A New Concept for Qualification and Quality Assurance of HEPA Filter Mechanical Reliability

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Abstract

High Efficiency Particulate Air (HEPA) filter units represent an indispensable component of nuclear air-cleaning systems. As typically manufactured in the US, they can be presently characterized as fragile elements, whose field reliability is dependent upon an inherently weak and brittle constituent, the glass-fiber filter medium. Moreover, they remain subject to variations in functional reliability resulting from fluctuations in manufacturing processes over time, transport from manufacturer to user, and handling between assembly line and their service locations; not to mention both prior and actual service operating conditions.

Qualification of a filter design as nuclear-grade is in part accomplished via the so-called "resistance-to-pressure test". It is essentially a proof test of new, clean filters conducted at an elevated filter pressure drop under extended exposure to the flow of air laden with fine water droplets. Its function is to simulate the magnitude of the mechanical stresses that the wet, fatigued filter medium and the pack adhesive of aged, dust-loaded filter packs could have to sustain under normal operating conditions. As currently performed, it cannot be employed on-site by filter end-users to periodically sample and control the quality of incoming filters, or the reliability of aged and fatigued filter units already in service.

Experiments have shown that clean water flowing through a HEPA filter can be used to create pressure drops equivalent to those generated by airflow, but at much lower volume flows. This translates into less power needed to produce the pressure drop required for a proof test. Additionally the required test apparatus would be simpler and more compact than one using water-droplet-laden air.

This paper describes a proof-of-concept study of proposed water flow test rigs for on-site qualification of nuclear-grade HEPA filters by end-users. Results of sample calculations presented for typical filter safety factors indicate the need for implementing not only such a test rig, but also more stringent filter proof-test conditions. Experiments were run using 610 x 610 x 292-mm HEPA filters to determine pressure drop as a function of water flow through the filters. Test results were used to perform a preliminary design and cost analysis of the proposed test rig. Comparisons were made to the current airflow proof test rig. A test rig based on water flow could be utilized in-house by filter end-users for cost-effective quality assurance testing. It might also serve filter manufacturers in the development of improved filter units. Moreover, it could also eventually replace the current resistance-to-pressure test employed to help qualify nuclear-grade HEPA filters.

Introduction

Current US codes and standards covering nuclear-grade filter elements having a glass-fiber medium are arguably the world's most comprehensive. However, among designs available worldwide, filter units built to US code specifications rank, at best, a distant third in mechanical and hence functional reliability.

This can primarily be attributed to the continued use of non-reinforced filter media of glass fiber, whose strength characteristics lie orders of magnitude below those of all other filter-unit fabrication materials(1). Another weakness results from a lack of measures to prevent the loosening of deep-pleat filter packs under operating conditions such as high air velocity, elevated temperature, and high air humidity. The world's most reliable filter design with a glass-fiber medium incorporates both a filter medium reinforcement and effective measures to inhibit pack loosening(2), for example.

Current US codes and standards do not fully recognize filter units in their service location as structural elements whose functional reliability is contingent upon their capability to maintain their physical integrity under a broad spectrum of operating conditions. A reliability – that in the case of filter units with a non-reinforced filter medium of glass fiber – can be significantly and adversely affected by numerous factors, which for the most part lie outside the direct control of the filter end-user. In contrast, air-cleaning system ductwork is generally recognized as a structural element whose code specified performance characteristics correspondingly do include suggested factors of safety(3). Similarly, filter mounting frames are required to sustain, without permanent deformation, an impact loading of 20.7 kPa (3 psi)(3) corresponding to a tornado-induced pressure pulse, while the filter units they hold in place are not.

Specifically, current US codes covering nuclear-grade filter units:

- mandate no factor of safety† for filters.

- do not take the detrimental effects of service-related aging and fatigue on filter medium strength into account.

- ignore the significance of fluctuations in filter reliability between production lots, which result from variations in the manufacturing processes of both the filter medium and the filter units themselves.

- fail to consider that adverse operating conditions sustained by filters sequentially, in combination, or both, can result in cumulative deteriorations in filter-unit burst strength.

- require requalification of a given filter design only after every five years, and moreover, fail to mandate the qualification testing of each size of a given design.

Prerequisites to Ensuring Filter Reliability

All the noted deficiencies leave the filter end-user in a situation where filter units offered on the open market as nuclear-grade may or may not fully satisfy code requirements. The user can only take the word of the manufacturer upon receipt of each delivery lot. Even if procured filter units do meet code specifications, there still exists the risk of filter functional failure in service, due to current insufficiently stringent filter qualification test specifications. The lack of a mandated factor of safety is a particularly acute code deficiency that safety-conscious end-users are left to address individually.

Actually, precedents exist for requiring a factor of safety for nuclear air-cleaning system (ACS) components. For instance, typical safety factors for ductwork – which must also withstand the maximum pressure generated by the blower – suggested by the same ACS component code(3) include values of 1.1 and 1.67. The requirement for ductwork was simpler to implement than one for filters will be, since the typical fabrication material for ductwork, i.e., metal, is clearly not susceptible to significant degradations in strength characteristics caused by aging, fatigue, and adverse operating conditions, as are glass-fiber filter media.

Ideally, end-users would have a simple and economic means to sample not only new, incoming filter units as to their mechanical suitability for the intended application, but also filter units in service as to their residual reliability. Filter evaluation according to current code qualification procedures does not appear to represent an economically viable solution to accomplish these, as noted in the next section.

To ensure filter reliability, users must be able to statistically verify either a proof strength or the average burst strength for the filter units in question. To determine a suitable proof strength, or to make practical use of burst strength values, first requires the filter user to set an acceptable factor of safety. Then to quantify – by evaluation or estimate – the deterioration in filter medium strength characteristics expected to result from aging, fatigue, and any anticipated adverse filter operating conditions.

Current Code Qualification Procedure Related to Implementing a Filter Safety Factor

One step in the code-based process of qualifying new, clean HEPA filter units in the US as nuclear-grade, involves the so-called "resistance-to-pressure" test. This is a proof test conducted for 1 h at an overpressure of 2.5 kPa (10 in w.g.) during exposure of the test filter to a flow of air laden with 16 ± 4 g of fine water droplets per m^3 of water vapor saturated air. The criterion for successfully passing the test is a maximum particle penetration of 0.03% at 20% of rated airflow in the post-test, wet condition. The filter units so tested are thus exposed simultaneously to free moisture and a slight over-pressure. Based upon a typical maximum blower-generated pressure drop of 2.5 to 3.8 kPa (10 - 15 in w.g.), this would correspond to a safety factor of at most one (1) for new, wet filters in a typical US nuclear ACS. The corresponding safety factor for wet filters from the same production lot, installed at their service locations and in other than in a new condition would be significantly lower.

However, it is its complexity and costs, as well as its lack of sufficiently high proof pressure capability and lack of applicability for field implementation that make this test unsuitable to serve as a basis for users to ensure filter reliability. A viable proof test for filter users must be free of such drawbacks.

† A factor of safety for HEPA filters should be based - at a bare minimum - upon the maximum pressure drop that can be generated by the system blower.

Concept for Proof Test Apparatus

In order to provide filter end-users with an economically acceptable means of evaluating the mechanical reliability of sample filter units from delivery lots or filter banks, an apparatus using water as the working fluid has been proposed. Though intended as a proof test rig, with only minor modifications it could also be employed to perform burst strength tests. It is based upon test data showing that water flowing through a nuclear-grade HEPA filter can be used to create pressure drops equivalent to those generated by airflow, but at much lower volume flows(4). This is indicated in Fig. 1.

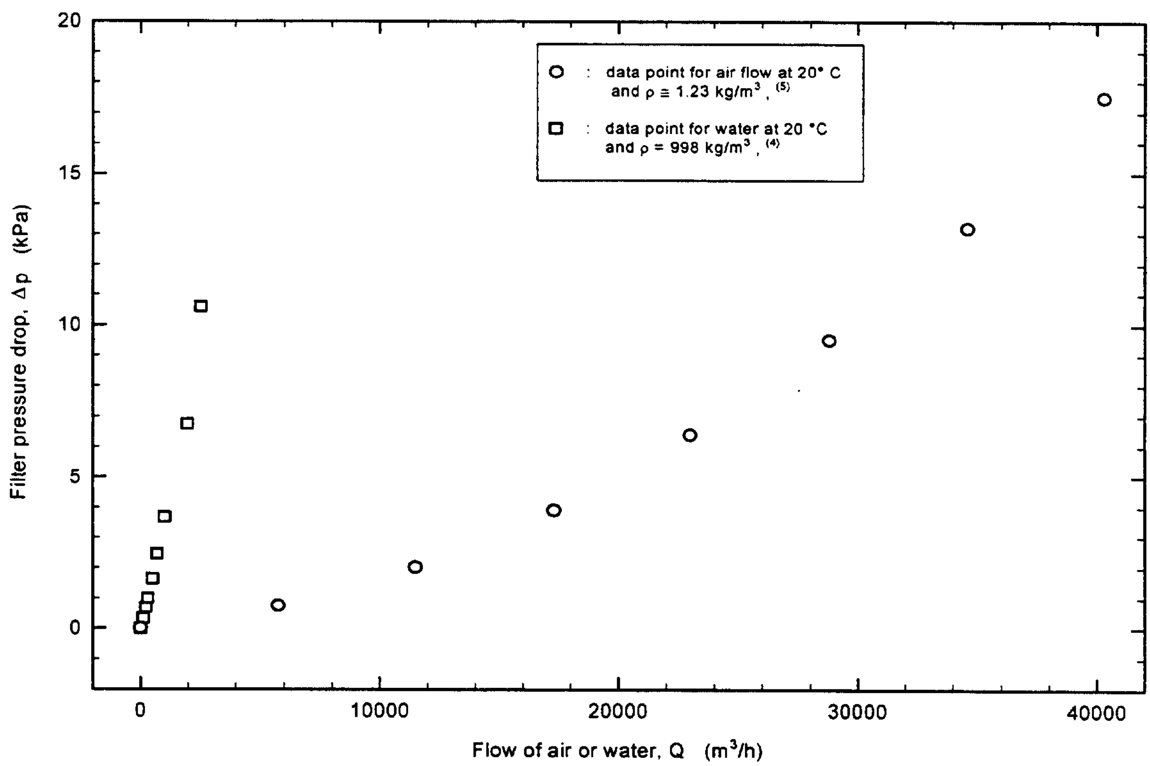

Figure 1 Flow resistance curve for a 610 x 610 x 292-mm nuclear-grade HEPA filter in water flow compared to one in airflow.

A schematic of the proposed apparatus is illustrated in Fig. 2. Water is drawn from the reservoir by a sump pump and proceeds through a pipe and diffuser to the HEPA filter. The water exits the filter, is discharged into the reservoir and recirculated through the system. Appropriate instrumentation, such as pressure transducers and a flow meter, is used to measure the pressure drop across the filter and the flow of the water.

Such a test rig could be used to verify the proof strength of all standard-size nuclear grade HEPA filter unit designs having a glass-fiber medium. It offers the possibility of performing the function of the current "resistance-to-pressure" test at both a lower investment and a lower operating cost. It also would have much smaller space requirements. The need for a blower sized to deliver 10 times the rated airflow of the largest size filter to be tested, at a total system pressure drop of approximately 6 kPa (24 in w.g.), would be eliminated. Moreover, the complexity of rig operation has the potential to be greatly reduced. There would be no need for steam injection or the difficult measurement of airstream liquid water content, for example.

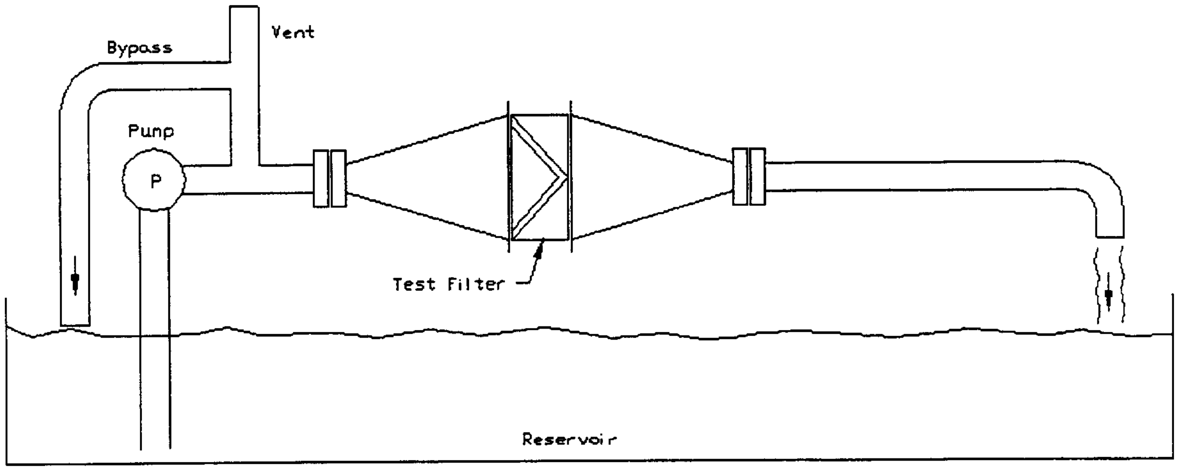

Figure 2 Schematic of a proof test rig for nuclear-grade HEPA filter units employing water as the working fluid.

Experimentation to Obtain Flow Resistance Curves for Design of Proof Test Rig

The size and capacity of the pump needed to generate the necessary pressure drop across the test filter depend upon the filter-unit flow resistance characteristics. Thus, in order to evaluate the feasibility of such a test rig, so-called flow resistance curves for prospective test filters need to be obtained. The apparatus of Fig. 3 was utilized to obtain measurements of filter pressure drops up to approx. 7.5 kPa (30 in w.g.) for water flows up to 114 m^3/h (500 gal/min).

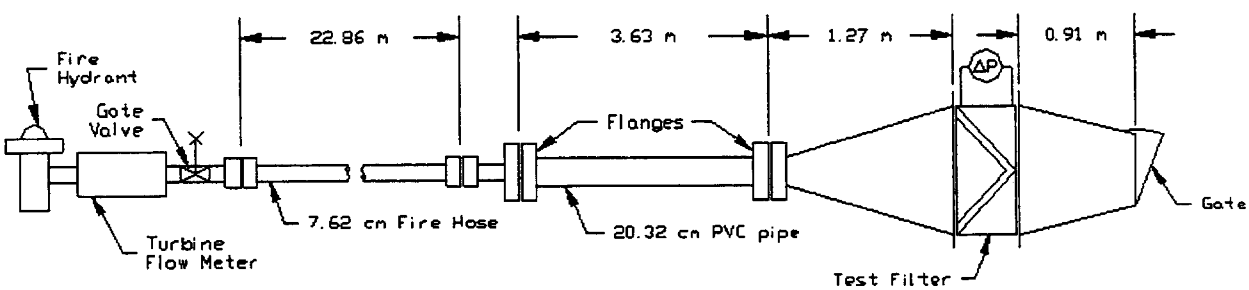

Figure 3 Schematic of the apparatus set-up used to obtain flow resistance curves for 610 x 610 x 292-mm nuclear-grade HEPA filters in water flow.

The flow of water was horizontal and the test filter mounted with the ends of the pleats in a vertical orientation. The water level on the filter downstream side was maintained at or above the top of the filter using the gate at the end of the discharge duct. The water flow was determined using a timer together with a turbine flowmeter that yielded a volume, representing a constant flow integrated over time. The pressure drop across the filter was read directly as the difference in height of two water columns connected to pressure sampling ports on the up- and downstream sides of the test filter. Two nuclear-grade filter units, one from each of two manufacturers were tested. Readings were taken twice for each; first with the filter in a clean condition and subsequently after loading with fine particles of soapstone (talc).

Pressure drop and flow were typically measured at constant flow values beginning at the lowest level. The flow was increased after each pressure measurement up to the maximum value; after which a final reading at the initial flow was again taken. The resulting flow resistance curves for the two filters in a clean condition are shown in Fig. 4. The Δp across both conventional filters is seen to reach 5 kPa (20 in w.g.) at less than or equal to 114 m^3/h (500 gal/min).

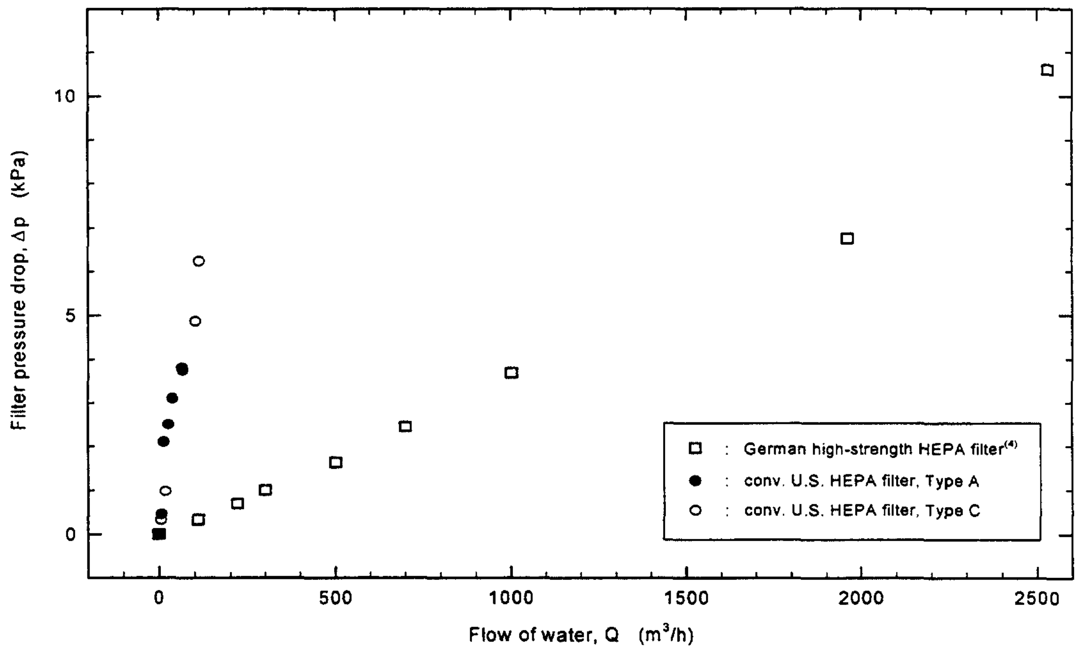

Figure 4 Flow resistance curves for clean 610 x 610 x 292-mm nuclear-grade HEPA filters in water flow from two US manufacturers (Type A and Type C) compared to that of a high-strength German design.

The corresponding flow at 5 kPa (20 in w.g.) for the curve of the high-strength filter unit (shown in both Fig.'s 1 and 4) is seen to be approximately 15 times higher. There are several possible explanations for this. One is the different orientation of the test filter with pleat ends horizontal and water flow vertically upward. Another is the filter pack, which consisted of a reinforced filter medium and stiffer separators configured to inhibit pack loosening. The high-strength pack is less prone to deformation of the filter medium onto the separators, making it less likely to seal itself off to the flow of the working fluid. Investigation of high-strength filter units in horizontal water flows would be necessary to clarify this. High-strength units were not used in the testing reported on here.

Particle loading of test filters was accomplished by injecting a suspension of 1000 g of particles per 8 liters (ℓ) of water at a rate of 2 ℓ/min into a 55-m^3/h (250-gal/min) flow upstream of the test filter. To better facilitate particle suspension, several drops of a surfactant were mixed with the 8 ℓ of water prior to adding the particles.

The flow-resistance curve for one of the conventional filter units (Type C) after loading with approximately 1.5 kg of fine-particle soapstone is plotted in Fig. 5. It is noted that less than 30 m^3/h (132 gal/min) of flow are required to generate a pressure drop of 5 kPa (20 in w.g.) across the test filter in a preloaded condition as compared to approximately 114 m^3/h (500 gal/min) for the clean condition. This corresponds to a reduction in the water flow required by almost a factor of four (4). The data points for this filter in a preloaded condition were different from the rest in that they were taken in steps of decreasing flow. This may have resulted in shifting the curve at lower flows slightly to the left by less than an estimated 10%.

The flow-resistance curve for the Type A filter after loading is not shown, as the filter medium sustained damage at an unknown time and low flow level leading to invalid data for essentially the entire resistance curve. One resultant benefit of the damage was confirmation that the same failure modes and mechanisms for deep-pleat filter units can occur in water flow as in airflow of high humidity. The two classical failure modes were clearly evident: tearing of pleat ends along the pleat lengths on the filter downstream side and tearing of the sides of the pleats through the pleat depth, close to the frame. Significant loosening of the filter pack was also observed. Clearly, substantial decreases in filter medium tensile strength, primarily due to its wet state can be expected to have played a major role in the failure, as did the loosening of the filter pack.

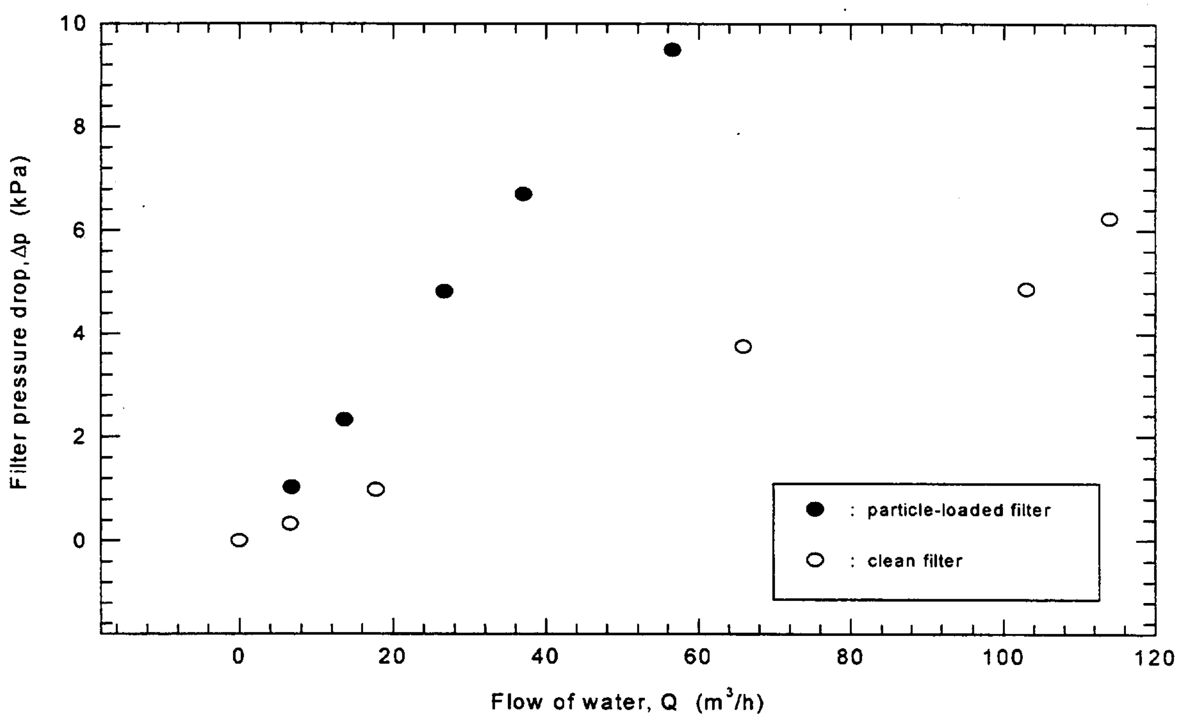

Figure 5 Water flow resistance curves for a 610 x 610 x 292-mm nuclear-grade HEPA filter (Type C) in clean and in particle-loaded condition.

Preliminary Design of Proof Test Rig

Based upon the flow resistance curves obtained for clean and preloaded 610 x 610 x 292-mm filter units in water flow, a preliminary design of a water flow based proof-test rig was carried out. Illustrated in Figs. 6 and 7 are the features of the resulting design for maintaining a constant pressure drop of 5 kPa (20 in w.g.) across conventional U.S. deep-pleat filters [rated flow = 1700 m^3/h (1000 ft^3/min)] in a wet condition

The design utilized a sump pump, the discharge of which was routed through the inlet housing of the test section with a riser exiting on the opposite side. This riser serves as a head tank with an additional by-pass function in the form of an overflow return to the reservoir. The pump discharge line within the test section inlet is perforated to help distribute the water flow uniformly across the filter face. The filter housing is provided with pressure taps for measuring the test filter pressure drop.

An overflow spout at the end of the test section discharge was used to keep the water flow level above the top of the test filter. Since water would be in free fall below the spout, the stilling channel section allows any entrapped air to rise to the water surface quickly. A vortex breaker is foreseen in the stilling channel outlet, from where the water enters a *Parshall* (critical flow) flume for flow measurement and subsequently returns to the sump via the reservoir.

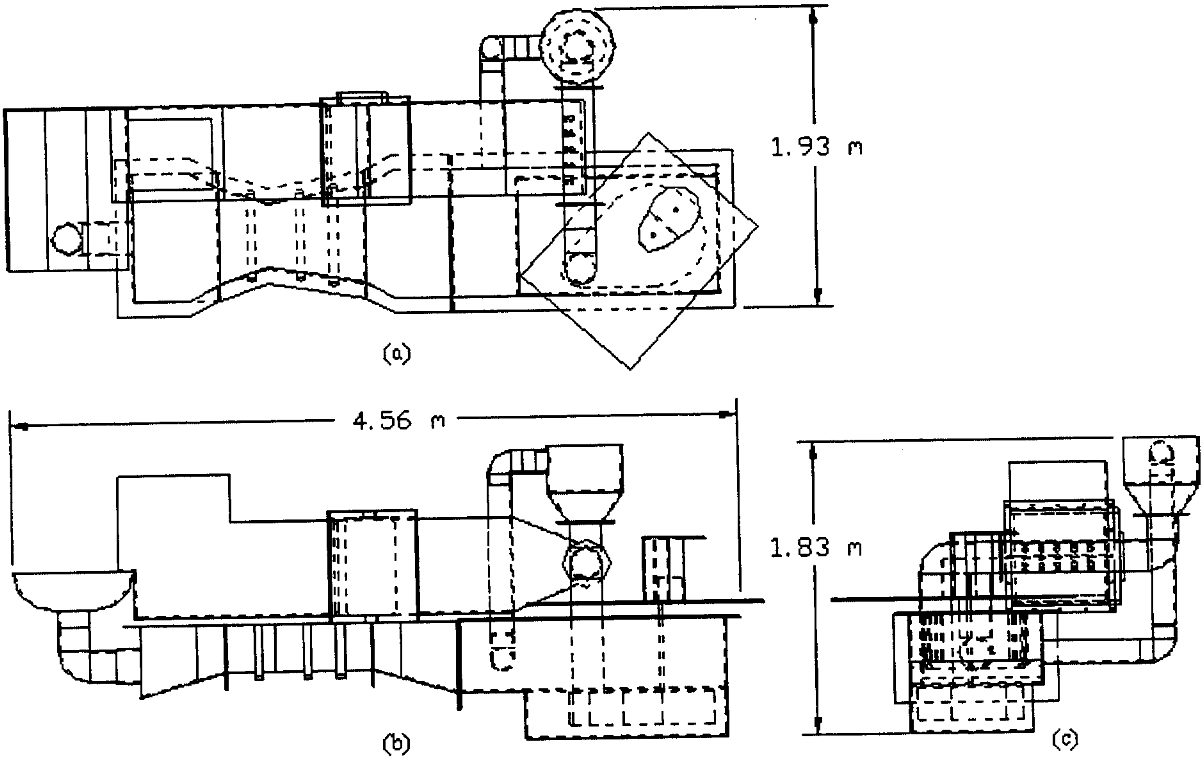

Figure 6 Top (a), side (b), and end (c) views of proposed water flow test rig.

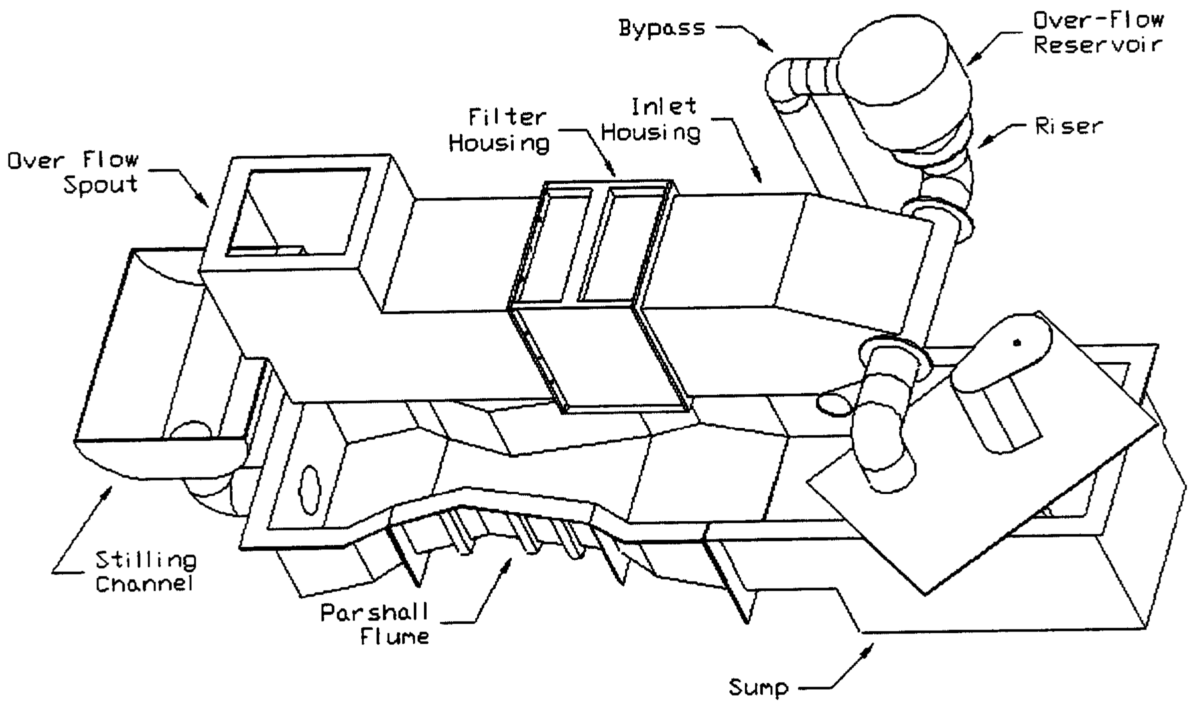

Figure 7 Isometric view of proposed water test rig.

Estimated Costs of Water Based Test Rigs and Comparison to Those of Current Apparatus

Table 1 summarizes the characteristics and estimated costs of water flow based test rigs for clean and preloaded filter units, as compared to the current "resistance-to-pressure" test. All estimated test rig costs were based upon the assumptions for the proof pressure drop and the filter type given above in the rig description. Costs for test rigs capable of testing other filter designs, such as high-strength or high-flow capacity types may be correspondingly higher, due to filter flow resistance characteristics different from those used in the above preliminary design.

The airflow test rig was assumed to be constructed of 14-gauge stainless steel sheet metal with an overall surface area of 69.7 m^2 (750 ft^2). Based upon the estimated area, the material cost was approximately $35,000. The costs of the blower and 50 HP-motor were projected to total approximately $13,500. The filter housing would cost $2,200 for stainless steel. The estimate to assemble the airflow test apparatus was an additional $10,000.

The water flow test rig utilizing clean HEPA filters was designed using primarily fiberglass and high-density polyethylene. The only steel components were the pump and filter housing. The pump, driven by a 5-HP motor, and the filter housing, cost $3,022 and $2,200, respectively. The costs estimated for the flume, sump, and the remaining housings, reservoir, piping, and fittings were $765, $1,110, and $4,000, respectively. The estimate to assemble the test rig was approximately $2,000. These fabrication costs thus totaled $13,097. The water-based rig for test filters preloaded with particles had estimated costs totaling $10,445, which were thereby approximately 20% lower than those of the rig for testing clean filters.

Table 1 Characteristics of airflow "resistance-to-pressure" test rig and of water flow test rigs for clean and preloaded filters.

Apparatus	Size		Weight	Power	Est. Cost
	Dimensions	Volume	(kg)	(kW)	($ U.S.)
Airflow Test Rig (test filter clean)	9.1 m x 4.3 m x 1.8 m high	70.4 m^3 (2520 ft^3)	19050	180	60,700.0 0
Water Flow Test Rig (test filter clean)	4.6 m x 1.9 m x 1.8 m high	15.7 m^3 (554 ft^3)	590	8	13,097.0 0
Water Flow Test Rig (test filter preloaded)	4.0 m x 1.8 m x 1.6 m high	11.5 m^3 (406 ft^3)	550	6	10,445.0 0

The fabrication cost of both water flow test rigs were 78% less than that of the airflow test rig. Not only would the initial costs be less, but so would the operating costs. The airflow test rig utilizes a 50-HP blower motor and steam generation, which accounts for 180 kW of required power. The two water flow test rigs only use a 5-HP or a 2-HP pump motor. Two (2) kW for a heater to attain a water temperature of 35 °C plus 2 kW for miscellaneous instrumentation are included in the total power requirements to operate the water test rigs. This results in the 8 kW and 6 kW of power, which are lower than the power requirements of the airflow test rig by more than a factor of 20.

Calculation of Safety Factors

Safety factor evaluation requires values for certain parameters, some of which must be based upon assumptions. The assumptions underlying the following calculations include:

- a typical filter service life of n = 24 months,
- an average value for the maximum pressure drop of the system blower, $\Delta p_{b\,max}$, is 3 kPa (12 in w.g.),
- $\Delta p_{b\,max}$ can appear across wet filter units at their service locations,

- average decreases in filter medium tensile strength during service are 0.8% per month due to aging[1] (monthly aging factor, $F_a = 0.992$) and 0.9% due to fatigue[6] (monthly fatigue factor, $F_f = 0.991$, at locations of highest stress),

and

- a proof test pressure drop, $\Delta p_{proof} = 2.5$ kPa (10 in w.g.), for filter units in a wet condition, based on the current "resistance to pressure" test specification[3].

There are at least two approaches to safety factor calculations. The more complicated and thus less practically suitable one requires knowledge of the failure mode involved and its stress model. Also required are values for initial filter medium tensile strength and empirical factors that quantify filter medium strength losses due to pleating and to moisture.

The simpler method, used here, requires only the information listed under the assumptions given above. Correspondingly, the filter unit safety factor after n months of service, S.F.(n), can be calculated by

$$S.F.(n) = \frac{RS_a(n) \cdot RS_f(n) \cdot \Delta p_{proof}}{\Delta p_{b\,\max}}, \tag{1}$$

where,

$RS_a(n) = (F_a)^n$, residual filter medium tensile strength due to aging: as a fraction of the initial strength; after n months,

and

$RS_f(n) = (F_f)^n$, residual filter medium tensile strength due to fatigue: as a fraction of the initial strength; after n months.

For the given values of the variables on the right hand side of Eq. (1), the safety factor decreases from 0.83 to 0.55 during the time between 0 and 24 months of service. This example calculation – based upon realistic assumptions and average losses in filter medium tensile strength with time[1,6] – indicates how inadequate the current proof-test Δp requirement is for nuclear-grade filters.

Calculation of Proof Δp Necessary to Attain a Required Safety Factor

Equation (1) can be solved for Δp_{proof} such that

$$\Delta p_{proof} = \frac{S.F.(n) \cdot \Delta p_{b\,\max}}{RS_a(n) \cdot RS_f(n)}. \tag{2}$$

Use of Eq. (2), S.F.(n) = 1.5, and n = 24, in addition to the above values for $RS_a(n)$ and $RS_f(n)$, yields $\Delta p_{proof} = 6.8$ kPa. Thus, the proof Δp necessary to ensure a safety factor of 1.5 after 24 months of service is 6.8 kPa (27 in w.g.), or a factor 2.7 times greater than the current code specification. The initial safety factor value, S.F.(n = 0), is found to be 2.26.

In comparison, a safety factor of 1.5 for the most reliable nuclear-grade filter design available with a glass-fiber medium requires a proof Δp of 15 kPa (60 in w.g.). This, based on the typical $\Delta p_{b\,\max}$ of 10 kPa (40 in w.g.) of German nuclear air-cleaning systems.

Conclusions

For all practical purposes, current US codes delineating qualification test specifications for nuclear-grade HEPA filter units implicitly leave it up to the filter end-user to specify and achieve a factor of safety necessary to prevent filter functional failure resulting from physical damage to the glass-fiber filter medium during service.

The results of preliminary investigations summarized here indicate that a proof test rig using water as the working fluid could offer filter users an economical means to help ensure an adequate safety factor throughout filter-unit service life. It would be particularly cost effective, as compared to the current "resistance-to-pressure" test. Preloading test filters with particulate prior to the proof test could further reduce both investment and operating costs of the proposed test rig. Such a rig has potential application for testing filter sample populations selected not only from incoming delivery lots, but also from banks of aged filter units during or at the end of service.

The rig could also be easily adapted to measure the burst strength of filter units in a wet condition. That the classical failure modes and mechanisms of deep-pleat filters in humid-air flows also occur in water flow, makes the test rig attractive additionally as a failure diagnostic tool for the improvement of filter mechanical reliability under high humidity conditions. The rig might also find application by filter manufacturers for filter development and statistical quality control.

Evaluation of the flow resistance curves for separatorless filter designs and high-capacity types such as the mini-pleat would be needed to finalize the design of such a proof test rig. Curves for the various standard sizes of all nuclear-grade filter unit designs would also be necessary.

Both a filtration efficiency measurement and a leak scanning procedure to be performed before and after the proof test should be investigated as measures of filter performance in withstanding the proof test. A criterion for filter performance based upon an allowable upper limit for post-test looseness of deep-pleat filter packs should be developed.

If the filter-unit preloading option is selected, optimization of the particulate loading process should be addressed with respect to minimizing the cost of the particulate employed and the loading time required. The primary variables can be expected to include particle cost itself and variables that influence particle effectiveness in increasing pressure drop, i.e., material properties such as density and surface characteristics, as well as shape and size distribution.

Calculations based upon the realistic assumptions made here, yield filter-unit safety factor values of less than one (1) for US nuclear air-cleaning systems. This can help provide explanations for reported filter failures in service. For the given assumptions, attaining a minimum safety factor of 1.5 at the end of service life would require the proof pressure drop of the current "resistance-to-pressure" test to be raised, on average, by a factor of 2.7, up to 6.8 kPa (27 in w.g.).

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