cross-section data for *h/t* of Table V.

If the pack depth, *t*, is set to equal *D*, and the highest maximum normal stress is calculated, it can be used as the baseline (denominator) for a dimensionless longitudinal stress ratio, r_σ. Various values for the numerator can then be calculated by decreasing *t* to create increasing values of $(D/t)^2$ against which

$$r_s = \frac{\sigma_{1\ max}}{\sigma_{1\ max\ at\ (D/t)^2 = 1}}\ , \qquad (4)$$

can be plotted. A linear curve fit is observed to pass through all of the resulting 40 data points for the four filter diameters of Fig. 9. A maximum allowable value of $(D/t)^2 = 4$ represents $t = D/2$ and corresponds to an $r_\sigma = 1.297$. This means that by limiting the pack depth to no less than one-half the pack diameter, the highest maximum normal stress in the filter medium is prevented from exceeding a level approx. 30% above

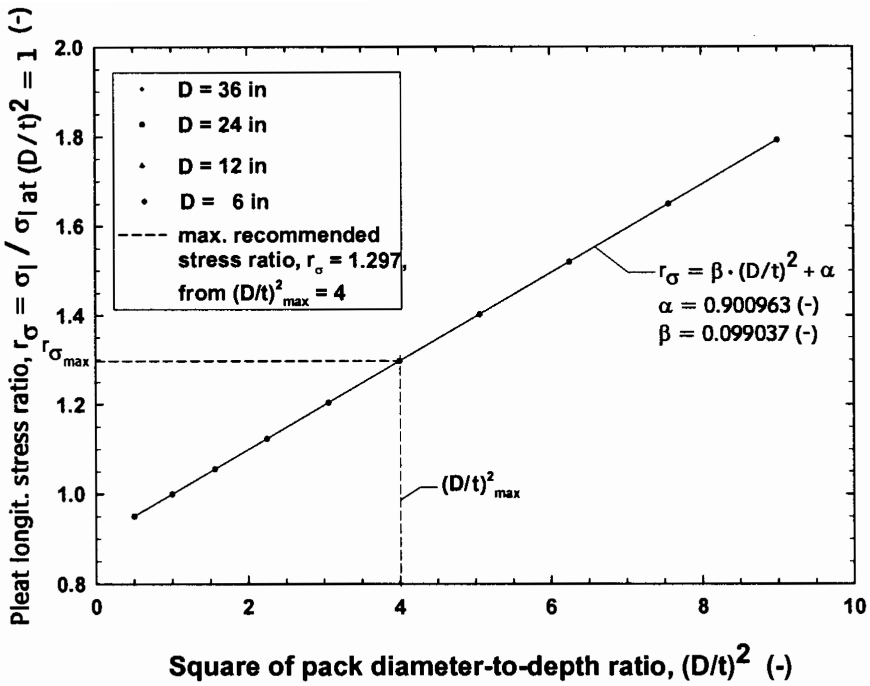

Figure 9: Variation in stress ratio with the square of pack diameter-to-depth ratio (a = 10 mm, D/A = 8.794 mm/pleat, d = 0.5 mm, and ε = 1%).

the baseline, which represents a pack with the depth equal to the diameter, i. e., $t = D$. This then precludes either standardization or qualification of an inherently weak pack in circular, axial-flow, deep-pleat filters with separators.

This result is essentially the same as what was accomplished for packs of square cross-section, as discussed above. Consequently, if every D in Fig. 9 is replaced by h, nothing else changes in the graph. Thus, Fig. 9 is also valid for deep-pleat filter packs of *square cross-section*, where $b = h$.

Revision of Codes and Standards: Future

The stress model and the test data gathered for its verification have some apparent prospective applications in future revisions of filter codes and standards. One might be to further discourage or to prohibit the use of the existing pack dimensions of the Size 4 filter unit in nuclear applications. It can be argued that requiring the pack to be tested in order to pass the current qualification test sequence does not make it any less liable to catastrophic failure. By helping to explain why, the stress model could be used to provide additional support to accomplish banning it. Particularly considering that the h/t ratio for it is twice that of any other pack of large or intermediate size in Section FC, as well as that of the proposed maximum for filters of circular cross-section to be covered in Section FK.

In hindsight, the wording of Section FC to allow filter units of lesser flows to be qualified by testing of ones with higher rated flow may not yet be the last word in balancing filter reliability against cost reductions in qualification testing. The number of pleats in a deep-pleat pack, A, can also influence $\sigma_{1_{max}}$, though not to the degree of h/t and D/t. The dilemma of the current wording in Section FC is that deep-pleat filters of Sizes 6 and 7, which are somewhat stronger due to having more pleats, can still be used to qualify Size 5 filters weaker than themselves.

Not being able to predict maximum stresses in other pleat configurations, places a handicap on using such an analysis tool to help develop or refine performance standards that also cover them. Unfortunately the stress model, developed for deep-pleat packs with separators, is not valid for the mini-pleat, separator-less, or radial flow designs. The failure modes for other designs are different and characteristic weaknesses associated with them make them less attractive candidates for improvements in mechanical reliability. For these reasons, not to mention the resources that would be needed for validation, it is unlikely that appropriate models for the other designs will be developed soon.

Reservations about current code-specified levels of performance being sufficiently stringent are not in the least allayed by the test results of Fig. 8. These represent a vast majority of available published data for used, dust-loaded filters in humid airflow. Failure pressures all lie below 6.7 kPa (27 in w.g.) with one-half of them below 3.7 kPa (15 in w.g.), the upper range of maximum blower Δp in US air cleaning systems. One filter failed after 12 min of exposure to the humid airflow.

If the curve fit slope of 1.004 in Fig. 6 validates the stress model for new filters, then the slope of 0.52 in Fig. 8 suggests: filter medium tensile strength at the failure locations of used filters was only 52% of that for the media samples removed from accessible locations to calculate predicted burst pressures via Eq. (3). This low percentage is attributed to a combination of mechanical interactions and filter medium fatigue at the failure locations close to the frame, from which filter media samples are not retrievable (see Evidence for the Detrimental Effects of Filter Medium Fatigue ...) . Aging of the filter medium in service is not a factor in the line slope here: to have taken it into account would have required having sampled tensile strength for media from equivalent new filters two years prior; data unfortunately not available.

One conclusion to be drawn is that qualification-test specifications for new filters may not be simulating the magnitude of the mechanical loadings that wet, fatigued, filter media of aged, dust-loaded filter packs may have to sustain in service under some operating conditions. A puzzling deficiency in current codes and standards is that filter units in their service location are not explicitly treated as structural elements, the physical integrity of which must be maintained under a potentially broad spectrum of operating conditions. To allow an inherently weak, air-cleaning system structural element - that is, moreover, highly susceptible to significant degradations in strength during service - to be qualified without a compensatory factor of safety, would appear to leave functional reliability of the entire system to chance.

Other system components are correctly recognized to be structural elements and their performance is accordingly so specified for qualification purposes. As an example, air-cleaning system duct work is generally recognized as a structural element whose code-specified performance characteristics correspondingly include suggested factors of safety[6]. Similarly, filter mounting frames are required to sustain, without permanent deformation, a pressure impulse loading of 20.7 kPa (3 psid)[6], corresponding to a pressure pulse induced by an NRC Region I tornado: yet, the filter units they hold in place are not.

Current US codes covering nuclear-grade filter units may need to be reviewed with respect to mandating a factor of safety for filters (based - at a minimum - upon the maximum blower Δp) and taking into account

- detrimental effects of service-related aging, fatigue, and mechanical damage by separators on filter medium strength,
- cumulative deteriorations in filter-unit burst strength resulting from serial and combined adverse operating conditions, and
- potentially significant fluctuations in filter reliability between production lots.

A case for higher strength HEPA filters

Responses to recommendations by Carbaugh[12,13] for the development of moisture-resistant filters have been made by two groups that published results of development and testing of high-strength filter units[1,14]. A follow-up case for higher strength filters is summarized in the histogram of Fig. 10. Here is a compilation of burst strengths for new, conventional filter units compared to those of a commercially avail-able high-strength design. The test conditions include: dry air at high velocity, fog conditions at rated flow, and shock-wave impingement. Delineated are the range of maximum blower-induced pressure drops to be sustained without filter failure, and the prospective Δp of an NRC Region I tornado. The maximum Δp for German in nuclear air-cleaning systems is noted as a reference.

Concern about filter reliability during exposure to liquid water is lent credence by the range of 1 - 9 kPa (4 - 36 in w.g.) for conventional units at rated flow under fog conditions. Once again evident is the complete overlap between this failure range and that of the maximum blower pressure drop of US nuclear air-cleaning systems. Moreover, all burst strength values are those obtained from tests of new filters. For 20 used filters (Fig. 8) tested in humid airflow after 24 months of service, 4.1 kPa (16 in w.g.) was the average measured failure pressure within a range of 0.9 - 6.7 kPa (3.6 - 27 in w.g.). An additional aspect of consideration is that while new filters have typically been found to fail only in supersaturated airflows, failure of used, dusted-loaded ones has been reported to occur at relative humidities less than 100%[15]. Thus, not only are used filters weaker than new ones, but they also can fail readily at air relative humidities below saturation.

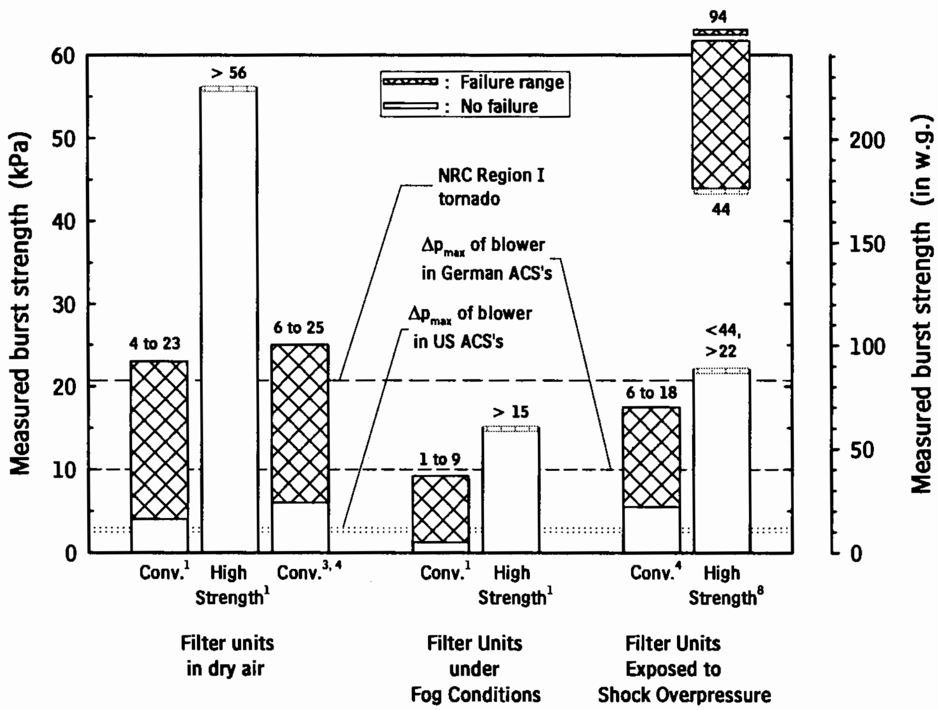

Figure 10: Burst strengths of conventional, new 610- x 610- x 292-mm HEPA filter units compared to those of a high-strength design.

Given that the filter medium represents the component of least strength in a HEPA filter unit of any design, providing it with reinforcement becomes an essential first step in developing high-strength units. This was the case for the commercially available, high-strength filters[1], for which test results are depicted in Fig. 10. With their feasibility and technical performance proven, it remains for revisions to performance specifications in codes and standards to force widespread adoption of higher strength filters in practice.

Conclusions

High Efficiency Particulate Air filter units represent an indispensable component in the air cleaning systems of nuclear facilities worldwide. As typically manufactured in the United States, they can be characterized as relatively fragile elements with a field reliability typically limited by an inherently weak and brittle constituent: the glass-fiber filter medium. Conventional, non-reinforced glass-fiber filter media remain the weakest construction material in filter pack design. Only slight physical damage to the medium can cause unacceptable decreases in filter removal efficiency, resulting in mechanical failure that prevents the filter from fulfilling its intended function. Their reliability 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. Almost no other system component is fabricated from weaker materials than are they; or can degrade, during service, to the point of functional failure under common operating conditions of nuclear air-cleaning systems, as can they.

Filter burst strength data obtained to establish filter-unit failure modes and to verify stress models have provided insights into understanding the mechanisms of failure and how to overcome weaknesses inherent to the deep-pleat design. For example, the model shows that to avoid catastrophic failure in filters of square or round cross-section with separators, the pack depth should never be less than one-half that of the pack height or pack diameter, respectively.

By helping to explain some failure modes, the stress models have in turn confirmed potential failure mechanisms and identified others. One stress model in particular has proven useful in the design of high-strength, deep-pleat filter packs and in the setting and revision of code performance specifications. After its having been verified for new filter units, its failure to predict actual failure pressures for used filters, helps to suggest that two other factors in combination may have as much, or greater influence on burst strength than aging of the filter medium. These are fatigue of the filter medium at locations of highest stress and mechanical interaction of the filter medium with the aluminum separators.

A comparison of reported failure pressures for new filter units under three sets of prospective operating conditions shows moisture to remain a most significant adverse factor of influence in reducing filter reliability. This is supported by data presented for decreases in filter medium tensile strength resulting from moisture exposure and five other factors. Burst strength data for used, dust-loaded filters in humid airflow are very limited, yet provide cause for concern due to reported rapid failure at air relative humidities less than 100%.

Many, if not most, questions of filter reliability in service could be addressed by the adoption of reinforced glass-fiber media. Given the commercial availability of such media and current knowledge of the filter medium as the Achilles' heel of conventional units: it seems likely that reinforced media would be universally mandated in codes for qualification of nuclear-grade filters, were they to be invented today.

With respect to future work, experimental verification of the reliability of used, high-strength HEPA-filter units under nuclear facility accident conditions remains yet outstanding.

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References

1. 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.

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

3. Horak, H. L., W. S. Gregory, P. R. Smith, and C. I. Ricketts,
Structural Performance of HEPA Filters Under Simulated Tornado Conditions;
LA 9197-MS NUREG/CR-2565, Los Alamos Scientific Laboratory, 1982.

4. Gregory, W. S. and P. R. Smith,
Response of Standard and High Capacity HEPA Filters to Simulated Tornado and Explosive Transients;
LA-9210-MS, Los Alamo National Laboratory, 1982.

5. Ricketts, C. I., V. Rüdinger and J. G. Wilhelm,
HEPA Filter Response to High Differential Pressures and High Air Velocities;
In: Proceedings of Fifth Int. Meeting on Thermal Nuclear Reactor Safety,
KfK 3880/2, Karlsruhe Nuclear Research Centre, Karlsruhe, Germany, p. 1572 ff, 1984.

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

7. Ricketts, C. I.,
The Behaviour of High-Efficiency Particulate Air Filter Units During Exposure to Humid Airflow
(in German); KfK 5057, ISSN 0303-4003, Kernforschungszentrum Karlsruhe,
D-76021 Karlsruhe, Fed. Rep. of Germany, 1992.

8. Fronhöfer, M., M. Neuberger, and J. G. Wilhelm,
Challenges within Ventilation Systems during Accident Situations; CONF 9020823 (1993),
Proceedings of 22nd DOE/NRC Nuclear Air Cleaning and Treatment Conference, pp. 510 ff.

9. Burchsted, C.A., Fuller, A. B. and Kahn, J. E.
Nuclear Air Cleaning Handbook; ERDA 76-21
Oak Ridge National Laboratory, Oak Ridge, TN, 1976.

10. *DOE Handbook Nuclear Air Cleaning Handbook*, DOE HDBK-1169-2003
http://tis.eh.doe.gov/techstds/standard/hdbk1169/index.html

11. Hayes, J. J., *task assignment in Section FK (Special HEPA Filters) Task Group meeting* during ASME/CONAGT meeting, Chicago, 30 July 2003.

12. 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

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

14. 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)
Proceedings of 22nd DOE/NRC Nuclear Air Cleaning and Treatment Conference, p. 617 ff.

15. Rüdinger, V., C. I. Ricketts, and J. G. Wilhelm,
Limits of HEPA Filter Application under High-Humidity Conditions, CONF-840806 (1985)
Proceedings of 18th DOE Nuclear Airborne Waste Management and Air Cleaning Conference, p. 1058 ff.