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FILTER PERFORMANCE SPECIFICATIONS AND A PROTOTYPE TEST APPARATUS FOR QUALIFICATION OF HIGH-STRENGTH HEPA FILTER DESIGNS

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Abstract

In the time since their inception in the early 1940's, the technical literature relevant to nuclear-grade, High Efficiency Particulate Air (HEPA) filters in the United States (US) shows several distinct periods during their development. The current phase, extending from approximately 1980 to the present, can be characterized as one involving few major improvements in the principal performance characteristics of US filters as they relate to units in their service locations. Rather, priorities appear to have been refocused in directions away from progressive development and towards consolidation of filter performance characteristics into the qualification-test specifications of codes and standards. In particular, Section FC of ASME's Code on Nuclear Air and Gas Treatment, AG-1 (1). Also evident is a trend towards optimizing the economics of filter manufacturing.

The retrenchment of the US nuclear power industry and the end of the Cold War both led to the redirection of resources; away from the nuclear safety arena, and towards US societal needs of higher priority. One result of this, was that new HEPA filters remain yet neglected as the weakest of components in US nuclear air-cleaning systems. Moreover, unlike the other, much more robust system components, their reliability can be significantly degraded during service by factors of influence that sometimes lie outside the direct control of the filter end-user. Furthermore, some users in the US have been unable to procure filters of functional reliability commensurate with the potential risk and liability inherently associated with certain industrial processes that require confinement of particularly toxic radioactive substances, such as plutonium.

One prospective remedy is *high-strength* nuclear-grade HEPA filters, which have been available in Europe for almost twenty years. The use of them, or prospective equivalents in select, critical applications in the US has in part been precluded by a lack of sufficiently stringent, code-based test standards that are prerequisite to qualification of high-strength designs. In turn, viable qualification tests rely upon time-efficient and economical test procedures. If allowed to continue, the ongoing lack of appropriate test standards will ever prevent high-strength units from being adopted in select US nuclear facilities as an essential safety technology.

Filter performance specifications have been recently compiled to address the need of some users for high-strength units. Additionally, a prototype test rig has been built to investigate how to best accomplish a more stringent version of one of the qualification tests for conventional filters: the so-called, "resistance-to-pressure" test, specified in Section FC. The underlying concept of the test rig is to replace the aerosol of air and H_2O droplets of Section FC, with water as the sole working fluid. This can significantly minimize the increases in test-rig size and energy costs related to scale-ups in rig performance needed to qualify high-strength units.

The proposed test conditions are presented. They are intended to stimulate discussion toward delineating performance specifications to qualify certain HEPA filter designs as meeting the designation of high strength. The new test rig is described and its performance characteristics summarized. Discussed are implications of preliminary evaluations of rig performance via simulated "resistance-to-pressure" tests of vintage, Size 5 deep-pleat filters of conventional designs from three US manufacturers performed using water. Foremost are those related to loosening of the filter pack and to the variability observed in filter resistance to water flow.

Introduction

The confinement of hazardously radioactive and toxic airborne particles within designated areas of US nuclear facilities is accomplished by HEPA filters qualified to be of nuclear grade as delineated in Section FC and the soon-to-appear Section FK of AG-1 [1]. The performance criteria levels of the two AG-1 sections serve to specify the minimum performance of what can be referred to as conventional filters. A number of disadvantages characteristic of conventional units make them unsuited for certain particularly crucial applications. These include nuclear facilities where plutonium or chemical explosives are processed, or ones in which contact of filters with liquid water, or even air relative humidities greater than 80%, cannot be entirely ruled out.

As is evident in Fig. 1., the Achille's heel of conventional filter designs is the filter medium itself. By one to three orders of magnitude, conventional, non-reinforced glass-fiber filter media remain the most inherently weak construction material in US HEPA filters. Moreover, during normal filter service, the detrimental effects of aging and fatigue, or even more adversely - moisture exposure - can result in increasing fragility of the filter medium (see Table I) and correspondingly significantly decreasing filter reliability. 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. Almost no other system component is fabricated from weaker materials than are conventional HEPA filter packs; or can degrade in structural strength during normal service in nuclear air-cleaning systems, as can they.

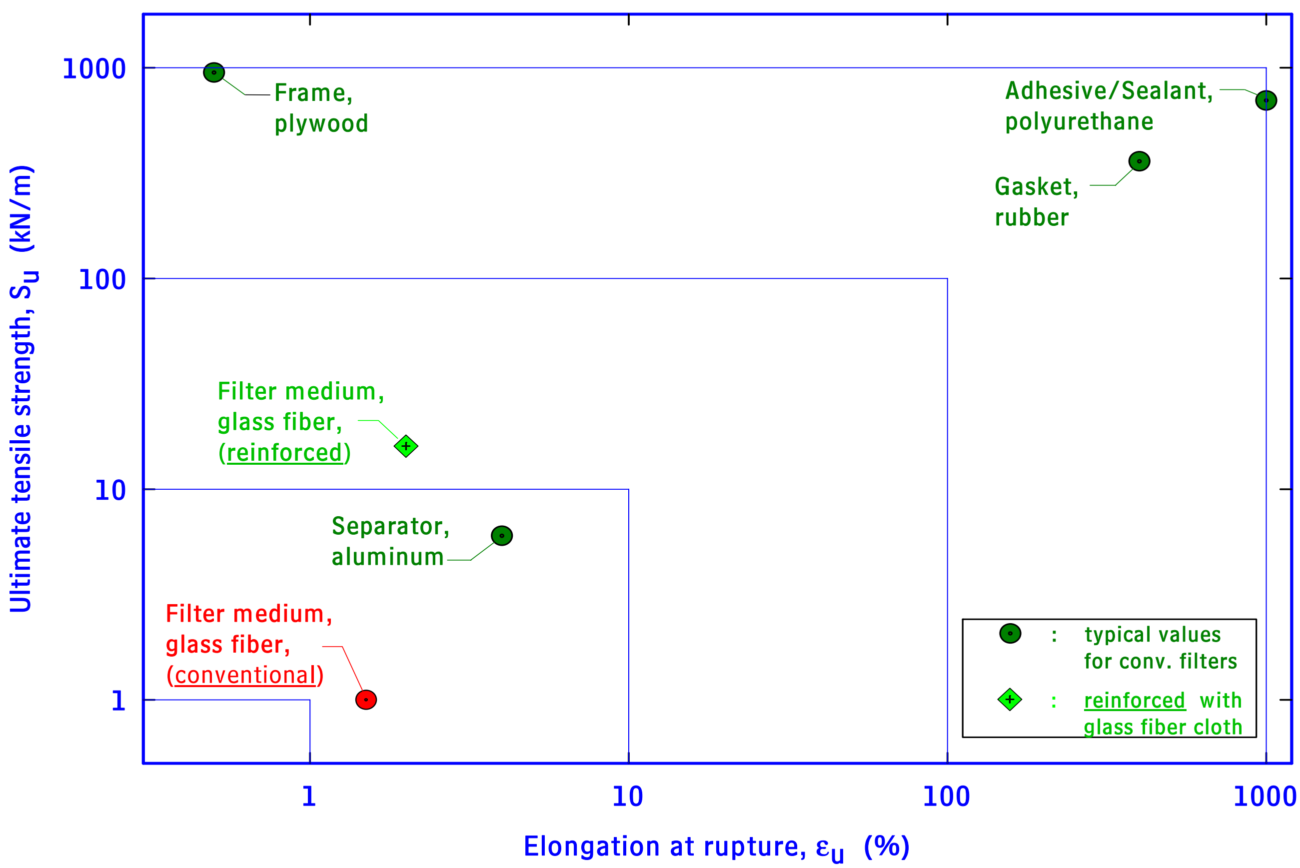

Figure 1: Strength characteristics for fabrication materials in conventional US nuclear grade HEPA filters [2].

Table I: The influence of several significant factors on the residual tensile strength of glass fiber, HEPA filter media of nuclear grade, in the machine direction at room temperature [2].

Factor of Influence	Residual Tensile Strength (%) Average value	Range of values	Quantity of Filter Units Sampled
Moisture: after 1 h soak at p_{abs} = 5 kPa; specimens wet; (new)	40	15 - 75	22
High air relative humidity: after 1 h at 99% RH; dust loaded; (used)	75	65 - 85	4
Normal service: after approx. 24 months; (used)	85	65 - 100	8

Relevant to the factors noted in Table I to decrease filter medium tensile strength is that their effects can be cumulative. Additionally, strong circumstantial evidence [3] suggests that fatigue of the filter medium at highly stressed locations in the pack can also reduce tensile strength at the stressed points, similar in extent to the factors listed in Table I. It is evident that any successful realization of higher strength filters must involve filter media of greater strength.

High-Strength Filters for Special Applications

In the early 1980's Carbaugh[4, 5] made recommendations for the development of moisture-resistant filters. Since then, three groups have published results following development and testing of filters higher in strength than conventional filter units [6 - 8]. A follow-up case [3] for higher strength filters has been summarized more recently. High-strength filter units brought onto the market in Germany in the late 1980's [7] were developed via systematic and thorough investigation of the failure modes and mechanisms characteristic of several common designs then available in both the US and Europe. The weaknesses inherent to the deep-pleat design with separators were then addressed: foremost, the typically low filter medium tensile strength and the loosening of filter packs in humid airflow. Although the end user responsible for their realization also developed a qualification standard for them [7], no published German national standards reflect this as yet [9]. This is in part explained by a lack of appropriate qualification tests and test apparatus characterized by simplicity and cost-effectiveness.

Similarly, several prerequisites remain to be met before any implementation of US high-strength filters in practice. These include their availability at reasonable cost and widespread acceptance of performance standards for their qualification. Suitably cost-effective apparatus capable of more stringent qualification testing is also needed. And ultimately, just as essential will be recognition of them by regulatory entities that would then mandate their use in special applications where reliable factors of safety greater than those attainable with conventional filters are called for.

Qualification Test Standards for High-Strength Filters

Tests of nuclear-grade filters under a variety of conditions deviating from normal operation show a wide deviation in burst strengths among the test filters of the many designs and manufacturers [(3)]. One conclusion to be drawn from these data is that the resistance-to-pressure test of Section FC in no way reflects filter burst strength. However, this is presently not its function. It is only intended to verify a modestly minimum proof strength, $\Delta p = 2.5$ kPa (10 in w.g.), for new filter units in a wet condition. Ideally, it would include a safety factor times the peak mechanical loading that the wet, fatigued, filter medium of aged, dust-loaded filter packs might have to sustain during service. At a minimum, this peak loading should be considered to be the maximum Δp of the system blower. However, 2.5 kPa falls far short of this in the level of mechanical loading applied [22]. This value is not even high enough to represent an average value for the maximum pressure drop produced by a blower in a modern air-cleaning system. Hence, for system design, or safety analysis purposes, the specified Δp is inadequate in magnitude for estimating meaningful factors of safety for filters in their service locations. Based upon published values for rated flow: new clean filters in supersaturated airflows (liquid water content > 0 g/m^3) can fail between 1 and 9 kPa (4 and 36 in w. g.) [(3)]. And used, dust-loaded ones can fail between 1 and 7 kPa (4 and 27 in w. g.) [(3)], at air relative humidities below saturation ($\varphi < 100\%$ RH).

Air-cleaning system duct work is generally recognized as a structural element whose code-specified performance characteristics correspondingly include suggested factors of safety. As less permanent and periodically replaced components, HEPA filters are not treated similarly. In current codes and standards, conventional filter units in their service location are not explicitly regarded as structural elements, the physical integrity of which, must be maintained under a potentially broad spectrum of operating conditions.

In a qualification test standard for higher strength filters, this deficiency could be remedied in several mutually reinforcing ways. One, by specifying the Δp of the resistance-to-pressure test so as to include a safety factor. Another, by mandating a minimum safety factor. Additionally, by recommending that the value calculated by the end-user be based upon a filter pressure drop no less than the maximum Δp of the system blower. And finally, for special cases - such as where filter exposure to explosion-driven shock waves might be anticipated, for example - advise the filter end-user to independently undertake testing that goes beyond minimum nuclear-grade qualification standards. All this, so as to better help ensure that sufficiently high factors of safety are not only specified and achieved, but also maintained during the entire filter service life.

Shown in Table II is the sequence of tests constituting the initial German qualification test standard that three filter units were required to pass for a design to be recognized as being of high strength [(7, 10)]. Each filter had to equal or exceed the final filtration efficiency measurement of Step 5, after being subjected to the previous four steps. Disadvantages to this standard were that it depended upon two cost-intensive research facilities which were ultimately dismantled. Also constituting a drawback was the 20-h duration of the resistance-to-pressure test of wet filters, during which the filter Δp only slowly increased up to approx. 7.5 kPa (30 in w. g.).

To alleviate the above drawbacks, a follow-on qualification test standard [(11)] included a single step consisting of four hours of exposure to a constant Δp of 5 kPa (20 in w. g.) at design flow and 30 °C in supersaturated airflow: in place of Steps 3 and 4. A leak-free requirement, as verified per DIN 24 184 [(12)], was also added to the first and last steps in the modified sequence. The smaller, less costly test rig used a 15-kW (20-hp) *Root*'s blower and regulated water flows of up to 150 kg/h through the spray nozzles to generate the pressure drop across the test filter. The disadvantage of this is the unacceptably low specified value of 5 kPa. Although twice that of the resistance-to-pressure test in Section FC, it is only one-third of the established lower limit of the asserted burst strength of high-strength filters, 15 kPa (60 in w. g.) [(7)].

Table II: Initial qualification test standard for German high-strength filters [7, 10].

Step	Performance Characteristic	Test Method or Conditions
1	Initial filtration efficiency	DIN 24 184, or equivalent
2	Static resistance to elevated temperature	130 °C in an oven for 23 h
3	Proof of minimum burst strength in dry air	rise to Δp of 25 kPa in 30 s dwell of Δp of 25 kPa for 60 s fall in Δp to 0 kPa in 30 s
4	Resistance to the effects of airborne water droplets and elevated pressure drop	30 °C and 5 g H_2O/m^3 of saturated air at rated flow for 20 h
5	Final filtration efficiency	DIN 24 184, or equivalent

Delineated in Table III is a proposed sequence of steps in a qualification test procedure for US high-strength filters for incorporation into a code. Individual descriptions of the bases for each test are summarized in Table AI. More detailed specifications of the recommended test conditions are also located in the Appendix. The selected tests and their performance sequence are intended to augment aspects of Section FC relevant to high-strength requirements, while retaining the overall simplicity and cost-effectiveness of the qualification process. Step 3 aids in ensuring that all fabrication materials meet the maximum continuous temperature rating of the filters. The resistance-to-pressure test specifies a value of minimum proof strength high enough to be useful for the calculation of useful factors of safety for filters in their service locations for most foreseeable applications. All together, Steps 3 - 6 take the effects of aging and fatigue into account via accelerated simulation of loadings that wet, dust-loaded filter packs could need to sustain during service: loadings such as thermal, mechanical (both static and dynamic), and structural. Requiring each of four filters to complete the seven-step process, ensures performance meriting the designation “high strength“. Not included in the test sequence is a resistance to shock-wave impingement.

Table III: Proposed sequence of steps in qualification test procedure for US high-strength filters.

Step	Performance Characteristic	Existing Test Standard Template , or New Test Conditions
1	Resistance to rated airflow	Par. 5110 in Section FC of AG-1
2	Test aerosol penetration at rated airflow and at 20% of rated airflow	Par. 5120 in Section FC of AG-1
3	Static resistance to elevated temperature, (in oven)	120 ± 3 °C for 20 h
4	Resistance to pressure, (in water flow at 60 °C)	rise to Δp of 15 kPa in 1min dwell of Δp of 15 kPa for 1 h fall in Δp to 0 kPa in 1 min
5	Pack tightness	Par. 8.1.2 of IEST-RP-CC001.4 [13, 14]
6	Resistance to rough handling	Par. 5130 in Section FC of AG-1
7	Test aerosol penetration at 20% of rated airflow only	Par. 5120 in Section FC of AG-1

Water Flow Apparatus for Resistance-to-Pressure Test

Over the course of a Spring semester, fifteen mechanical engineering technology students at New Mexico State University (NMSU) designed and built a prototype filter rig for 610 x 610 x 292-mm (Size 5) filters based upon a recirculating water loop concept. The rig is to be evaluated as a forerunner of a more compact prospective test rig suitable for the resistance-to-pressure test of Table III. The design rendering is shown in Fig. 1 and the as-built rig in Fig. 2. The nominal performance specifications are listed in Table IV.

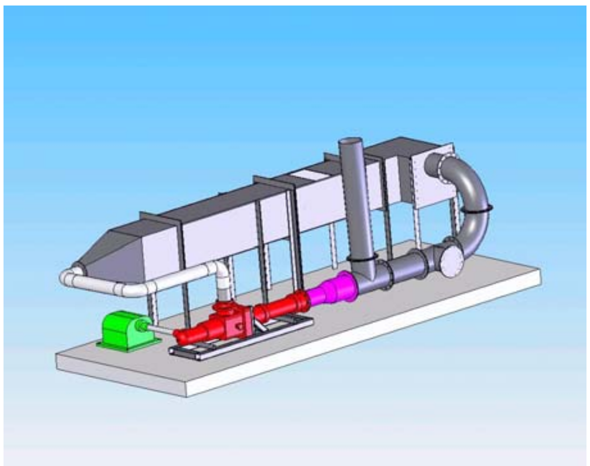

Figure 1: Design rendering of water loop test rig with initially foreseen stand pipe.

Figure 2: Photo of as-built test rig without stand pipe.

Heart of the rig is a single-stage, axial-flow irrigation pump that delivers the water flow to a round-to-square transition section. Located just downstream of the transition are straighteners and a screen that serve to condition the flow at the test section entrance. Downstream of the test filter is an elbow of the same 0.585x 0.585-m (23.5 x 23.5-in) cross-section, which connects directly to a vertically offset 0.303-m (12-in) diameter pipe that returns the flow to the 0.203-m (8-in) pump inlet. An optional stand pipe at the pump inlet was foreseen in the design for cases of possible pump cavitation at the higher operating temperatures.

The pump speed is varied via a mechanical belt-drive system driven by an electric motor. The filter is installed in the test section from the top through an opening underneath a hinged cover. The opening is one-half meter upstream of the elbow at the downstream end of the test section. With the working gasket located on the downstream side of the test filter, the pressure drop across the filter presses it onto the sealing surface within the duct, acting effectively to both hold and seal the filter in its test position.

Table IV: Nominal performance characteristics and utility requirements for water loop test apparatus.

Parameter	Value
Testing temperature range	20 - 60 °C (70 - 140 °F)
Max. differential pressure across test filter at $\dot{V}$ = 114 m^3/h (500 gal/min)	7.5 kPa (30 in w. g.)
Max. volume flow at $\Delta p_{filter} = 0$	160 m^3/h (700 gal/min)
Max. volume flow at Δp_{filter} = 15 kPa (60 in w. g.)	45 m^3/h (200 gal/min)
System working fluid	liquid H_2O
Total volume of working fluid in system	2 m^3 (530 gal)
Max. power rating of pump drive motor	11 kW (15 hp)
Range of pump speed	350 - 2800 rpm
Max. power rating of electrical heating system	10.5 kW

Results of Preliminary Rig Performance Evaluation

In order to evaluate the effectiveness of using water as a working fluid in place of air, three vintage, clean Size 5 HEPA filters verified in the Spring of 1979 as nuclear grade (at the HEPA Filter Test Facility in Rocky Flats) were placed in the test rig to simulate resistance-to-pressure tests similar to that of Section FC. Water temperatures were maintained within the range of 35 ± 2 °C. Filtration efficiency measurements were performed in air at rated and at 20% of rated flow in a separate test rig, before and after the water test. A six-stem Laskin generator and an ATI Model TDA-2C photometer were employed. The DOP droplets were assumed to have the commonly accepted count mean diameter of 0.4 µm and mass mean diameter of 0.7 µm. The minimum recommended droplet/air concentration of 100 mg/m^3 was readily met. Results of these preliminary investigations of test rig performance are summarized in Table V.

The most important implication from these tests is that the resistance to water flow varied greatly among the test filters and decreased significantly with time for two of the three during the 1-h duration test. Under the then temporarily restricted pump flow conditions, it was not possible to successfully hold the filter pressure drop constant at 10 kPa during Tests 1 and 2. In the first case, primarily because of catastrophic damage to the filter pack that began within 5 min after the test start. For all three filters, the filter pressure drop was highest at the beginning and decreased with time. The water flow was increased in attempting to hold the Δp constant. This was successful only in the case of Test 3, where the filter exhibited the highest initial Δp and the slowest decrease with time.

Significant loosening of the filter packs was evident only for Test 1. This indicates that the filter Δp was not high enough to ensure that any potential loosening of the filter pack was made evident during the relatively short 1-h test duration. Or alternatively, that the test duration was not long enough to make pack loosening evident, for the low test pressure drop applied. Generating a sufficiently high pressure drop quickly and economically is a challenge also faced by concepts that employ airflows and water sprays. In one rig, the issue has been successfully overcome by reducing the mean water droplet diameter to the smallest diameter practical, < approx. 5 µm, and delivering water to the spray nozzles at rates of up to 88 g/m^3 of saturated airflow [11]. The results of the pre- and post-test filtration efficiency tests prove, that at least for the case of vintage, clean filters, the water rig concept is capable of testing units of conventional design beyond their burst strength limits.

Table V: Summary of preliminary results from rig shakedown testing.

Filter Test (No.)	Δp at rated air flow (Pa)	Δp_{avg} in water flow during 1- h test (kPa)	Visible damage	initial η at rated air flow (%)	final η at 20% of rated airflow (%)
1	249	1.24	extensive	99.985	$\cong 0$
2	237	1.67	none	99.987	99.98
3	217	2.48	none	99.99	99.95

Summary

Some progress is being made in evaluating options that might eventually allow filter users with special applications to implement high-strength filters as an important safety technology in air-cleaning systems of US nuclear facilities . Four major prerequisites to implementation were identified, two of which were partially addressed by the work performed.

Toward addressing their absence in codes, prospective high-strength filter performance specifications were proposed for consideration and discussion. A prototype rig based upon a water loop concept was designed and built to gather data needed to help develop a qualification test rig for performing a suitably stringent and cost-effective resistence-to-pressure test. The rig could serve multiple purposes. First, to fully evaluate the practical feasibility of the water loop concept as a means to accomplish the resistance-to-pressure test. Should its practicality appear to become viable, its second function would be to help clarify how to quickly and economically generate sufficiently high pressure drops for the resistance-to-pressure test of high-strength filter units. Preloading of test filters was one option identified for possible future investigation.

Preliminary evaluation of the water loop test rig included three simulated “resistance-to-pressure” tests of clean, vintage, Size 5, conventional deep-pleat filters from three US manufacturers.

Conclusions

Identifying the aspects remaining as major prerequisites to prospective high-strength filter implementation provides a basis for planning future work. The proposed qualification test standards for high-strength nuclear-grade HEPA filters opens up the topic for discussion and evaluation by manufacturers, practitioners, and users. Realization of a prototype test rig represents a major step toward being able to judge the viability of the water loop concept for qualification of filter performance as being of ”high strength”.

The results of preliminary testing indicate that the water loop test rig concept is readily capable of pressing vintage, clean filter units of conventional designs to their structural limits. The advantages and disadvantages of the proposed multi-test qualification sequence need to be more fully investigated using the test rig, before any far reaching conclusions can be drawn with respect to the qualification of higher strength filter units. The wide variability in filter resistance to water flow and its time dependency represent a particular, yet not surprising, challenge to be addressed early in the ongoing process.

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Joseph Cruz	Raul Griego	Kevin Lindsey	Jeff Nelson	Ernest Udero .

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Appendix
Proposed Qualification Test Specifications

The following are detailed recommended specification of test conditions for high-strength HEPA filters proposed to be incorporated into ASME AG-1.

Fx-5xxx RESISTANCE TO PRESSURE OF HIGH-STRENGTH FILTERS

The high-strength filter shall be tested for resistance to pressure in a re-circulating water flow apparatus capable of testing in accordance with Table Fx-5xxx-a. Prior to being tested for resistance-to-pressure, the clean filter shall be first conditioned in an oven with dry air at 248 ± 5 °F (120 ± 3 °C), under atmospheric pressure for 20 hours minimum. *After being conditioned, each filter shall be preloaded with particles to the maximum particulate loading of Table Fx-5xxx-b; just prior to being tested for resistance to pressure. The particles shall be of xxxxx and have a mean diameter of xx mm. (optional)*

After being conditioned *and preloaded*, the filters shall withstand the differential pressure in water flow listed in Table Fx-5xxx-a without rupture of the filter media.

Within 15 minutes after completion of the resistance-to-pressure test and while still wet, the filter shall be tested for pack tightness according to Paragraph 8.1 of IEST-RP-CC001.4.

Within 30 minutes after completion of the pack tightness test and while still wet, the filter shall undergo the resistance to rough handling test.

Within 15 minutes after completion of the resistance to rough handling test and while still wet, the filter shall meet the requirement of Fx-5x20 at 20% airflow.

TABLE Fx-5xxx-a
TEST GROUPS AND SEQUENCE FOR HIGH-STRENGTH FILTERS

Group	Quantity	Requirement	Test Paragraph
I	4	Resistance to rated airflow	Fx-5x10
		Test aerosol penetration at rated airflow and at 20% of rated airflow	Fx-5x20
		Resistance to pressure	Fx-5x40
		Resistance to pack loosening	RP-CC001.4
		Resistance to rough handling	Fx-5x30
		Test aerosol penetration at 20% of rated airflow only	Fx-5x20
II	1	Resistance to spot flame (See Note 1)	Fx-5x60
III	3	Resistance to heated air (See Note 1)	Fx-5x50
		Test aerosol penetration at rated airflow only (See Note 1)	Fx-5x20

Notes:

1. UL-586 qualification is an acceptable substitution for Group II and III qualification tests. If the filter is qualified to UL-586, then the total filter quantity submitted to the Filter Qualification Test Facility shall be four (4) filters total.

TABLE Fx-5xxx-b
RESISTANCE-TO-PRESSURE TEST CONDITIONS AND REQUIREMENTS 0F HIGH-STRENGTH FILTERS

Test Conditions	Test Requirements
Temperature of water	140 ± 5 ˚F (60 ± 3 ˚C)
Pressure differential across filter	61 ± 2 in. of water (15 ± 0.5 kPa)
Time to reach pressure differential	1 minute, maximum
Time duration at sustained differential pressure	1 hour, minimum
Time to remove pressure differential	1 minute, minimum
Water flow	That required for producing the above pressure differential
Preloading or loading of filter (*optional*)	*To be determined*

Table AI: Function of qualification tests in sequence proposed for US high-strength filters.

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 max. particle penetration requirement at relevant flows
3	Static resistance to maximum rated temperature for continuous service	Verify resistance to maximum rated temperature for continuous service Accelerate off-gassing of volatiles from adhesive/sealant, filter medium, and gasket, before resistance-to-pressure test
4	Resistance to pressure	Represent a safety factor 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 factor-of-safety calculations Ensure that any potential loosening of the filter pack that could occur during service is made evident
5	Pack tightness	Verify that pack loosening after the resistance-to-pressure test does not exceed a maximum allowable limit
6	Resistance to rough handling	Induce mechanical interactions between separators and filter medium pleats, after the resistance-to-pressure test Accelerate fatigue of the filter medium, after the resistance-to-pressure test
7	Test aerosol penetration at 20% of rated airflow only	Verify that filter meets maximum particle penetration requirement at relevant flow after test sequence of resistance to maximum rated temperature, to pressure, and to rough handling