On the Implications of Treating High Efficiency Particulate Air Filters as Structural Elements in Nuclear Air Cleaning Systems

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ABSTRACT

Ventilation and air treatment systems provide for the health safety and the thermal comfort of personnel in facilities that contain hazardous or toxic materials. The high, fine-particle removal efficiencies of these systems are made possible by High Efficiency Particulate Air (HEPA).

Filters of nuclear grade represent an indispensable part of the confinement barriers in air treatment systems within nuclear facilities worldwide. Unlike more durable system components having service lives that typically approach, or equal the useful life of the nuclear facility, HEPA filters are replaced in service following much shorter time intervals. When a prescribed differential-pressure limit, or service time interval, or in-place aerosol particle leak test value is exceeded, or when moisture exposure occurs.

As is the case for other air-cleaning system components, HEPA filters are expected to perform reliably throughout their whole service lives, not only during normal facility operations, but also under possible abnormal or so-called accident conditions of comparatively shorter durations. As disposable components, HEPA filters are inherently much less robust than the permanent system components. As commonly manufactured, they can be characterized as being fragile and having levels of reliability during service limited by one inherently weak and brittle design material: the 0.5-mm thick glass-fiber filter medium.

Nuclear-grade filters also serve in a structural role by forming an integral part of the barriers and pressure boundaries between uncontaminated and contaminated zones within nuclear facilities. To ensure the reliability of their crucial filtration function, the physical integrity of the filter medium must be maintained. This in turn requires the filter pack to retain a sufficiently high level of robustness throughout filter service life. However, unlike almost every other type of structural barrier having a similar function, the filters are not mandated to demonstrate factors of safety in their design. Instead, reactive control systems are primarily relied upon to help preclude harmful differential pressures from appearing across fragile HEPA filters in service.

In current practice, qualification specifications for filters having a nonreinforced medium typically provide no bases for calculation of meaningful margins of reliability, for filter units as structural elements. Although periodic in-place aerosol particle leak tests are used to verify the absence of significant leaks, their results by no means provide a measure of residual filter structural reliability.

Administrative limits on filter service are intended to provide some reassurance that, over time, filter reliability does not fall below levels at which material failures may be prone to occur. They may also help somewhat contribute to reductions in the risk of filter medium rupture, should active-control systems malfunction. But nonetheless, without definitive and verifiable means of ensuring the determination of meaningful safety factors, uncertainty yet outweighs either certitude, or hope.

The adoption of stringently-qualified high-strength filters is one measure to minimize the uncertainty of decreases in levels of filter performance reliability, particularly for high-risk applications. The underlying analysis was undertaken from the perspective of good practice in mechanical engineering design.

INTRODUCTION

Non-reinforced HEPA filter media of glass fibers represent by 1-3 orders of magnitude the weakest design material utilized in filter fabrication; to a degree that makes them susceptible to tearing under relatively small, applied forces; beginning with filter manufacture through filter transport, handling, and service [Fig. A]. Glass-fiber media are also severely handicapped by a susceptibility to degradations in their material properties: not only with increasing age and fatigue of the filter medium over time in service, but potentially more adversely, via exposure to moisture [1], or to corrosive or caustic chemical compounds. Both filter medium strength properties and water repellency characteristics can significantly decrease under the influence of the noted factors [2].

An acute drawback to filters having a nonreinforced glass-fiber medium is that only slight localized physical damage to the medium, via tearing, can cause unacceptable decreases in filter removal efficiency. This equates to a loss of filter physical integrity via a design material failure (of the filter medium) that precludes the filter from fulfilling its fundamental intended function.

Banks of HEPA filters serve as structures forming a critical part of the barriers and pressure boundaries between uncontaminated and contaminated zones within nuclear facilities. However, unlike almost every other component having similar functions, the filters themselves are not mandated to demonstrate factors or margins of safety in their service locations. As compared to structural elements of steel, such as ductwork, or filter mounting frames and housings, or moisture separators, for examples.

The current resistance-to-pressure test Δp of 10-in w.g. (2.5 kPa) in a wet condition for filter qualification to ASME Code [3] section FC and FK specifications provides no bases for determinations of meaningful levels of performance reliability for filters in their service locations. Instead, active control systems are relied upon in practice to help preclude harmful overpressures from appearing across banks of fragile HEPA filters in service. However, active electronic-based or mechanical controls cannot be considered fully malfunction free. Self-actuating tornado valves represent an example of a reactive mechanical component for an extreme off-normal operating condition in an air cleaning system. High-strength HEPA filters [4-9] represent examples of passive backup mechanical components having structural properties able to sustain or mitigate a variety of normal, or extreme off-normal operating conditions.

Overview of Aspects Relevant to HEPA Filters as Structural Elements of the Confinement Barriers and Pressure Boundaries within Nuclear Facilities

Characteristics of airborne particles to be captured

Sizes of airborne particles to be captured typically lie on the scale of nanometers, in both the submicron (<1 μm) and the ultrafine (<0.1 μm) size ranges. Captured particles can play a structural loading role on both micro and macro levels when they influence filter medium flow resistance via their capture, or their migration under capillary [Fig. C] and aerodynamic forces during filter medium exposure to moisture.

Glass fibers of submicron diameter as structural elements

The diameters of the borosilicate glass fibers employed to create the micro/nano structures of HEPA filter media lie within the range of 2 to 500 nm [10]. Their lengths can be as large as several mm. The glass as a design material is characterized as very brittle. As compared to the sizes of the airborne particles to be captured, the diameters of submicron glass fibers are of similar orders of magnitude. Particles captured by fibers within the filter medium during service modify the surface geometry of the initial fiber structure and thereby increase filter medium flow resistance. In comparison to the filter medium thickness, the diameters of the submicron glass fibers are some 3-5 orders of magnitude smaller.

The HEPA filter medium as a nano-/micro-structure

A HEPA filter medium is a composite design material of glass fibers having an organic acrylic resin binder, surface treated with a chemical film in a finishing process to create an overall high level of water repellency. In detail, it is a three-dimensional, highly porous (>90%), microstructure of random and intricate webs (in the x-y plane normal to the airflow) of submicron-diameter glass fibers layered in the airflow z-direction. The fibers are nonuniformly bound to each other by the surface coatings of the binder. Filter medium thickness (≅ 0.5 mm) is equivalent to multiple-hundred fiber layers of webs.

Even in an un-pleated pristine condition, these non-reinforced anisotropic filter media are inherently not only fragile, but quite brittle. The filter medium manufacturing process typically creates a greater tensile strength in the "machine" direction in which the fibers tend to lie more longitudinally, as compared to the normal, or "cross" direction. Elongations at rupture typically lie between 1 and 2% in a new, dry state.

Only slight localized physical damage to the medium, via tears, creasing, or punctures of as small as 1-2 mm in size, can result in unacceptable decreases in filter particle removal efficiency. This equates to a loss of filter physical integrity via a design material failure (of the filter medium) that precludes the filter unit from fulfilling its fundamental intended function [Fig. A].

Particles captured by fibers by on the upstream surface and within the filter medium during service modify the geometry of the initial microstructure of the medium. The structure in a particle loaded condition is not necessarily fixed. Under the influence of gas flows having high air relative humidity, captured particles can be displaced by capillary and aerodynamic forces. Adverse consequences include increases in filter medium differential pressure [Fig. B].

Qualification standards specify minimum strength and water repellency requirements for nuclear-grade HEPA filter media. In both pristine, dry and wet conditions and following exposure to heated air and to gamma radiation.

Pleat separators as structural elements

As structural elements, spacers between adjacent pleats in a filter pack serve to maintain open channels for airflow and to lend a greater or lesser rigidity to the pack, depending upon their design material and geometry. Materials can include string or ribbons of glass, corrugated aluminum, and embossment of the filter medium itself. The minimum thickness and allowable alloys for the most rigid type (that of corrugated aluminum), are specified toward ensuring a minimum level of stiffness. As used in a deep-pleat filter pack, the minimum thickness of the aluminum foil is approx. $^{1}/_{10}$ that of the filter medium, while exhibiting an ultimate tensile strength of some 10 times greater.

HEPA filter packs as structural elements

Pleated packs of a given filter medium also qualify as structures, on dimensional scales of some 3-4 orders of magnitude greater than that of the filter medium thickness. The pleats within a filter pack act as beams of z-cross section under uniformly distributed loads created by the differential pressure across the pack [11]. The given pack design determines the beam boundary (end) conditions, as well as the pleat support geometry and material for the given pleat separators.

The sandwich construction of deep-pleated filter media supported by much stiffer corrugated aluminum spacers is an intrinsically robust one. So long as the pack retains a minimum tightness and rigidity. One current missing link in filter qualification standards is that the pack is not given status as a structure.

HEPA filter cases and faceguards as structural elements

Like for aluminum separators, a minimum thickness and allowable alloys are specified for metal case and faceguard design materials [3], toward ensuring minimum levels of stiffness and rigidity. The minimum thickness for the case material is 4 times and for faceguards 20% greater than that of the filter medium.

HEPA filter units as structural elements

HEPA filter units consist primarily of a filter pack bonded to a packaging case of four sides [3]. The case encloses the filter pack and provides it with a rigid shell, thereby helping protect it from damage during transport, handling, and service.

The differential pressure across a filter at which any component of the filter irreversibly ruptures can be designated as the filter burst strength, or the filter structural limit. Due to the fragile nature of a non-reinforced filter medium, it will typically rupture before any other component, such as the bonding agent, gasket, faceguard, or case.

Unlike almost every other air cleaning system component having a structural function, filters are not mandated to demonstrate safety margins in their service locations. As in the instance of the filter pack, the assembled filter is not recognized as a structural component by qualification standards and filter users.

HEPA filter banks as structural elements

In large air cleaning systems, it is common for multiple filters to be mounted next to each other in arrays on lattice frames of steel. Such a group of filters is referred to as a bank of filters, or filter bank. Although the assemblies of filter arrays and lattice frames represent part of the structural barrier and pressure boundary between contaminated and noncontaminated zones, they are addressed separately for qualification purposes.

HEPA filter mounting frames as structural elements

Lattice structures on the scale of 10^1 m, known as filter mounting frames, are recognized as structural elements required to sustain a pressure impulse loading of 20 kPa (psid) without exceeding the elastic limit of the design material [3]. The differential pressure of 20 kPa (3 psid) corresponds to the peak pressure of a Region I tornado formerly delineated by the Nuclear Regulatory Administration [12]. Included in the specification is a load multiplication factor of 1.25 which essentially reflects a minimum factor of safety. A design limit on lattice frame deflection is also specified.

Filter housings as structural elements

Filter housings are recognized both as structural elements and as pressure boundary components subject to potential material deteriorations [3]. As such they are subject to a requirement to identify environmental service conditions toward selection of suitable design materials by the manufacturer. Their design is also required to meet specifications for structural strength and rigidity.

Ductwork sections as structural elements

Ductwork sections of steel that connect blowers, filters, and other components together are also recognized as structural elements [3]. Allowable stresses in ductwork are specified using factors multiplied by design stresses. And stress limits are imposed based both on design and on service conditions.

Moisture separators as structural elements

Moisture separators are recognized as structural elements for which mechanical loads and load combinations are specified, as are allowable values for design stress [3].

Adoption of High-Strength Filters having a Glass-Fiber Medium in Nuclear Facilities: toward addressing the limitations of non-reinforced filter media - Advantages include the following.

- Allow calculation of meaningful safety factors for filters as structural elements in service.
- Create or enhance margins of filter functional reliability in service.
- Increase filter leak-testing and change-out intervals toward providing cost savings to users, via lower filter life-cycle expenses.

Prerequisites to more widespread adoption - In essence, the prerequisites include the following.

- The availability of sufficiently robust filter units [4-9].
- Filter qualification specifications tailored to filter performance capabilities [Table A, Table B, 14].
- Test stand concept to economically verify minimally acceptable levels and long-term residual filter pack robustness (via proof strengths based upon derated burst strength values) [Fig. D].
- Administrative limits on HEPA filter service based upon adverse operating conditions and age – toward differentiating between limits for conventional and for high-strength filter pack designs.
- Additional regulatory mandates for use of high-strength filters in particularly high-risk applications

Disadvantages of the *status quo, i. e.*, the ongoing use of nonreinforced glass-fiber filter media as design materials for nuclear applications - In essence, the disadvantages include the following.

- Existing safety risks remain higher than necessary in some crucial filter applications.
- Lack of meaningful safety factors for filters as structural elements in service leaves a residual degree of unnecessary uncertainty about current levels of and margins for filter reliability in service.
- The foregone potential for overall cost savings by air cleaning system owners.

CONCLUSIONS

Despite their many performance advantages in many applications for temperatures ≤ 120 °C, un-reinforced HEPA filter media of glass fibers represent an inherently flawed design material option in some higher risk nuclear applications for which reinforced glass-fiber media are much better suited. It is not surprising that a design material intended to function on a nanoscale would pose unique challenges when interfaced to a macro environment having geometries some 10^3 - 10^8 times greater, particularly when expected to meet extra ordinary performance levels. It took some 40 years of generic HEPA filter development to achieve the milestone of a marketable reinforced medium of glass fibers [4, 5]. Followed several years later by the release of stringently-qualified high-strength HEPA filters onto the European market [8]. And then another 30 years to be able to witness nascent filter adoption in North America [6].

Simply the advent of high-strength filters is not sufficient for their acceptance into practice. They need to be recognized and treated by standards organizations, users, and regulatory entities alike, as structural components. A similar secondary level argument can be made for conventional HEPA filters, in the ongoing absence of viable methods to determine meaningful safety margins or reliability levels for them in service.

Appendix A An Overview of the Limitations to In-Service Reliability of Nuclear-Grade HEPA Filters Having a Non-Reinforced Glass-Fiber Filter Medium

The reliability of HEPA filters during service can be significantly and adversely affected by numerous factors of influence and degradation processes. Filters can also be brought to temporary states of malfunction under certain operating conditions [Fig. A]. Of lowest strength and durability among typical filter design materials, non-reinforced glass-fiber media most limit levels of filter reliability in all nuclear service applications.

The strength properties of the medium are especially susceptible to degradation: during filter manufacture and exposure to moisture, as well as with increasing filter medium fatigue [13] and age over filter time in service. Filter medium water repellency can also deteriorate with the same factors.

Manufacturing processes detrimental to filter medium integrity include pleating to form the filter pack [11] and the insertion of relatively stiff and sharp-edged/-cornered aluminum separators into the folds between the pleats of the comparatively fragile filter medium.

Degradation of the Filter Medium due to Moisture Exposure

Operating conditions leading to the appearance of liquid water in HEPA filter media represent particularly acute threats to filter reliability levels. They can create both immediate and longer-term untoward consequences. One example is prompt migration of the soluble constituents of captured particles onto the uncontaminated downstream side of otherwise physically intact filters. Another adverse effect can be a rapid increase in filter resistance to air or gas flow accompanied by increases in filter Δp. As a result, filter volumetric flows can be temporarily reduced to an unacceptably low level; limited by the capability of the system blower and its controls to maintain design flows through the air- or gas-treatment system. Design flows maintain the intended cascade of sub-atmospheric pressure levels between confinement zones of differing contamination levels.

Water represents not only a direct but also a latent challenge to the physical integrity of the filter medium and consequently to filter functional reliability. Increases in filter medium differential pressure, significant decreases in filter medium strength, and a loosening of the filter pack are all adverse ramifications of liquid water incorporated into glass-fiber filter media. In concert, they can lead immediately, or eventually, to a tearing of the filter medium and to resultant increases in filter particle penetration above the maximum accepted value, even at air volume flows equal to or less than the design value.

After drying, filters that have not failed directly by moisture-induced tearing of the filter medium in a wet state, remain degraded in pack robustness, a result of irreversible loosening of the filter pack and partially irreversible decreases in filter medium strength. Both exhibit cumulative degradation upon repeated exposure to moisture. Residual filter margins of safety for reliable removal of entrained fine particles from air and gas streams during subsequent service can be thus reduced, though particle removal efficiency remains initially unimpaired.

Decreases in pack tightness can facilitate mechanical interactions between the pleated filter medium and the pleat separators, thereby creating new and amplifying preexisting stress concentrations that increase the likelihood of filter medium rupture. Pack loosening can thereby accelerate the detrimental effects of filter-medium fatigue caused by the varying mechanical loads induced by fluctuating airflows, vibration, and pleat movements due to aerodynamic forces. Longer filter service time prior to the moisture exposure speeds the pack loosening process initiated by moisture and magnifies the extent to which the loosening can occur.

Water Transfer Mechanisms and Sources

Potential mechanisms of water transfer into the filter medium include physical adsorption (and chemisorption, in some cases of particle loading), capillary and dew-point condensation, droplet interception, and unconfined surface water flows resulting from spillage, leaks, film condensation, or clogged drains. Moisture sources can include high flow-stream relative humidity, combustion gases, fire suppression systems, as well as pipes carrying water, coolant, or steam.

Detrimental Effects of Filter Service Prior to Moisture Exposure

Particle loading of filters during service can induce numerous potentially adverse effects in the context of subsequent moisture exposure. It much reduces the water repellency of the filter medium, and it can thereby greatly enhance both sorption kinetics and the amount of liquid water transferred via adsorption and capillary condensation (a follow-on absorption process) [Fig. C]; at levels of air or gas relative humidity significantly lower than those for new, clean, water-repellent media. Additionally, particle loading can greatly exacerbate increases in filter medium flow resistance and Δp caused by the presence of water within the pores of the microfibers and collected fine particles. Dynamic agglomeration of captured particles via capillary forces can also contribute to increases in filter medium differential pressure.

As compared to ones having a new, clean, water-repellent medium; aged, particle-loaded filters having a fatigued and slightly elongated, non-water repellent filter medium are overall, much more likely to fail in service at relative humidity levels below 100%. And they are extremely sensitive to increases in flow resistance (and thus filter Δp), for any given relative humidity [Figure B, 2], or concentration of entrained water droplets in the flow stream [2].

For cases of elevated temperature in combination with high relative humidity, counterintuitive effects of temperature on changes in the flow resistance of aged, particle-loaded filter media at design airflow can occur [2]. Higher temperatures can shift the relative humidity at which the greatest increase in filter medium flow resistance occurs, to lower values of relative humidity. And for a given relative humidity, the rise to peak flow resistance values can be greatly accelerated at higher temperatures, as compared to lower ones.

Depending upon particle characteristics and at temperatures above 50 °C, decreases in filter medium Δp are also possible at high humidity airflows. This represents a single known advantage for moisture exposure. One that could be applied in the regeneration of filters in their service locations.

The factors underlying changes in filter medium flow resistance under the influence of high air relative humidity are complex [2] and include air temperature and velocity, as well as the numerous properties characterizing any captured fine particles. The moisture threat to filter medium integrity via increases in differential pressure and decreases in tensile strength, as well as accelerated filter medium fatigue and pack loosening is significantly greater in aged, particle-loaded filters.

Degradation of the Filter Medium in Service due to Fatigue

Brittle design materials characteristically exhibit not only relatively small elongations at rupture of some few percent, but also a relatively short service life under cyclical mechanical loadings. They can thus become susceptible to rupture, under what had initially been sustainable (in the pre-fatigued state) dynamic mechanical loads, due to a fatigue-induced diminishing ultimate strength, after relatively few loading cycles. They are also much more liable to fail catastrophically without warning, unlike ductile materials which typically exhibit visible deformations prior to rupture.

The pleated anisotropic glass fiber medium in the filter pack represents a fragile and brittle material configured in geometries infrangibly burdened by localized stresses of relatively high values and gradients [2, 11], both of which fluctuate under the dynamic pressure loadings of an air or gas flow. Such local intensifications of stress due to design material geometry, or discontinuities in the material, or in the load applied to the material, are referred to as stress concentrations.

In deep-pleat pack designs, the flow-induced stresses within the filter medium have been recognized to have maximum values on the upstream side, at the top and bottom of the pleats where they are embedded in the bonding agent that holds the pack to the frame [2, 11]. Stress gradients are also found to be highest close to the locations of greatest stress. At the pleat ends, these locations of stress concentration coincide in an adversely compounding manner with pleat creases which have the most-degraded values of initial material strength and elongation at rupture, resulting from the pleating process during filter manufacture.

Fatigue effects can be greatly exacerbated in cases of pack loosening which can provide space for pleat lateral and longitudinal movements under fluctuating aerodynamic forces over extended time durations.

Threat to Filter Medium Integrity during Service due to Pack Loosening

The sandwich-style pack design of deep-pleat filters having rigid separators is intrinsically robust - for as long as the pack remains tight enough to hold the geometry of filter medium pleats and pack-reinforcing separators in their originally intended configurations. Pack robustness is ensured not only via reinforcement of each pleat by its adjacent separators. But also, by the effective transfer of Δp-induced bending moments from pleat to pleat and ultimately to the vertical sides of the filter case via high friction forces. Filter pack stability is therefore crucially essential to the filter's two functions. That of a fine-particle removal device, the performance of which depends upon its physical integrity as a structural barrier.

Pack loosening to an extent that enables relative motions between the fragile filter medium and stiffer, sharp-edged separators represents the underminings of filter pack stability and structural reliability levels, that in turn put filter medium integrity and ultimately containment-barrier functionality at risk.

Under varying stresses over relatively long times in service, glass fiber filter media can become slightly elongated. (Moisture exposure greatly exacerbates the irreversible elongation process.) In more extreme cases, the filter medium can relax enough to somewhat take on the profile of adjacent pleat separators. This can result in imperceptible yet potentially unfavorable decreases in the stability of an initially tight filter pack, in addition to increases in filter Δp. Undue loosening of the filter pack during service threatens the integrity of the fragile and brittle filter medium, within relatively short time intervals.

Direct mechanical interactions between the pleated filter medium and the pleat separators, create new and amplify preexisting stress concentrations that together increase the likelihood of filter medium rupture. Pack loosening accelerates filter-medium fatigue caused by the dynamic mechanical loads induced via fluctuating airflows, vibration, and pleat movements due to aerodynamic forces.

A loss in initial pack tightness during service represents a precondition that can facilitate rapid pack loosening upon any subsequent exposure to moisture. Increasing filter service time prior to the moisture exposure can accelerate the moisture-related pack loosening process and magnifies the extent to which the loosening can occur.

Degradation of the Filter Medium in Service due to Aging

Aging of filter-unit construction materials, particularly the filter medium, is a process during which the performance characteristics of relevant design material typically change detrimentally with time [13]. These changes in material properties result primarily from chemical reactions, but can also be caused by radiation, or relaxation of the filter medium under pressure loadings over extended time in service. In principle for the generic case of the filter medium, relevant time intervals can include both storage under static conditions, stand-by service, and service during dynamic air-treatment system operations.

The high specific surface areas of glass-fiber HEPA filter media and of captured fine particles help to facilitate the enhancement of physisorption interactions and chemical reactions with airstream gases in contact with the microstructures of the glass fibers and any captured particles, or adsorbates involved.

Important filter medium characteristics subject to degradation over time include water repellency, ultimate tensile strength, elongation at rupture, and resistance to fatigue. And hence, all have adverse consequences for filter performance reliability.

Degradation of the Filter Medium in Service due Radiation Exposure

Important filter medium characteristics subject to adverse radiation effects include water repellency, ultimate tensile strength, elongation at rupture, resistance to fatigue and residual fine-particle penetration.

Current Countermeasures to Filter Medium Limitations in Need of Updating

Administrative limits on filter service conditions and age

When implemented, administrative limits on filter service and age are currently intended to reassure that over time, filter functional reliability (*i. e.*, filter medium mechanical strength) does not fall to a level below that at which design material failures (such as filter medium rupture) could occur. They are also aimed at somewhat mitigating the risk of filter medium rupture, should active control systems fail. Ironically, their existence implicitly recognizes filter packs as structural elements. Limits for conventional HEPA filters provide a baseline beyond which limits for high-strength filters having a reinforced medium can be established.

Improvements in HEPA filter designs

In the context of filter reliability, research results reported from the mid 1950's through the mid 1980's have been intermittently utilized in improving both HEPA filter designs and the codes and standards that delineate their minimum performance specifications. Examples of the early 2000's include faceguards on deep-pleat filters and grilles on mini-pleat filter packs. Both of which serve to better protect filter packs from damage during transport and handling, as well as from catastrophic pack failure due to overpressure in service.

Pack designs having improved robustness via a reinforced glass-fiber filter medium and other measures to enhance pack robustness [6, 7, 9] represent filter improvements of greatest significance toward enhanced performance reliability throughout filter service life. Such filter designs have been proven in service since the mid 1980's in German nuclear air cleaning systems. Were a filter pack design engineer of today to start from a time zero, knowing of the availability of filter medium reinforcement options, it is difficult to imagine them being deselected as design material alternatives for nuclear applications.

Appendix B
An Overview of Aspects Related to the Adoption of High-Strength HEPA Filters Having a Reinforced Glass-Fiber Filter Medium

Advantages of High-Strength HEPA Filters

Unlike instances for more conventional designs having a non-reinforced medium, adoption of high-strength filters allows for the calculation of meaningful safety factors for filters as structural elements in their service locations. Dependable margins of filter functional reliability in service can thus be created or enhanced. They are particularly well suited to high-risk filter operating conditions. An added benefit of high-strength designs to users is the potential for much lower filter life-cycle costs, via increased intervals for in-place leak-testing and change-out of filters. This despite the greater initial cost of the high-strength designs.

Availability and Performance Specifications for Qualification of High-Strength HEPA Filters

More widespread adoption of high-strength designs is first contingent upon the availability of sufficiently robust commercial filter units qualified to specifications tailored to filter performance capabilities and practical applications. These hurdles would appear to have been for the most part overcome in several instances [6, 7, 9] that serve as examples.

One of the most important aspects underlying the robustness of high-strength HEPA filter pack designs is the increased tensile strength of the reinforced filter medium - more than one order of magnitude greater than an otherwise equivalent non-reinforced medium. Of equal importance with respect to long-term residual filter burst strength during service is the capability to reliably maintain an effective minimum level of pack tightness throughout filter service life. This is ensured via one proposed sequence of tests [Table A] performed for filter qualification. Verification of long-term residual filter pack robustness is ensured by steps 3a - 5.

The final aerosol particle penetration test at 20% of rated airflow is performed on filters in a post-wet damp state [Table B]. This corresponds to a filter having an area specific liquid (free) water content < 0.05 kg H_20 per m^2 (< 0.01 lb H_2O per ft^2) of clean filter medium. This state represents the condition of the once wet test filter, following a process of dewatering and drying undertaken prior to the final particle penetration test. This process ensures that a maximum acceptable amount of water within the filter medium is not exceeded (≅ 10% of the interstitial volume of the filter medium). Below which relatively constant and reasonably accurate aerosol oil droplet penetration values can be expected to be measured at 20% of the rated volume airflow of the filter.

The set of sequential tests includes an impulse pressure test as step 4e. This involves a test stand [Fig. D] able to verify minimally acceptable filter proof strengths, based initially upon filter burst strength values also established in the test stand. This concept represents a simpler and overall less-expensive version, compared to the one presented in [15]. It is one that also recommends itself as an economical alternative for qualification of filter designs having a non-reinforced filter medium.

Remaining Prerequisites to Adoption of High-Strength HEPA Filters for Higher Risk Applications

These include the implementation of commonly accepted administrative limits on HEPA filter service based upon adverse operating conditions and age – that differentiate between limits for conventional and those for high-strength filter pack designs. Additionally, regulatory mandates for use of high-strength filters in particularly high-risk applications have made intermittent progress [6, 9], which in part lags gaining greater acceptance for the concept of recognizing HEPA filters as structural elements.

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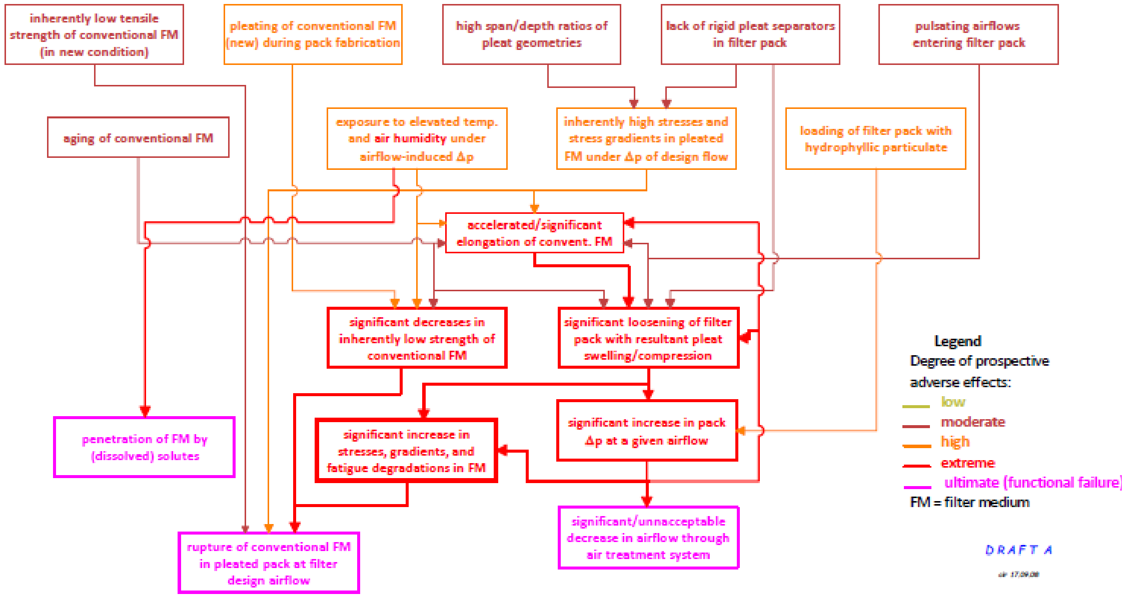
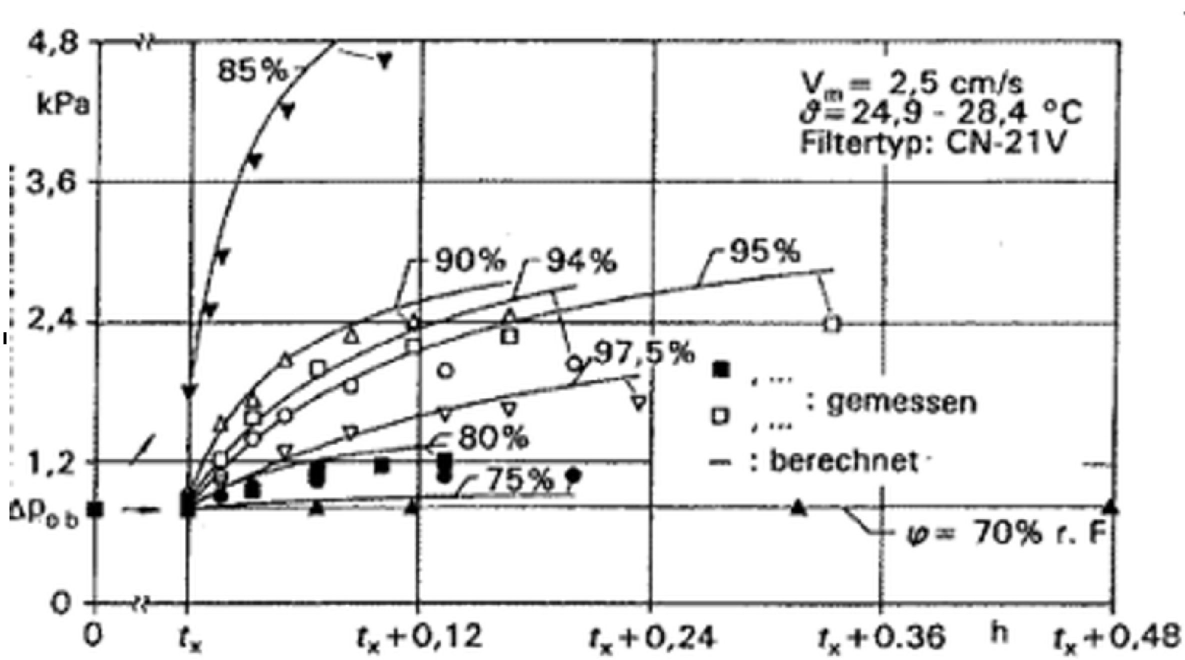


Figure A: Prospective mechanisms and relationships underlying functional failure of radial-flow HEPA filters (without rigid pleat separators) having an unreinforced, filter medium in an aged, non-water repellent, fatigued, and particle-loaded condition, during operation in their service locations.



Time of exposure to humid airflow, hours

Figure B: Variation of filter medium Δp with exposure time to humid airflow for various air relative humidity values (solid lines based upon curve fit to *whole set* of experimental data from tests on 100-mm dia. specimens from a nuclear-grade HEPA filter loaded with fine dust to 14.7 g/m^2 to $\Delta p_{0\,b}$ [kPa] in normal service, dry). Air temperature, θ = 24.9–28.4 °C, and superficial filter medium velocity, V= 2.5 cm/s. Time value, t_x, is that of first measurable dynamic Δp data point in lab-scale test rig for transient Δp values.

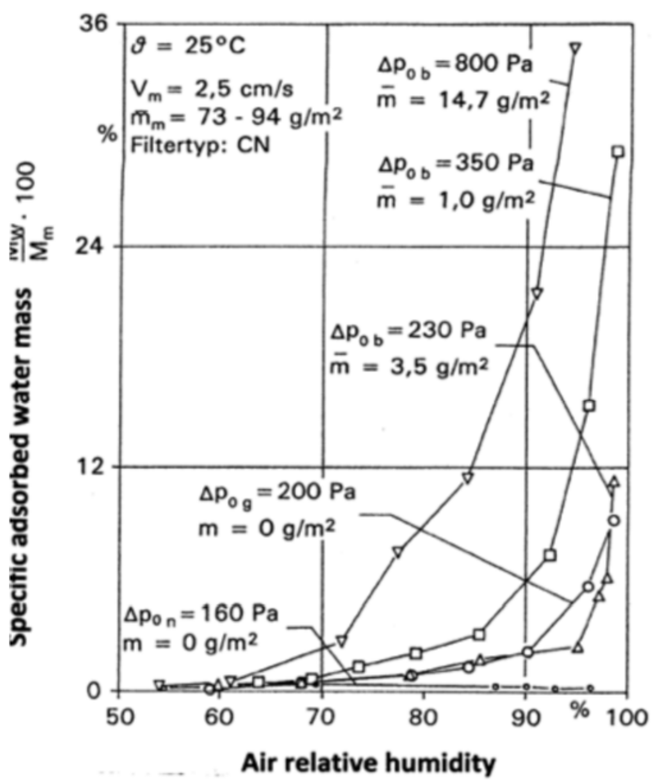


Figure C: Adsorption isotherms for 100-mm dia. specimens of (typical) HEPA filter media removed from nuclear-grade filters (Type CN) in various conditions at superficial filter medium velocity of 2.5 cm/s. Value m = pretest, in-service particle loading of filter medium in grams/square meter of filter medium, dry. New filter medium, no particle loading: $Dp_{0\,n}$ = 160 Pa, dry. Aged filter medium, no particle loading, after approx. 24 months of exposure to *pass-by* airflow during normal service: $Dp_{0\,g}$ = 200 Pa, dry. All others, particle loaded after approx. 24 months of *pass-through* airflow during normal service: $Dp_{0\,n}$ = 230 Pa, 350 Pa, or 800 Pa, dry [2].

Table A: Functions of in-sequence qualification tests proposed for US high-strength HEPA filter units.

Step	Performance Characteristic or Action	Function(s) of Test or Action
0	Visual inspection, initial Prerequisite to 1 and 2) below:	Visually verify the initial physical integrity of the filter and its constituent components (new), in the as-received condition at the test laboratory
1	Resistance to rated airflow, initial	Verify that filter (new) initially meets the maximum flow resistance requirement at rated airflow
2	Aerosol particle penetration test at rated airflow and at 20% of rated airflow, initial	Verify that filter (new) initially meets the maximum particle penetration requirement at relevant airflows
3a	Resistance to rough handling, dry filter Conditioning prior to 4a) below:	Verify a sufficient level of initial robustness for pack, case, joints, bonding agent, filter medium, separators, and faceguards: as integrated into the filter design Apply fatigue cycles to the filter medium (dry) Begin relaxation of filter pack tightness, <u>before</u> the static oven test; toward de-selection of marginally robust filter pack designs in Step 5 below

3b	Visual inspection Prerequisite to 4a) below:	Visually verify initial filter (new) overall ability to sustain mechanical shock and vibration during transport and handling in dry state, without visible structural damage
4a	Static resistance to maximum rated temperature for continuous service (static oven) Conditioning prior to 4b) below:	Verify resistance of filter constituent materials (under static conditions): · to maximum rated temperature for continuous service and · to thermal expansion incompatibilities Accelerate off-gassing of volatiles from case, bonding agent, filter medium, gasket, and separators; before resistance-to-pressure-impulse test. Further relax filter pack; toward de-selection of marginally robust pack designs via Step 5 below
4b	Submersion of dry filter at elevated conditioning temperature into water bath at room temperature (thermal shock) Conditioning prior to 4c) below:	Verify compatibility of filter constituent materials as incorporated into the filter design, with respect to thermal contraction (via thermal shock), before resistance to rough handling test wet. Further relax filter pack; toward de-selection of marginally robust filter pack designs via Step 5 below
4c	Visual inspection Prerequisite to 4d) below:	Visually verify filter residual physical integrity after exposure to elevated temperature and to thermal shock test
4d	Resistance to rough handling, wet filter Conditioning prior to 4e) below:	Apply additional fatigue cycles to the filter medium (water-saturated); and induce mechanical interactions between separators and pleats of the water-saturated filter medium; before the resistance-to-pressure-impulse test Further relax filter pack; toward de-selection of marginally robust filter pack designs via Step 5 below
4e	Resistance to pressure impulse Prerequisite to 4f) below:	Quantify a minimum filter design proof strength (filter wet) that can be used in margin-of-safety calculations Represent the product of a safety factor multiplied by the peak mechanical loading that a fatigued, filter medium (wet) of aged, dust-loaded filter packs might have to sustain during service Approach maximum potential relaxation (loosening) of filter pack that could occur during service; toward de-selection of marginally robust filter pack designs via Step 5 below
4f	Visual inspection, final Prerequisite to 5) below:	Visually verify filter residual physical integrity after rough-handling test (filter wet) and the resistance-to-pressure-impulse test (filter wet)
5	Aerosol particle penetration at 20% of rated airflow	Verify that filter design (for post-wet, damp state) meets maximum particle penetration requirement at relevant flow, after test sequence of resistance to rough handling (dry), to maximum rated continuous static temperature, to thermal shock, to rough handling (wet), and to pressure-impulse Ensure that marginally robust filter pack designs do not pass qualification requirements

Table B: Proposed characterization of (1) a critical value of equilibrium water content and the underlying approx. values of air relative humidity at 25 ℃ - for the case of bound† water and
(2) a critical value of equilibrium water content for the case of free†† water,
within new clean, aged clean, and aged particle-loaded nuclear-grade HEPA filter media.

Filter Medium Degree of Wetness (Description)	**Type of Water (Designation)**	**Area Specific Moisture Content (mc) (g H_2O/m^2 filter medium)**	**Relevant Physical Phenomena (Designation)**	**New, Clean Filter Medium / approx. Air Relative Humidity (Designation / % RH)**	**Aged, Clean Filter Medium / approx. Air Relative Humidity (Designation / % RH)**	**Aged, Particle Loaded Filter Medium / approx. Air Relative Humidity (Designation / % RH)**
absolute dry	none	mc = 0	none	all / 0	all / 0	all / 0
dry	bound	0 < mc < 0.5	phys. & chem. adsorption	water repellent / 55 - 96	non-water repellent / 55 - < 70	non-water repellent / ≥ 55
damp-dry	bound	0.5 ≤ mc < **5**[1]	phys. & chem. adsorption	water repellent / **> 96**[2] - *(> 99[3])*	non-water repellent / 70 - **≤ 95**[2]	non-water repellent / ≥ 55 - **75**[2]
damp	bound	5 ≤ mc < 50	phys. & chem. adsorption	non-water repellent / NA	non-water repellent / > 95 - *(> 99[3])*	non-water repellent / > 75 - 94 *(> 99[3])*
			Internal Void of Filter Medium (Description)	**New, Clean Filter Medium (Designation)**	**Aged, Clean Filter Medium (Designation)**	**Aged, Particle Loaded Filter Medium (Designation)**
damp-dry	free	0.5 ≤ mc < 5	< 1% filled with H_2O	non-water repellent	non-water repellent	non-water repellent
damp	free	5 ≤ mc < **50**[4]	< 10% filled with H_2O	non-water repellent	non-water repellent	non-water repellent
moist	free	50 ≤ mc < 100	< 20% filled with H_2O	non-water repellent	non-water repellent	non-water repellent
wet	free	100 ≤ mc < approx. 500	< 100% filled with H_2O	non-water repellent	non-water repellent	non-water repellent
soaking wet	free	mc = approx. 500	filled (saturated) with H_2O	non-water repellent	non-water repellent	non-water repellent
dripping wet	free	mc > approx. 500	internally saturated and externally surface layered	non-water repellent	non-water repellent	non-water repellent

[1] critical upper limit on filter medium moisture content (of 5 g H_20/m^2 filter medium), above which the level of risk for both significant and immediate performance degradations becomes probable for aged in-service filters having a fatigued filter medium containing captured particles.
[2] approx. value of air relative humidity at which the equilibrium value of filter-medium bound moisture content equals 5 g H_20/m^2 filter medium, as a result of the adsorption of water vapor from the surrounding air by the micro-structures of the filter medium and the captured particles; and as a result of water vapor absorption via capillary water.
[3] estimated maximum value of *(>99% RH)*, contingent upon degree of water repellency and based upon extrapolation to a practically effective and measurable upper limit. Essentially *equivalent to* ≤ *100% RH*.
[4] conservative upper limit on filter-medium free moisture content (*unrelated* to water vapor adsorption), below which relatively constant and reasonably accurate values of aerosol oil droplet penetration can be expected to be measured at 20% of filter design airflow.
† based upon sorption isotherms as reported in [2, Fig. C].
†† based upon filter testing underlying the derivation of performance qualification specifications for high-strength HEPA filters, (*Ricketts et al.*) unpublished.

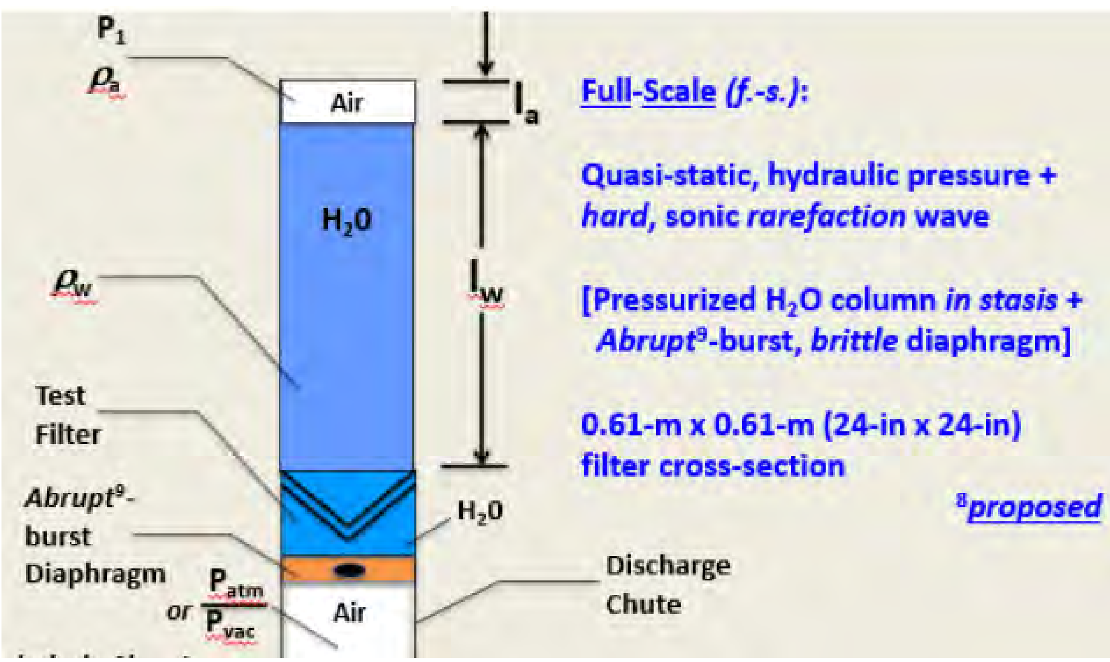


Figure D: Schematic of proposed resistance-to-pressure impulse test stand based upon the quick release of a pressurized water column initially *in stasis*, toward qualification of nuclear-grade HEPA filters. Simplification of dynamically pressurized H_2O column of [15].