31st Nuclear Air Cleaning Conference

REALIZATION OF PERFORMANCE SPECIFICATIONS FOR THE QUALIFICATION OF HIGH-STRENGTH HEPA FILTERS

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Abstract

The confinement of radioactive and toxic airborne particles within controlled areas of nuclear facilities worldwide is accomplished by High Efficiency Particulate Air (HEPA) filter units. These filters typically contain a filter medium consisting of an approx. 0.5-mm (0.015-in) thick mat of submicron diameter glass fibers. Units having a glass-fiber filter medium are qualified to be of nuclear grade in the U.S. according to Sections FC (*HEPA Filters*) and FK (*Special HEPA Filters*) of ASME's AG-1(1) Code on Nuclear Air and Gas Treatment. The performance criteria of these two code sections serve to specify the minimum performance levels of what can be referred to as conventional filter designs, *i. e.*, those which incorporate a filter medium of glass fibers without any strength reinforcement.

A number of characteristics of conventional units make them less well suited for a number of particularly crucial applications. These include nuclear facilities where plutonium or explosive chemicals are processed, or ones in which exposure of filters to airborne water droplets, or to airflow of greater than 80% relative humidity, can not be ruled out.

Although high-strength nuclear-grade HEPA filters have been available in Europe for more than twenty years, their use in select, critical applications within the U.S. has been precluded by the lack of code-based test standards which are prerequisites to their qualification and implementation in practice.

A new AG-1 Code Section is under development to address many of the limitations that glass-fiber medium HEPA filters can exhibit under certain adverse operating conditions. Designated as Section FM and titled, *High Strength HEPA Filters*, it is intended to provide performance specifications for the qualification of nuclear-grade HEPA filters having a glass-fiber filter medium reinforced by a cloth of glass fibers. It also addresses the qualification of filter designs having greater pack mechanical robustness and longer-term reliability as compared to conventional ones qualified according to Sections FC and FK.

Summarized here are the ramifications of filter exposure to moisture, as an example of one challenge to the reliability of conventional filters that underlies the need for higher strength filter units for select applications. The prerequisites to and benefits of the implementation of high-strength HEPA filters in practice are addressed. Both safety-related and prospective economic benefits of high-strength filter implementation are included. Remaining prerequisites to implementation include finalization of performance specifications for the pressure-impulse test of Section FM and realization of a full-scale test stand for routine filter qualification to these specifications. Justification for the pressure-impulse test is provided and some proof-of-concept results from an intermediate-scale test rig are reported. Also outlined are the guiding principles and methodology followed in creating Section FM.

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 nuclear-grade HEPA filter units. Under benign operating conditions, HEPA filters serve globally as reliable and economical components in the air cleaning systems of nuclear facilities.

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 air relative humidity: ideally without performance decreases that would result in unacceptable losses of particle containment or confinement. The effects of earthquakes(2), tornados(3), fires(4), fire-suppression measures(5), as well as explosion-induced shock waves(3), also represent challenges that may need to be taken into consideration toward ensuring for the protection of filters in their service locations.

Within the most common filter designs for nuclear applications - qualified in accordance with Mandatory Appendix FC-I of ASME's AG-1 - the filter medium consists of a fragile 0.5-mm (0.015-in) thick mat of submicron diameter glass fibers. Filter units are currently qualified as nuclear grade according to Sections FC (*HEPA Filters*) and FK (*Special HEPA Filters*) of ASME's AG-1 Code(1). These three code sections serve to specify minimum performance levels for qualification of conventional filter designs which incorporate a filter medium of glass fibers with no strength-augmenting reinforcement.

Currently a new AG-1 Code Section (FM) with Mandatory Appendix FM-I is under development for high-strength HEPA filters. For units designated as Level I, only reinforcement of the glass-fiber filter medium is anticipated. Also included are requirements for Level II filters which are foreseen to have additional measures toward maintaining filter-pack robustness for higher reliability and longer service intervals. Non-mandatory guidelines for both filter shelf and service life, as well as for safety-margin calculations are also proposed aspects of Section FM. Underlying the latter is risk-informed safety-margin determination, an analysis which ensures that risk information and risk insights are integrated into the decision making process such that there is a blended approach using both probabilistic and deterministic information(6).

Need for High-Strength HEPA Filters

A number of characteristics of conventional nuclear-grade HEPA filter units make them less well suited for a spectrum of particularly crucial applications. These include nuclear facilities where plutonium or explosive chemicals - such as perchlorate salts - are processed, or ones in which contact of filters with airborne water droplets, or with air at greater than 80% relative humidity(7), are possible.

The Achille's heel of conventional glass-fiber filter designs is commonly recognized to be the inherent fragility of the relatively brittle filter medium(8) and its susceptibility to degradation in both storage and service(9, 10). By one to three orders of magnitude, conventional, non-reinforced glass-fiber filter media in new condition remain the weakest construction material in US HEPA filter units(11) (see Fig. 1). Moreover,

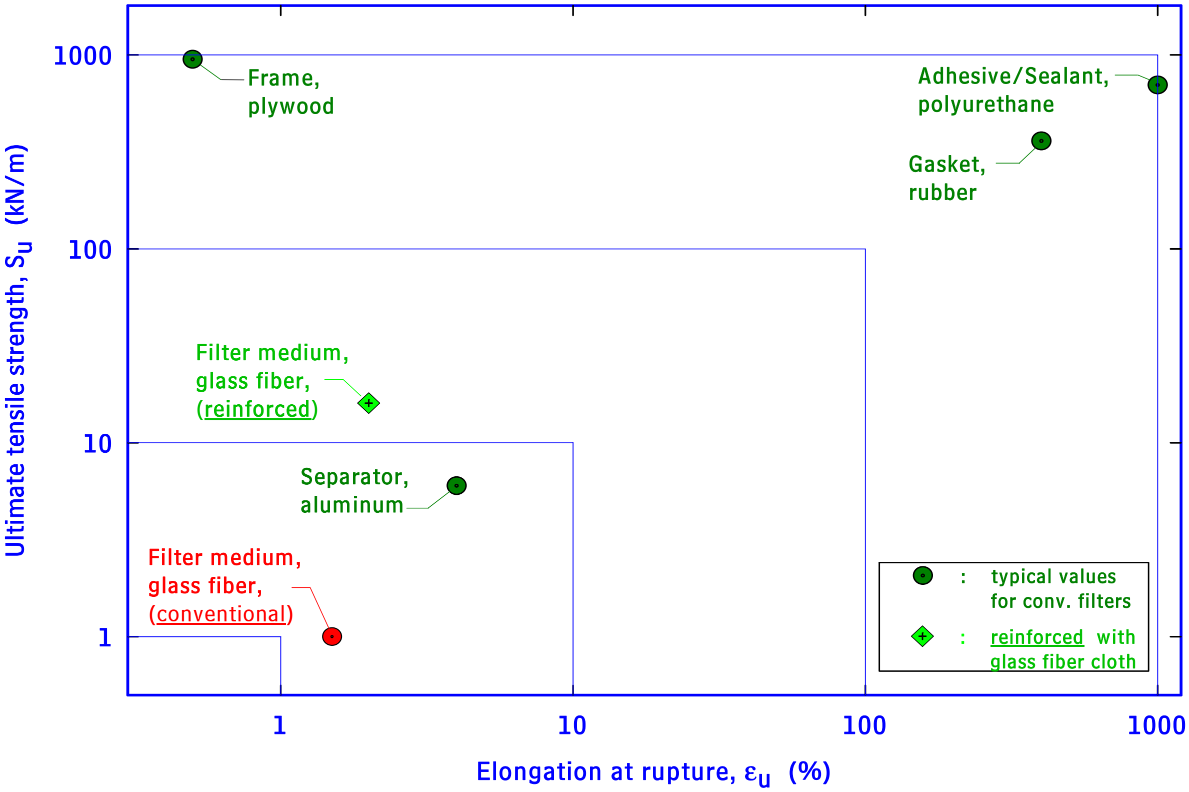

Figure 1: Strength characteristics for fabrication materials in conventional US nuclear-grade HEPA filters(9).

during normal filter service, the detrimental effects of filter medium aging and fatigue - or even more adversely, moisture exposure - can result in degradation and increasing fragility of an unreinforced filter medium, with correspondingly significant decreases in filter reliability. Filter functional failure, via unacceptable decreases in filter removal efficiency, can result from only slight physical damage to a glass-fiber medium.

Adverse ramifications of filter exposure to liquid moisture in the context of prospective mechanical failure : as one example of a challenge to filter reliability

The sensitivity of HEPA filters to performance degradations resulting from moisture exposure has been recognized since at least the early 1960"s(12, 13, 14). Resulting countermeasures fell into two primary groups. Those in the first were aimed at conditioning air and gas flows upstream of HEPA filter service locations to eliminate air-entrained water droplets and to lower air relative-humidity values to innocuous levels(15). This was accomplished via strong recommendations(16, 17) for moisture (*i. e.*, droplet) separators and heaters to be located directly upstream of HEPA filter service locations. Comprising the second group were requirements intended to enhance the moisture-resistance of filter construction materials. Examples include minimum values for the water repellancy and wet tensile strength of clean, new filter media. The intent of these latter countermeasures was to minimize the risk of filter malfunction during inadvertent, short-interval exposure of filters to liquid water.

Despite the implementation of both groups of countermeasures, the need for higher strength, moisture-resistant HEPA filter units of nuclear grade was brought to the forefront in the early 1980's(18, 19) and again in the late 1990's(20, 21). In retrospect, this should not have been totally unexpected. The earlier adopted countermeasures addressed neither the intrinsic fragility of glass-fiber filter media, nor their susceptibility to cumulative degradations in strength properties resulting from aging and fatigue. And although the strength loss due to moisture exposure itself was mitigated by water repellency treatments for new media, the positive effects are normally soon compromised by aging and particle loading in service(7).

The presence of liquid water in a glass-fiber filter medium typically results in significant decreases in tensile strength and an increase in pressure drop. In combination, these readily facilitate a relaxation of the delicate filter medium and subsequent nesting of adjacent separators, which leads to loosening of the filter pack. Any pack loosening is accompanied by an appreciable portion of the mechanical loads on the pleated filter medium no longer being transferred to the two sides of the filter case. Thus, the mechanical loads upon the filter medium grow, at the same time its strength characteristics are being degraded.

The detrimental effects of a even a single event of moisture exposure in a pleated, conventional filter medium can be expected to cascade, even beyond subsequent drying-out of the medium. The limited recovery of filter medium tensile strength upon drying is one factor of concern. However, it pales in prospective significance compared to any loosening of the filter pack, which remains essentially irreversible. In a loosened filter pack, the robustness of the intrinsically-strong, sandwich-style construction of the pack becomes severely compromised.

During service time following moisture exposure, four relevant post-loosening phenomena have been identified. These include: increased bending stresses within the pleats, pleat movement under aerodynamic forces, filter medium fatigue at locations of highest stress, and mechanical interactions between pleats and separators(7). They can combine to significantly lower the burst strength of the filter pack, and correspondingly filter performance reliability. Moreover, the risk of catastrophic failure of the filter pack increases simultaneously with the progress of these phenomena. Any repeated exposure to moisture during service only accelerates progression of the adverse processes.

Thus, the dependability of the filter medium - one of the most fragile and most critical components in an air cleaning system - remains significantly and adversely affected during service by numerous factors of influence that may lie outside the direct oversight and control, if not the awareness, of the filter operator.

To specifically address these processes, high-strength, nuclear-grade HEPA filters were developed for the European market more than twenty years ago(8). Their use in select, critical applications in the U.S. has been precluded by a lack of code-based test standards necessary for their qualification and implementation. For instance, when personnel at Lawrence Livermore National Laboratory began upgrading exhaust filtration systems in the late 1990's, high-strength HEPA filters of European design were considered, but not selected; because no accepted US standards existed for their qualification(22). This illustrates a case of a filter operator having been unable to procure filters of performance commensurate with the potential risk and liability associated with processes that require confinement of particularly toxic radioactive substances. In this case, processes involving plutonium.

The case for higher strength nuclear-grade HEPA filters

Responses to recommendations by Carbaugh(18, 19) for the development of moisture-resistant filters were made by three groups that independently published results of the development and testing of high-strength filter units(8, 23, 24). An augmenting case for higher strength filters is summarized in the histogram of Fig. 2. Therein lies a compilation(25) of burst strengths for new, conventional filter units, compared to those of the European high-strength design. The test conditions include: dry air at high velocity, fog conditions at rated flow, and shock-wave impingement. Delineated are one range of maximum blower-induced pressure drops to be sustained without filter failure in older US facilities, the prospective Δp of an NRC (Nuclear Regulatory Commission) Region I tornado, and a maximum blower Δp of 37 kPa (150-in w.c.) to possibly be found in some future US nuclear air-cleaning systems. The typical maximum Δp in German nuclear air-cleaning systems is noted as the baseline for the safety margin of greater than 1.5, professed for the high-strength filter units(8) in humid airflow.

Discernable decreases in filter reliability resulting from accelerated exposure to liquid water are illustrated by the range of 1 - 9 kPa (4 - 36 in w.c.) for conventional units at rated flow under fog conditions. Evident is the overlap between this failure range and that of the conservatively-low range of maximum blower pressure drops typical of older US nuclear air-cleaning systems. Moreover, all burst strength values are those obtained from testing new filters. For 20 used, deep-pleat filters tested in humid airflow after 24 months of service, 4.1 kPa (16 in w.c.) was the average measured failure pressure within a range of 0.9 - 6.7 kPa (3.6 - 27 in w.c.). An additional significantly relevant aspect is that though

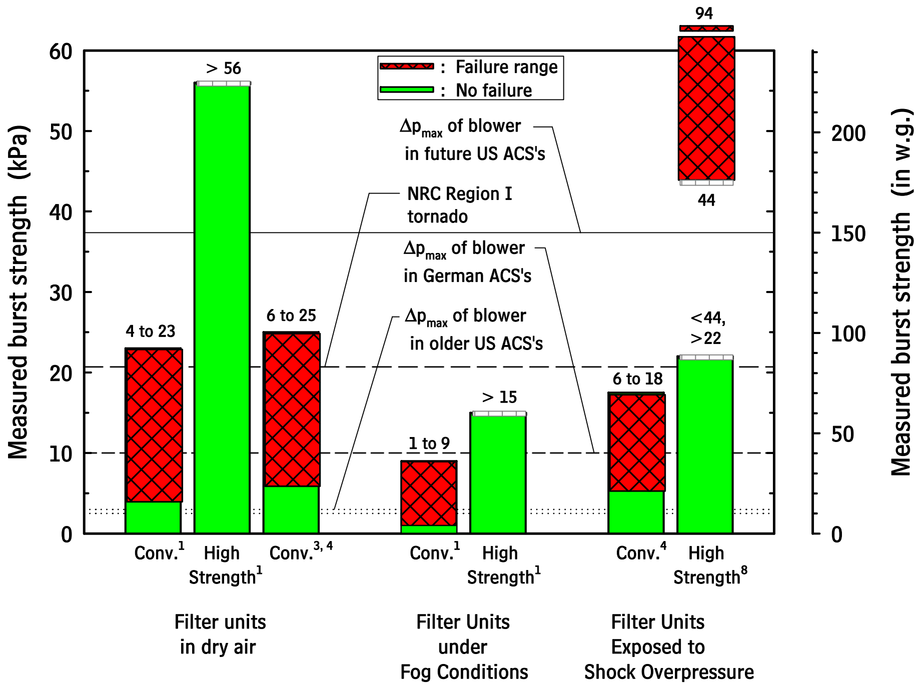

Figure 2: Burst strengths of conventional, new 610-mm x 610-mm x 292-mm (24-in x 24-in x $11^1/_2$-in) HEPA filter units compared to those of a high-strength design(25) (s.(25) for source references).

new filters have typically been found to fail only in airflows entrained with water droplets, failures of used, dusted-loaded ones have been reported for air relative humidities less than 100%(7). Thus, not only can used, dust-loaded filters be expected to be less robust and reliable than new ones, but they also have been found to fail at low differential pressures for design flows and air relative-humidity values below saturation (100% r h). It is no coincidence that they have also been observed to be particularly susceptible to an accelerated loosening of the filter pack in flows of humid air.

High-strength filter realization

Given that the filter medium represents - by far - the most delicate component 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 commercial high-strength filters(8), for which test results are depicted in Fig. 2.

The high-strength filter units introduced onto the European market in the late 1980's(8) represented a combination of technical solutions that addressed the major weaknesses of filter designs incorporating both deep pleats and separators. Under both dry and wet conditions, proof strengths of the European high-strength filters have been demonstrated to be high enough to permit meaningful margins of safety to be quantitatively specified for filter units in their service locations within nuclear air-cleaning systems(8). This was based for the most part on utilizing a cloth of glass-fiber to reinforce the glass-fiber filter medium. The result was a filter medium tensile strength some 16 times greater when dry, and some 90 times greater when wet, than those of a typical conventional glass-fiber medium at the time.

Prospective Safety Benefits of High-Strength Filter Implementation

Air-cleaning system components can generally be classified either as permanent or as requiring periodic replacement. Correspondingly, there tend to be some premised-based differences between performance specifications for the one group, as compared to the other. Not only within the guidelines of operators, but also within those of codes and standards. As one example, air-cleaning system duct work is presently recognized as a structural element, for which code performance characteristics correspondingly include suggested factors of safety(1). Whereas, an analogous margin of safety is not typically associated with HEPA filters in US nuclear applications. As another example: filter mounting frames within housings are required to sustain - without permanent deformation - a pressure-impulse loading of 20.7 kPa (3 psi)(1), corresponding to the effects of a tornado-induced pressure pulse. Yet the HEPA filter units mounted to them currently are not.

The implementation of nuclear-grade HEPA filters having significantly higher proof strengths offer opportunities for advances to be made in nuclear safety practice (see Fig. 3). By recognizing filter units in their service locations as structural elements and better ensuring their physical integrity under a broad range of operating conditions, their reliability in critical applications can be significantly increased. Even to approach levels of permanently installed air-cleaning system components, such as duct work, housings, and mounting frames.

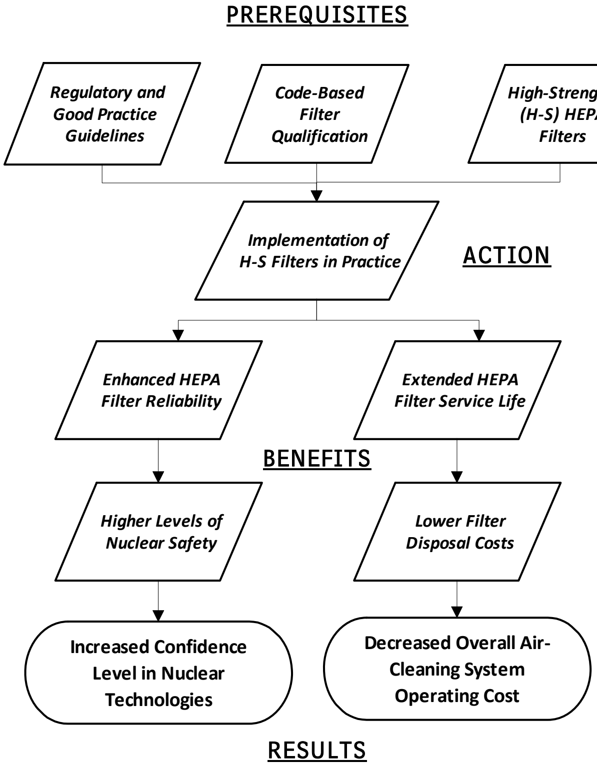

Figure 3: Prerequisites to and benefits of the implementation of high-strength HEPA filters in practice.

The current *status quo* can be interpreted as reflecting the historical perception of HEPA filters as replaceable cartridge-like components, characterized by an intrinsically-low proof strength for new units and uncertain burst strengths for aged ones in service. They have been allowed a pass on firm requirements for demonstrable reliability and realistic safety margins, in both performance specifications and guidelines for good practice. This can primarily be attributed to the characteristic fragility and the susceptibility of glass-fiber filter media to degradation with increasing age and service time. Another relevant factor relates to the economics of system operation, for which priority is generally set upon minimizing the direct replacement costs of expendable components. However as described below, the direct replacement cost of a typical nuclear-grade HEPA filter can make up less than 10% of the cost associated with its life cycle.

Prospective Economics of High-Strength Filter Implementation

It is to be expected that glass-fiber filter media will continue to play a dominant role in nuclear applications into the foreseeable future. Moderate cost, high filtration efficiency, low flow resistance and density, reasonable degree of chemical inertness, and fair resistance to radiation, elevated temperature, and fire, all constitute a set of characteristics that other filtration materials cannot match at present.

Similarly, the conventional deep-pleat design with separators has proven itself superior in strength and reliability to comparable FC-type separatorless and mini-pleat designs, under most simulated adverse operating conditions. This helps explain why the basic filter design selected for economic upgrades to higher strengths is one characterized by deep pleats, separators, and a reinforced glass-fiber medium.

With respect to the economics of conventional filters, Table I summarizes results of cost analyses based upon a survey of filter users in the DOE complex over a four-year period in the late 1980's(26). The data set encompassed nearly 46,000 conventional filters, 64% of which were of the 610-mm x 610-mm x 292-mm (24-in x 24-in x $11^1/_2$-in) size. The weighted average life-cycle cost per filter was $US 4 753, more than ten times the estimated cost of $US 450/filter for purchase, receipt, certification, and storage, *i. e.*, those costs typically associated directly with filter replacement. The latter category included:

- purchase cost
- purchasing overhead
- all shipping charges
- storage costs
- transportation labor and overhead
- receiving labor and overhead
- quality assurance costs.

The purchase cost is noted to be a relatively small percentage of the total cost over the life cycle of the filter, *i. e.*, less than the approx. average of 10% represented by the above cost category grouping.

Other cost categories in the life-cycle analysis included:

- filter change-out
- pre-packaging assay
- filter packaging/size reduction
- post-packaging assay
- shipping and handling
- final disposal.

Among these, filter change-out costs were found to be up to 3.7 times and final disposal costs up to 17 times the average total cost of purchase, receipt, certification, and storage, *i. e.*, the $US 450 per filter.

Based upon the cost assessment cited above, typical initial purchase costs for high-strength filters of two to three times more than those of conventional filters would not significantly add to the life-cycle cost of a nuclear-grade HEPA filter. Given that non-mandatorily recommended values of both service life (in most applications) and shelf life will be greater for high-strength filters, the life-cycle cost for them could typically be expected to be close to cost neutral for low-level waste streams. In the instances of filters processed as transuranic or high-level waste, lower life-cycle costs than those for conventional units might be anticipated, as indicated in Fig. 3.

Moreover, given that an implementation of high-strength filters would result in a significant reduction in the potential risk of an inadvertent loss of containment or confinement, the probability of avoiding costly clean-up and mitigation following a mishap is correspondingly increased. And additionally, the likelihood of maintaining public confidence in and acceptance of nuclear-related technologies would also be enhanced. Attempting to quantify the beneficial value of these latter two aspects of filter implementation would exceed the scope of this summary.

And finally, the implementation of high-strength filters could offer operators additional options and flexibility when considering the replacement of aging filters in the air cleaning systems of an aging U.S. nuclear-facility infrastructure. This, in the context of economic analyses toward justifying whether the service life of a given system would be better extended or alternatively terminated.

Table I: Summary of estimated life-cycle costs for conventional nuclear-grade HEPA filters in the DOE complex for 1987-1990(26).

Waste Level	Life-Cycle Cost ($US †/ filter element)	Total Filter Sample Population, Fraction of (%)
Low	3,000	80
Transuranic	11,700	19
High	15,000	01

† 1987-1990 dollars US.

Basis for the Pressure-Impulse Test in the H-S Filters Qualification Process

Resistance-to-pressure test

The series of qualification tests in Sections FC and FK for conventional filters include the so-called resistance-to-pressure test as one step (see Fig. A-3 and Table A-III). Its function is to verify a quite modest, minimum filter strength value for qualification purposes, equal to Δp_{filter} = 2.5 kPa (10 in w.c.). It is somewhat analogous to a proof strength for new filter units in a wet condition. In this case, however, it is neither intended to reflect, nor is it based upon, a filter burst strength.

Filter burst strength is typically quantified by the pressure drop across the filter at which rupture of the filter medium results in an irreversible increase in penetration above the maximum allowable value of 0.03%. Empirical burst strength values would typically be determined first. A proof strength value would then be set at a predetermined percentage of the burst strength, to allow for variabilities in filter manufacturing processes. In the case of high-strength filters, recommended values could be expected to be set between 75% and 80% of those at failure, both for the filter medium (based upon its ultimate tensile strength) and for the filter pack as affixed within the filter case (based upon its burst strength).

However, the 2.5-kPa (10-in w.c.) value of Sections FC and FK is so low that it is not suitable for any useful margin-of-safety calculations. For practical application, it would need to take into account a safety margin and a peak mechanical loading that the wet, fatigued, filter medium of aged, dust-loaded filter packs might be estimated to face during service. At a minimum, the peak loading should be quantified by the maximum Δp of the system blower. However, the 2.5 kPa (10 in w.c.) falls short of this. Hence, for system design, or safety analysis purposes, the specified Δp is inadequate in magnitude for calculating meaningful margins of safety for nuclear-grade HEPA filters in their service locations.

Pressure-impulse test

For the qualification of high-strength filters, a sufficiently stringent test analogous to the resistance-to-pressure test of Sections FC and FK is required. The intended functions of the resistance to pressure-impulse test are summarized in Tables A-I and A-II for Level I and Level II filters, respectively. One of the primary functions of the pressure-impulse test is to serve as a proof test to quantify a minimum wet-filter burst strength that can be utilized in realistic margin-of-safety calculations. Figures A-1 and A-2 illustrate how the pressure-impulse test is integrated into each of the proposed overall qualification test sequences for filters of the Level I and Level II designations.

Toward qualifying HEPA filter units of higher strength, numerous prospective test-rig concepts were evaluated toward selecting an economically suitable one(27, 28). The chosen option was based upon the quick release of an initially stationary column of water, followed by its acceleration in free fall through a vertical distance, and finally its impact upon the horizontally-oriented upstream face of the test filter. As initially envisioned, gravity was to be the sole agent of acceleration(28).

Preliminary small-scale pressure-impulse tests carried out on 7.5-cm (3-in) dia. samples of both conventional and high-strength filter media and similarly-sized hand-fabricated model filter packs proved promising(28). Consequently, an intermediate-scale test apparatus was assembled, based upon a vertical column of nominal 250-mm (10-in) ID PVC pipe and a manually-actuated butterfly valve. It had a flow cross-section of 0.052 m^2 (0.56 ft^2), a fall distance of 3.2 m (10.6 ft), max. water column height of 4.2 m (13.8 ft), and total height of 7.6 m (25 ft). Proof-of-concept tests were then performed on manufacturer-supplied 203-mm x 203-mm x 149-mm (8-in x 8-in x $5^{7}/_{8}$-in) filters - conventional units and high-strength proto-types; each group consisting of three filters each.

Shown in Fig. 4 is a plot of the differential pressure with time across a prototype high-strength unit, as measured 9 cm (3.5 in) upstream of the test filter during a pressure impulse test. The respective rise time and dwell of the 130-kPa (differential) (18.5-psid) peak pulse were approx. 385 ms and 790 ms. The subsequent two peaks resulted from decaying pressure oscillations in the water column above the test filter and exhibit resonant-like periods of approx. 1 s. Very similar periods of post-peak-pressure oscillations were observed for the other intermediate-scale filters tested. This was also the case for the 7.5-cm (3-in) dia. samples of high-strength filter medium investigated earlier(28).

For peak filter impulse pressures between 83 and 130 kPa (differential) (12 and 18.5 psid), both pre- and post-test particle penetration values for the three prototype high-strength filters in a dry state were not greater than 0.03%. No visible post-test damage to the filter medium was evident in any of the high-strength prototypes.

In comparison, each of the three conventional filters failed catastrophically during tests having peak impulse pressures between 46 and 94 kPa (diff.) (6.6 and 13.6 psid). Thus, no post-test filtration efficiency measurements were considered to have been necessary and none were undertaken. Post-peak pressure oscillations were less pronounced for the three conventional filters. This was attributed to the mode of catastrophic failure which somewhat dampened reflections of the pressure-impulse wave back up through the water column as it drained through the test filter after impact.

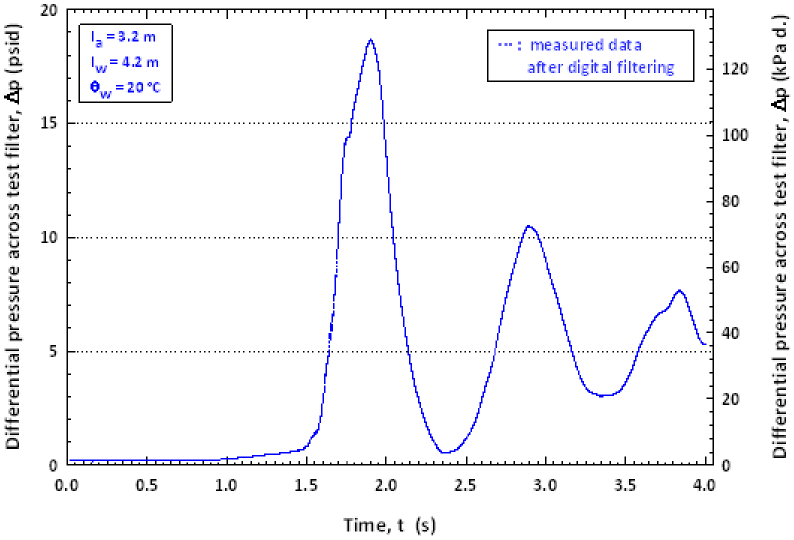

Figure 4: Plot of differential pressure across a 203-mm x 203-mm x 149-mm (8-in x 8-in x $5^{7/}{}_{8}$-in) prototype, high-strength filter during a pressure-impulse test.

Full-scale prototype test rig for pressure-impulse qualification test

After the proof-of-concept test results were judged to be successful, attention turned to the design of a full-scale prototype test rig. This led to consideration of size reduction measures, when the projected height of the full-scale test stand became greater than that which could be accommodated at the anticipated qualification test location. The concept selected is based upon augmenting the acceleration of the falling water column, using compressed air above it as a propellent medium. Both the required height of the water column and its fall distance can be accordingly reduced. The compressed-air modification to the falling-water-column concept was implemented in the design of a full-scale test rig (Fig. 5) that is expected to serve as a prototype for the test stand planned for high-strength filter qualification. This future test stand is foreseen to be located at the Edgewood Chemical Biological Center of Aberdeen Proving Ground.

Figure 5: Side view of prototype full-scale rig for qualification of 610-mm x 610-mm x 292-mm (12-in x 12-in x $11^{1/}{}_{2}$-in) high-strength filters to pressure impulse test, less test section. (left)

The maximum fall distance of the water is 1.7 m (5.5 ft) and the effective maximum water column height, 3 m (10 ft). Currently, the rig is characterized by an overall height of 6 m (20 ft) and a footprint of 4.5 m x 4.5 m (15 ft x 15 ft) due to having been outfitted with wind-load support braces for its current location outside. The footprint can be reduced to only 1.2 m x 1.2 m (4 ft x 4 ft) by removing the braces, for any prospectively permanent interior location.

A side view is shown in Fig. 5. It has a flow cross-section of 0.26 m^2 (2.8 ft^2). Empty, it has a mass of 1.8 metric tons (4000 lb) and can effectively hold up to 0.85 m^3 (30 ft^3) of liquid, corresponding to 910 kg (2000 lb) of water. The maximum gage pressure on the high-pressure side, upstream of the 0.61-m (24-in) dia. butterfly valve of ductile iron is limited to 1.7 MPa (250 psi), providing a nominal safety factor of 5 (five) for a max. anticipated air pressure of 350 kPa (gage) (50 psig).

Methodology Followed in the Development of Section FM

During the initial stage of the development process, current releases of Sections FC and FK were used as baselines, from which as much relevant content as practical was adopted. Updated specifications from ongoing revisions to Sections FC and FK also served as invaluable sources. Also drawn from were protocols of an existing German qualification test sequence for high-strength filters(8, 29).

The delineation of performance requirements for high-strength filters required several hurdles to be overcome. One lay in establishing requirements for high-strength filter media. Test values were obtained for the ultimate tensile strength of dry, wet, flat, and folded specimens, in both the machine and cross directions of the commercially available filter medium employed in German high-strength filters. Values corresponding to 75% - 80% of these were incorporated as proposed performance specifications for high-strength filter media(28) in Mandatory Appendix FM-I of Section FM (see Fig. A-4).

A multiple step process became necessary while addressing the inherently higher performance requirements of the test apparatus needed to qualify the much greater structural capabilities of high-strength filters. As described under the *Pressure-impulse test* section above, this involved initial testing with a small-scale apparatus followed by proof-of-concept tests using an intermediate-scale rig. Positive results in each case led to the design and realization of a full-scale prototype test rig.

Qualification cost considerations

For any set of qualification tests to be acceptable, the implementation of each test must be as simple and low in cost as possible. And correspondingly, the overall equipment, personnel, and utility costs associated with a given set of tests cannot be allowed to exceed practical limits. These were the guiding principles applied during the selection of performance tests related to media and filter elements of high-strength. This was accomplished by first using - or appropriately modifying - as many existing performance tests and test criteria as possible. Secondly - as in the case of the pressure-impulse test - straightforward, cost-effective solutions were sought for a new qualification test for overpressure, which was by necessity much more stringent in nature than the existing one for conventional filters. Lastly, by being able to apply the series of stringent qualification tests to the same high-strength units, the number of test filters required by Section FM was reduced from 12 ea. to 8 ea., as compared to Sections FC and FK (see Fig.'s A-1 through A-3).

Conclusions

High efficiency particulate air filter units represent cost-effective, indispensable components 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 primarily limited by the inherently weak and brittle glass-fiber filter medium. 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. Moreover, filter reliability during service can be significantly and adversely affected by numerous factors of influence and degradation processes, some of which can readily lie outside the direct oversight and control of the filter operator.

Exposure to operating conditions that lead to the appearance of liquid water in the filter medium represents a particularly acute threat to filter reliability. Since their inception, measures employed in the U.S. to preclude moisture exposure or counteract its effects have not entirely resolved the sensitivity of filters to the effects of exposure to liquid water. Practically, the effects of aging and fatigue of glass-fiber filter media remain yet unaddressed by countermeasures. An emerging factor in practice is the layout of some air cleaning systems having blowers with maximum pressure drops of greater than 37 kPa (150 in w.c.)(30) which will pose implicit challenges to the reliability of conventional filters in these systems.

Most doubts 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 challenges posed to conventional filters: it seems highly likely that reinforced media would be mandated in most codes for qualification of nuclear-grade filters, were HEPA filters to be invented today.

The longstanding availability of high-strength filter units in Europe indicate that their technical obstacles have been overcome. Further enhancement of filter reliability in critical applications within U.S. nuclear facilities depends upon implementing such filter designs in practice. Life-cycle cost analyses for conventional filters in the literature indicate that the higher initial cost of high-strength filters should not necessarily represent an economic hurdle precluding their adoption. Some future cost reductions for filter units meeting upgraded standards can be anticipated to be realized through design and manufacturing optimizations, economies of scale, and market competition.

Completion of Section FM of AG-1 represents one remaining milestone to be accomplished before high-strength filter implementation becomes a reality in the U.S. Specifications for the pressure-impulse test of this code section remain yet to be delineated. The almost completed full-scale prototype test rig needs yet to be evaluated toward subsequently transforming it into the final version of the test stand to be utilized for routine qualification testing of high-strength filters at the Edgewood Chemical Biological Center of Aberdeen Proving Ground.

An additional task on the horizon is anticipated to involve facilitating the cooperative involvement of filter operators and regulatory entities, who carry the ultimate responsibility for helping to ensure that the operations of U.S. nuclear facilities do not adversely affect the health and safety of both facility personnel and the public.

Acknowledgments

Appreciatively recognized are the dedicated efforts of the following engineering technology students who evaluated concepts related to what eventually became the pressure-impulse test and performed empirical studies toward its realization. Their project-related contributions were accomplished in fulfillment of academic requirements for the bachelor of science degree in engineering technology (mechanical). These teams of recent NMSU graduates included the following individuals:

Spring 2009: Curtis Aday Mario Jiménez John Rodke
Fall 2009: Richard Gomez Cayetano Mendoza Aaron Thomas .

Appreciatively and most highly recognized are the extraordinary efforts of the students who designed and brought into realization the full-scale prototype rig for the pressure-impulse test:

Spring 2010: Ruben Altamirano Anthony Lucero Jeff McNierney John Saulietis Adrian Toledo .

Special mention for invaluable support is accorded to Derek Toledo, A.S., for his welding expertise that helped make fabrication of the full-scale prototype test rig possible.

Also making contributions were: Lawrence Araiza Levi Benitiz Gary Chavarria .

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Appendix

Background Information on Qualification Testing of Proposed High-Strength HEPA Filters

Information on Proposed Qualification Testing of H.-S. HEPA Filters

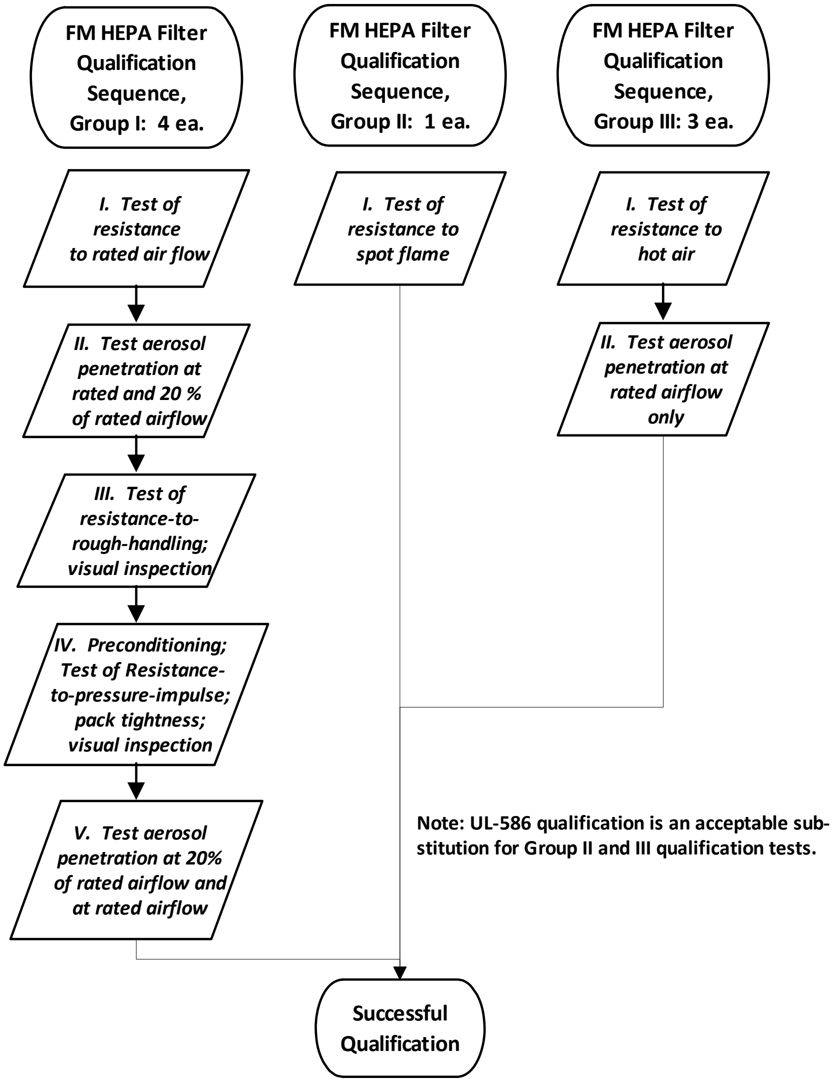
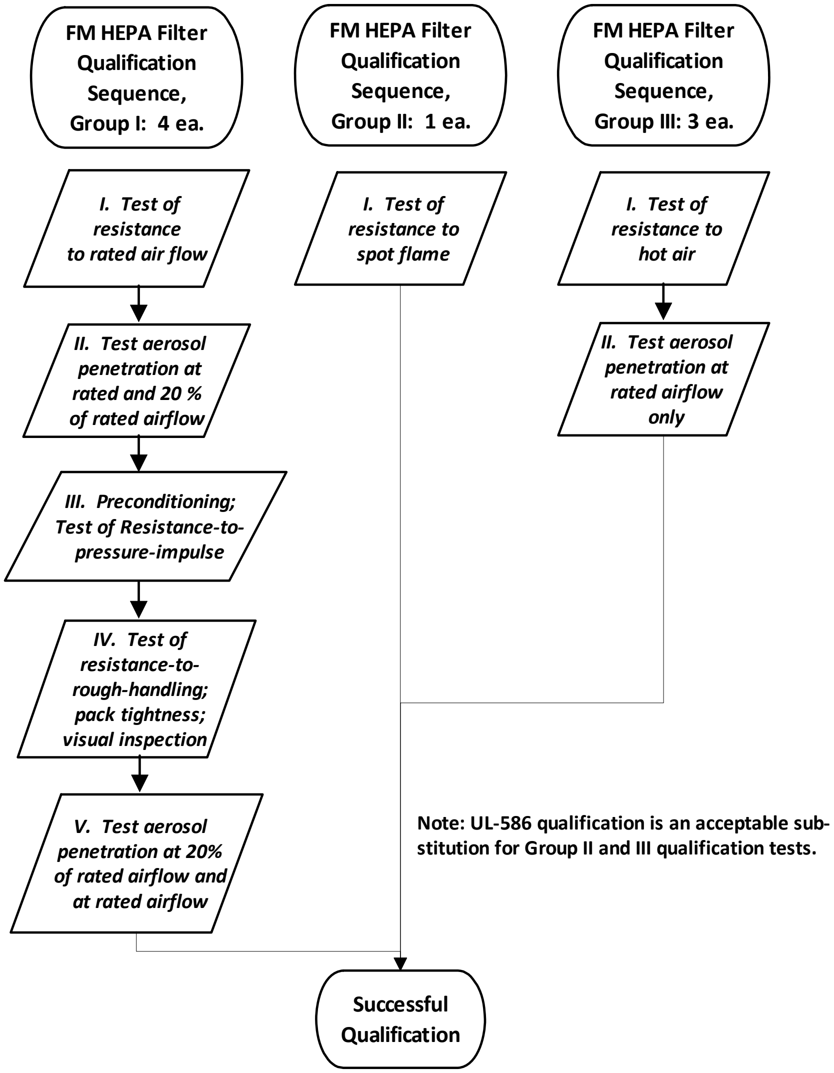


Figure A-1: Schematic of qualification tests in sequence proposed for Level I US high-strength filters.

Table A-I: Function of qualification tests in sequence proposed for Level I US high-strength HEPA filters (FM).

Step	Performance Characteristic Tested	Functions of Test
1	Resistance to rated airflow	Verify that filter meets maximum pressure drop requirement at rated flow
2	Test aerosol penetration at rated airflow and at 20% of rated airflow	Verify that filter initially meets maximum particle penetration requirement at relevant flows
3	Resistance to rough handling	Induce mechanical interactions between separators and (dry) filter medium pleats, before the static resistance-to-maximum-rated-temperature test and before the resistance-to-pressure-impulse test Accelerate fatigue of the dry filter medium, before the static resistance-to-maximum-rated-temperature test and before the resistance-to-pressure-impulse test
4a	Preconditioning to 4b) below: Static resistance to maximum rated temperature for continuous service	Verify resistance to maximum rated temperature for continuous service Accelerate off-gassing of volatiles from frame, adhesive/sealant, filter medium, gasket, and separators before resistance-to-pressure-impulse test
4b	Preconditioning to 4c) below: Submersion of dry filter at elevated conditioning temperature in room-temperature water bath	Verify compatibility of constituent components under varying temperature conditions with respect to thermal expansion and contraction; via thermal shock before resistance-to-pressure-impulse test
4c	Resistance to pressure-impulse	Represent the product of a safety margin multiplied by the peak mechanical loading that the wet, fatigued, filter medium of aged, dust-loaded filter packs might have to sustain during service Serve as a proof test to quantify a minimum wet-filter burst strength that can be used in margin-of-safety calculations Ensure that any potential loosening of the filter pack that could occur during service is made evident
4d, e	Pack tightness, visual inspection	Verify that pack loosening after the resistance-to-pressure-impulse test does not exceed a maximum allowable limit
5	Test aerosol penetration at 20% of rated and at rated airflow	Verify that filter meets maximum particle penetration requirement at relevant flow after test sequence of resistance to maximum rated temperature, to rough handling, and to pressure-impulse

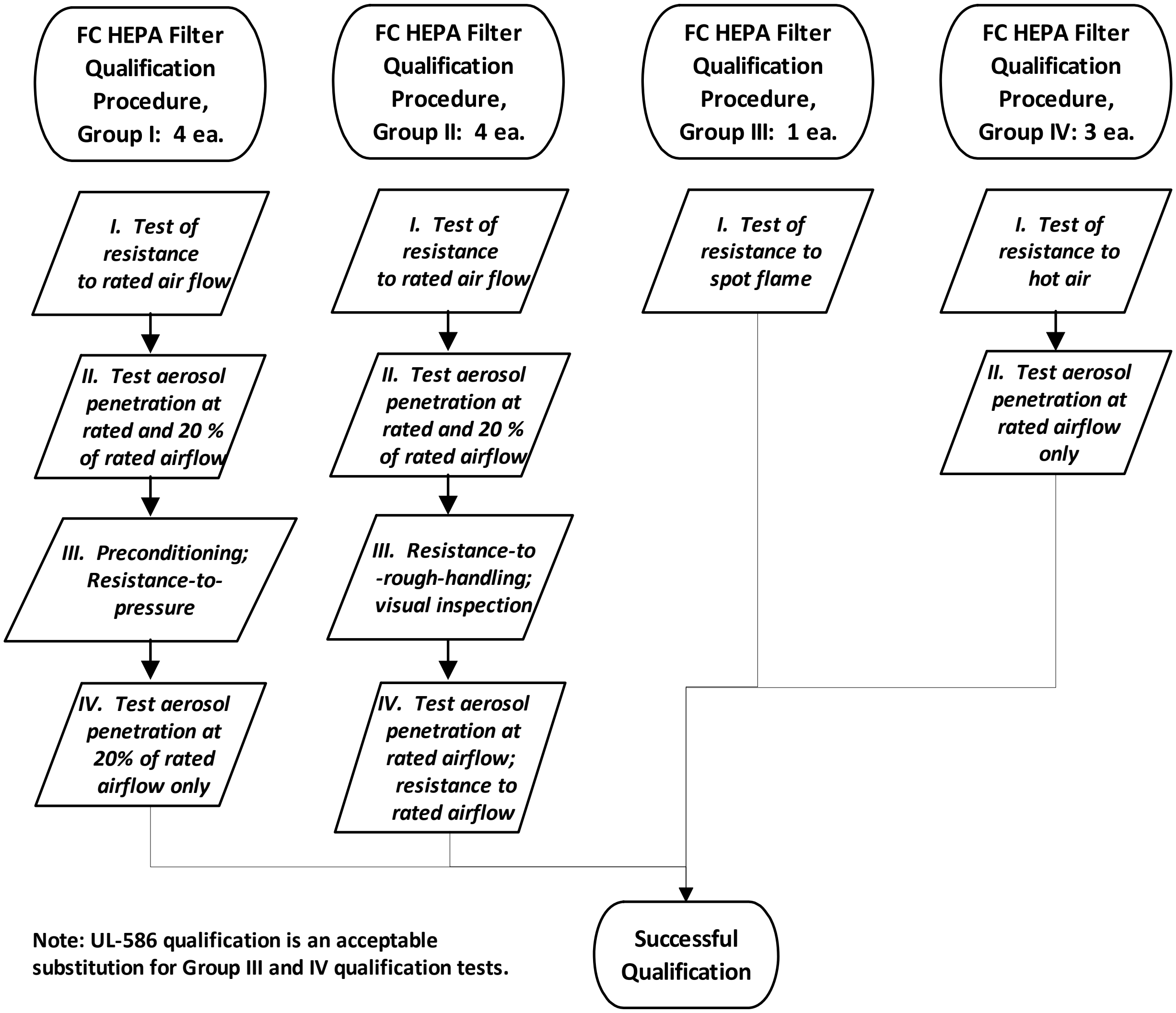


Note: UL-586 qualification is an acceptable substitution for Group II and III qualification tests.

Figure A-2: Schematic of qualification tests in sequence proposed for Level II US high-strength filters.

Table A-II: Function of qualification tests in sequence proposed for Level II US high-strength HEPA filters (FM).

Step	Performance Characteristic Tested	Functions of Test
1	Resistance to rated airflow	Verify that filter meets maximum pressure drop requirement at rated flow
2	Test aerosol penetration at rated airflow and at 20% of rated airflow	Verify that filter initially meets maximum particle penetration requirement at relevant flows
3a	Preconditioning to 3b) below: Static resistance to maximum rated temperature for continuous service	Verify resistance to maximum rated temperature for continuous service Accelerate off-gassing of volatiles from frame, adhesive/sealant, filter medium, gasket, and separators before resistance-to-pressure-impulse test
3b	Preconditioning to 3c) below: Submersion of dry filter at elevated conditioning temperature in room-temperature water bath	Verify compatibility of constituent components under varying temperature conditions with respect to thermal expansion and contraction; via thermal shock before resistance-to-pressure-impulse test
3c	Resistance to pressure-impulse	Represent the product of a safety margin multiplied by the peak mechanical loading that the wet, fatigued, filter medium of aged, dust-loaded filter packs might have to sustain during service Serve as a proof test to quantify a minimum wet-filter burst strength that can be used in margin-of-safety calculations Ensure that any potential loosening of the filter pack that could occur during service is made evident
4a	Resistance to rough handling	Induce mechanical interactions between separators and water-saturated filter medium pleats, after the resistance-to-pressure-impulse test Accelerate fatigue of the water-saturated filter medium, after the resistance-to-pressure-impulse test
4b, c	Pack tightness, visual inspection	Verify that pack loosening after the resistance-to-pressure-impulse and rough-handling tests does not exceed a maximum allowable limit
5	Test aerosol penetration at 20% of rated and at rated airflow	Verify that filter meets maximum particle penetration requirement at relevant flow after test sequence of resistance to maximum rated temperature, to pressure-impulse, and to rough handling

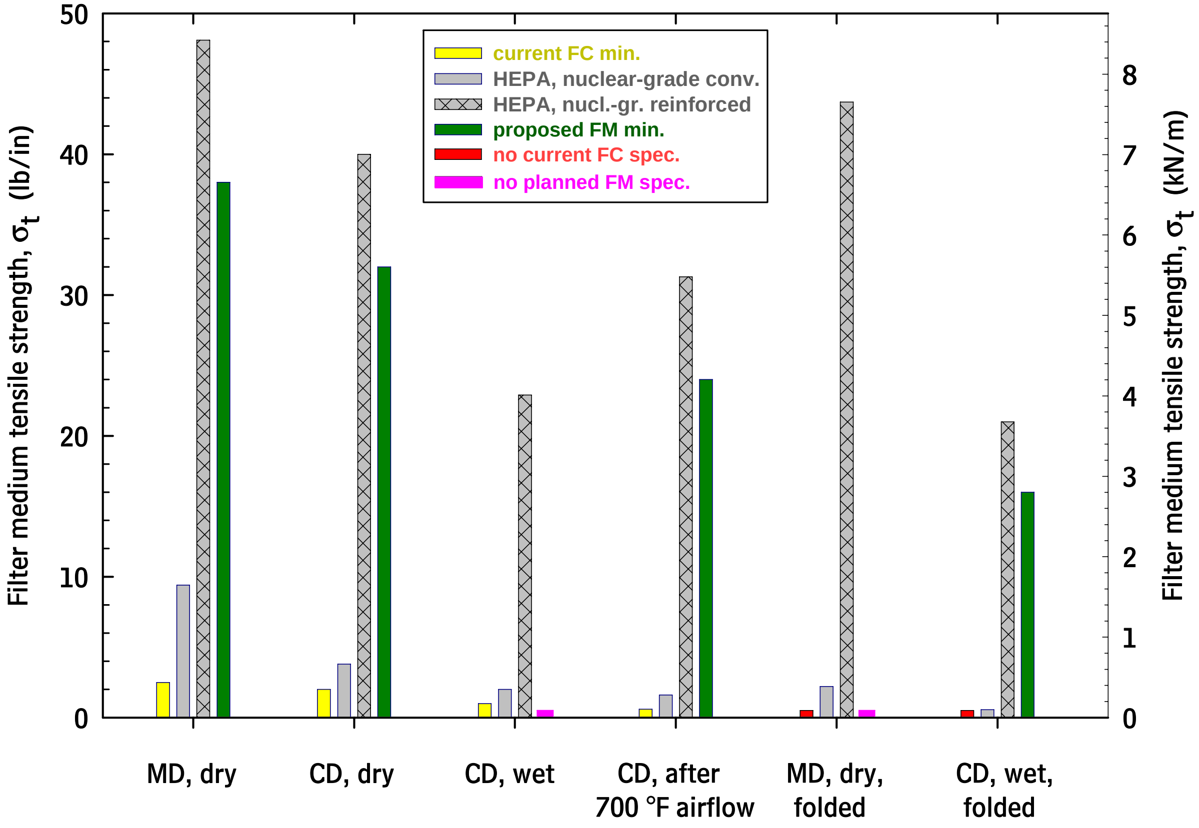


Note: UL-586 qualification is an acceptable substitution for Group III and IV qualification tests.

Figure A-3: Schematic of qualification tests in sequence for conventional HEPA filters (FC and FK).

Table A-III: Function of qualification tests in sequence for conventional HEPA filters (FC and FK).

Step	Performance Characteristic Tested	Functions of Test
1	Resistance to rated airflow (Groups I and II)	Verify that filter meets maximum pressure drop requirement at rated flow (Groups I and II)
2	Test aerosol penetration at rated airflow and at 20% of rated airflow (Groups I and II)	Verify that filter initially meets maximum particle penetration requirement at relevant flows (Groups I and II)
3	Resistance to pressure (Group I), *or* Resistance to rough handling (Group II)	Serve as a proxy proof test to quantify a minimum wet-filter burst strength that is so low that it can be used in few if any practical margin-of-safety calculations (Group I), *or* Serve to evaluate pack tightness and robustness of case, joints, adhesive, filter medium, separators, and faceguards: all in an integrated unit; overall ability to sustain shocks in transport without structural damage (Group II)
4	Test aerosol penetration at 20% of rated airflow (Group I), *or* Test aerosol penetration and resistance to airflow, at rated airflow (Group II)	Verify that filter meets maximum particle penetration requirement at relevant flow after resistance-to-pressure (Group I), or Verify that filter meets maximum particle penetration requirement and resistance to airflow at relevant flow after resistance to rough handling (Group II)



Summary of the Strength Specifications for
Nuclear-Grade High-Strength HEPA Filter Media

Figure A-4: Comparison of filter medium strength specifications in Mandatory Appendix FM-I of proposed Section FM to existing ones in Mandatory Appendix FC-I of Section FC of AG-1.