THE CASE FOR IMPROVED HEPA-FILTER MECHANICAL PERFORMANCE STANDARDS REVISITED

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Abstract

Under benign operating conditions, High Efficiency Particulate Air (HEPA) filter units serve as reliable and relatively economical components in the air cleaning systems of nuclear facilities worldwide. Despite more than four decades of filter-unit evaluation and improvements, however, the material strength characteristics of the glass fiber filter medium continue to ultimately limit filter functional reliability. In worst-case scenarios involving fire suppression, loss-of-coolant accidents (LOCA's), or exposure to shock waves or tornado induced flows, rupture of the filter medium of units meeting current qualification standards cannot be entirely ruled out. Even under so-called normal conditions of operation, instances of filter failure reported in the literature leave open questions of filter-unit reliability.

Though developments of filter units with improved burst strengths have been pursued outside the United States, support for efforts in this country has been comparatively minimal. This despite user requests for filters with greater moisture resistance, for example. Or the fact that conventional filter designs result in not only the least robust component to be found in a nuclear air cleaning system, but also the one most sensitive to the adverse effects of conditions deviating from those of normal operation.

Filter qualification-test specifications of current codes, standards, and regulatory guidelines in the United States are based primarily upon research performed in a 30-year period beginning in the 1950's. They do not seem to reflect the benefits of the more significant developments and understanding of filter failure modes and mechanisms achieved since that time. One overseas design, based on such knowledge, has proven reliability under adverse operating conditions involving combined and serial challenges. Its widespread use, however, has faltered on a lack of consensus in upgrading filter performance standards.

One basis of the approach taken here is the premise that filter-unit mechanical failure needs to be prevented in humid airflow and at pressure drops as large as those which the system blower is capable of generating. To this end, improvements to current US filter codes and standards dealing with qualification testing are suggested. The introduction of a filter-unit factor of safety is viewed as indispensable, for example. Overall, recommendations are based upon more recently established failure modes and mechanisms of filters under adverse conditions of operation.

Though the focus is on guaranteeing the integrity of wet filter units for blower generated flows of humid air, reliability under more adverse operating conditions would also be increased. The realization of high-strength filter units overseas illustrates that the widespread implementation of more reliable filter designs can be driven only by more stringent performance standards. In particular, ones initiated by independent regulatory entities and resulting from close cooperation on the part of both filter users and manufacturers, working together with representatives of national codes and standards organizations.

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 (ACS's) also prevent the release of contaminated airborne particulate and gases to the surrounding environment. The required high particle removal efficiencies at relatively low pressure drops are made possible by the use of High Efficiency Particulate Air (HEPA) filter units.

As part of the containment barrier between contaminated zones and the environment, HEPA filters must perform reliably not only during normal facility operations but also under possible abnormal or so-called accident conditions. Filter units may be called on to withstand individual or combined challenges of elevated temperature, pressure drop, or high air humidity: ideally without performance decreases that would result in a loss of containment or confinement. In addition, filters must be free of leaks and nonflammable, as well as resistant to the effects of high radiation fields, rough handling, mildew, and vibrations caused by blowers, airflow, or earthquakes. Some applications also demand a degree of resistance to corrosion, shock waves, or degradation by organic solvents.

To fulfill the wide range of requirements and the high levels of performance expected from contemporary filter units has taken decades of improvements in filter construction materials and their manufacturing processes, particularly in the case of the filter medium. Brittle as well as fragile, and thus easily torn, the filter medium has invariably been, and remains yet, the weakest construction material in filter design. Only slight physical damage to it can cause substantial decreases in filter medium removal efficiency resulting in filter functional failure. It is above all due to media strength characteristics that conventional filter units in the United States retain a susceptibility to damage, not only during manufacture, shipment, and installation, but also in service.

The testing of filter units under conditions intended to simulate those anticipated in nuclear facilities during various types of accidents dates back to the 1950's. After the necessity for requiring nuclear grade filters to be nonflammable became evident, for example, investigations during the mid 1950's led to the widespread use of aluminum separators and glass-fiber filter media [(1)]. These replaced separators of kraft paper and media of cellulose and asbestos fibers. Wooden frames began then also to be made fire retardant by impregnation with salt solutions.

During the development of filter units resistant to fire and corrosive fumes, pressure drop increases with resultant decreases in flow were first reported for filters exposed to an airflow saturated with water vapor [(2)]. Tearing of the filter medium at low pressure drops was also observed. A search began for measures to counter the detrimental effects of moisture on filter-unit integrity and performance.

Evaluations were initially carried out to determine the effects of fog-entrained air at elevated temperatures and higher than design flows on filter-unit performance. Test conditions simulated those associated with loss-of-coolant accidents in water-cooled power reactors. Later studies dealt with the adverse effects of water sprays proposed to protect filter units from hot combustion gases and high soot-particle concentrations in the event of fires. Results of the investigations of the 1960's and 1970's into the effects of moisture exposure led to the realization of important countermeasures: some intended to prevent the exposure of filter units to high humidity air, others to mitigate any adverse effects of water on filter-unit construction materials in cases of inadvertent exposure. Droplet separators and air heaters upstream of HEPA filter and iodine adsorption filter stages typify exposure prevention countermeasures.

Those oriented toward damage mitigation during unintentional exposure are, for example, water-repellant filter media and the so-called "resistance to pressure test", specified to help qualify new, clean filter units as nuclear grade [3]. The latter is essentially a proof test conducted at an elevated pressure drop under extended exposure to the flow of air laden with fine water droplets. The minimum function of this test should be to simulate the magnitude of the mechanical loadings that the wet, fatigued filter medium and the pack adhesive of aged, dust-loaded filter packs could have to sustain without damage under normal operating conditions.

As illustrated by the examples noted above, test results for a number of adverse operating conditions have found direct applications in the development of the codes and standards that set minimum filter performance characteristics. These, in turn, have led to numerous and significant performance improvements. Such cases exemplify successful application of research results to nuclear safety practice, via performance specifications in codes and standards.

In other instances, published test results remain yet to be exploited in furthering development of codes and standards in the United States. Such information has potential application for additionally improving filter reliability in US nuclear facilities. Relevant to filter mechanical performance in this context are results obtained during the 1970's for pressure pulses simulating tornados [4] and explosions [5]. Understanding gained from tests carried out in the 1980's under hot dynamic conditions [6] or high air humidity [7], or more recently those into aging effects [8] and serial-challenge qualification testing [9] also falls into this category. Full implementation of this knowledge could engender relatively extensive revisions of some US filter standards, a potentially arduous if not impossible endeavor if not well planned.

For example, developers of improved filter units overseas made use of more recently established modes and mechanisms of filter failure documented in the open literature for a range of adverse operating conditions [10]. The resulting high-strength filters were then prescribed in purchasing specifications by the particularly safety-conscious filter user responsible for their realization [11]. Nevertheless, it has not yet been possible within the country of the filters' origin to build consensus for revisions to national codes and standards that reflect the full potential of the actual improvements achieved. Both the opposition of filter manufacturers and users and the variations in regulatory policies and inspectorates by region have limited widespread implementation of the improved filter units. This illustrates the need for independent national regulatory entities, as well as close cooperation on the part of both filter users and manufacturers, working together with representatives of national codes and standards organizations.

Intended functions of codes and standards pertinent to HEPA filter performance

The intended function of codes and standards dealing with hardware is to provide minimum requirements covering all component-related aspects - from design through maintenance - that will ensure proper operation of the given component throughout its service lifetime. The fundamental performance characteristics of nuclear-grade filter units can be considered to number six. One, dust holding capacity, though much investigated [12], is generally not directly safety related and therefore not dealt with in codes and standards. Typically addressed are particle removal efficiency, pressure drop at rated flow, and some measure of minimum burst strength, usually in the form of a proof test [3]. Also in this group are nonflammability and resistance to the effects of moisture. For practical reasons, requirements are specified solely for new filter units in a clean state.

Codes and standards covering performance characteristics of filter-units and their construction materials

For HEPA filter units in the United States alone, there exists a plethora of codes and standards that partially overlap each other (13). Even for the estimated 5% of the total market for glass fiber filters represented by the nuclear industry (14), duplication of standards has been noted (13). The code with the most promise of long term viability for nuclear applications, nationally as well as internationally, appears to be ASME AG-1-1994 (3, 15).

In addition, regulatory guidelines exist that address some of the service conditions to which air-cleaning system components could be exposed in systems designed for normal operation (16) and those for atmosphere cleanup following postulated accidents (17) in nuclear power plants. Moreover, users of filter units or owners of facilities typically have their own set of standards (18). These rely heavily upon commonly accepted predecessors to AG-1, AG-1 itself, and military standards for filter media and units, as examples.

Characterization of filter-unit mechanical failure

Filter-unit mechanical failure can be said to take place when the particle removal efficiency irreversibly falls below the minimum value specified for new, nuclear grade units. This can result from physical damage to, or deterioration in, almost any of the components making up a filter unit. Though tears in the filter medium constitute the most likely potential cause, functional failure of the frame, the gasket, or the pack sealant can also cause unacceptable decreases in filtration efficiency.

The prevention of filter mechanical failure, however, does not rule out malfunctions of air cleaning systems and filter units due to other potential causes (7, 19, 20). In the case of humid airflow, for instance, these include increases in filter flow resistance that restrict airflow such that the distribution of facility subatmospheric pressures is adversely affected. Another example involves decreases in particle removal efficiency involving phenomena other than macroscopic physical damage to the filter medium. These can encompass penetration of the filter medium by liquid water or moisture-induced changes in conditions affecting the filtration properties of the particles or the filter medium.

The above examples indicate that in some cases, maintaining the physical integrity of filters, by itself, will ensure proper functioning of neither the units nor the air cleaning system within which they are located. Nevertheless, ensuring physical integrity under normal operating conditions would constitute an overdue first step toward improving filter unit reliability for all adverse conditions of operation. It would also address not only user requests for filters with greater moisture resistance (21) that have gone unheeded in this country for more than a decade, but also more general concerns (22).

Mechanical loadings on filter units

The maximum pressure loading that might occur for a HEPA filter operating under normal conditions can be assumed to be the maximum pressure drop that the blower supplying the airflow to the filter can generate. For a nuclear air-cleaning system in a US facility, a pressure drop at the upper end of the range is 3.8 kPa (15 in w.g.) (23), but in other countries the pressure drop can be higher, for example 10 kPa (40 in w.g.) (7).

Under adverse operating conditions, pressure loading can be much higher. For example, a maximum pressure drop of 20.7 kPa (83 in w.g.) is specified for a NRC Region I tornado (24). In the contiguous United States, tornado passage over a nuclear facility has a fairly high probability of occurring. For ACS's not equipped with flow limiting devices, expanding steam, combustion heat, or damper-actuated diversion of airstreams could also generate transient flows and pressures above those capable of being produced by the blowers at steady-state conditions. Estimates of filter loadings for such instances can be obtained from computer simulations of air-cleaning system operation during nuclear facility accident conditions. In the case of earthquakes, loadings are specified in terms of ground acceleration (25) rather than pressure drop.

It is more difficult to pin down the loadings on HEPA filters that might occur due to explosions. Pressure impulses caused by shock waves generated by explosions depend upon the location of the explosion relative to the location of the filters (5, 26). However, one might specify a range of 3.4 to 34 kPa (13.8 to 138.0 in w.g.), which is equivalent to the specifications for the strength of single-pane window glass and frame walls, respectively, typically stipulated in building structural codes. Actual explosive overpressures can be much higher than these.

Burst Strengths of filter units

Actual burst strengths of HEPA filter units have been reported by numerous investigators for various adverse operating conditions and well summarized by Bergman et al. (27) in the form of threshold values required to damage deep-pleat filters. The burst strength is highly dependent upon design, manufacturer, and filter medium tensile strength, as well as the parameters defining the test conditions. For pressure change rates equivalent to the NRC Region I tornado (24), burst pressures have been found to range from about 6.9 to 20.7 kPa (27.7 to 83.0 in w.g.) (5, 26), one baseline datum of the compilation and comparisons made by Bergman et al. According to their summary, five of the six factors addressed can reduce filter burst strength by more than 50%, acting individually.

The burst strength of HEPA filter units challenged by the sixth, shock waves, depends upon impulse per unit area rather than simply upon shock overpressure. However, explosive shock waves have very short duration, so overpressures reported for the shortest shock duration give a good estimate of the explosive overpressure needed to tear the medium of HEPA filters. For units from six manufacturers, the damage overpressure was reported to range from 6.9 to 17.5 kPa (28 to 70 in w.g.) (5, 26).

New, clean filter units have been documented to sustain respective peak accelerations above 1 g (28) and above 10 g (29) without notable decreases in filtration efficiencies. Yet, earthquake related damage to aged filter units during service has been reported to occur for estimated peak ground accelerations of less than 0.3 g (25).

Deteriorations in construction materials related to mechanical failure of filter units

Aging of the filter medium during normal operations has been implicated in explaining decreases in tensile strength (30) and filter-unit burst strength (31), not to mention loses in water repellency (7). During long-term service, the outgassing of volatiles from some prospective pack adhesive/sealants of the elastomeric type has the potential for causing shrinkage and resultant adverse effects on the filter medium or the adhesion of the filter pack to the frame.

Exposure to humid air, as another example, can degrade the performance characteristics of HEPA filter units through detrimental changes in the properties of the filter construction materials. High air humidity fosters the corrosion of aluminum separators and metal frames. Moisture can also work to reduce the adhesion forces between the filter pack and frame or leach the fire retardant salts from wooden frames. The filter medium is particularly liable to deteriorations in performance. The presence of liquid water in the glass fiber microstructure can effect significant and partially irreversible decreases in tensile strength, the rigidity of the pleats, and the tightness of deep-pleat filter packs. All of these result in decreased filter-unit burst strength.

Decreases in filter medium tensile strength [(32)] and elongation at rupture (see Table III in Appendix) resulting from elevated temperature involving sublimation or burn-out of the binder can also be very significant.

Modes of mechanical failure (deep-pleat designs)

The modes of mechanical failure for deep-pleat filter designs have been noted to be very similar for greatly differing, adverse conditions [(7)]. Each of the three frequently documented modes that involve tearing of the filter medium has been observed to result from filter exposure to most, if not all, of the numerous single challenges investigated. These include high air velocities, elevated temperatures, shock waves, and flows of high humidity air; not to mention handling and shipment. The many causes of such similar failures point to locations of inherent weakness or maximum stress in the filter pack.

Mechanisms that contribute to mechanical failure

Many of the mechanisms responsible for filter-unit mechanical failure are also common to failures caused by different adverse conditions. This implies that known failure mechanisms have not been sufficiently well addressed in current filter designs.

A summary of the primary underlying failure mechanisms would include the following. First, the inherent weakness and brittleness of glass fiber filter media lacking reinforcement: typical characteristic values are 1 to 2 orders of magnitude below those of other construction materials as indicated in Fig. 1 and Table I of Appendix. Equally relevant are the additive decreases in filter medium tensile strength and elongation at rupture; due to the effects of pleating, aging, and fatigue in normal service, or exposure to moisture or to elevated temperature. A relative comparison of the respective decreases is given in Fig. 2 and Table II in the Appendix.

Of no less significance is the loosening of conventional filter packs that leads to increased stresses and fatigue in the filter medium, as well as to mechanical interaction between filter medium and separators. Though of secondary nature, the nonuniform distribution of pressure drop induced stresses in the filter medium of deep-pleat designs, nonetheless explains the failure modes and weaknesses of certain deep-pleat geometries and why they should be avoided [(10)].

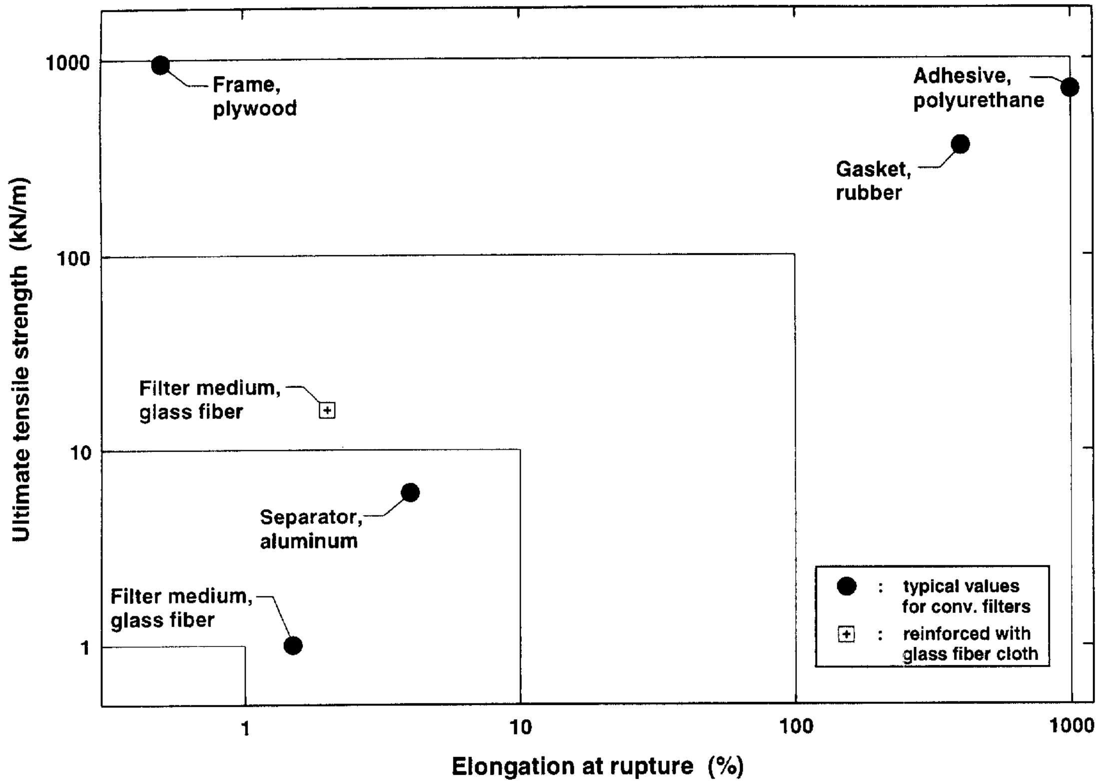

Figure 1: Strength characteristics for the fabrication materials employed in the designs of conventional deep-pleat HEPA filter units.

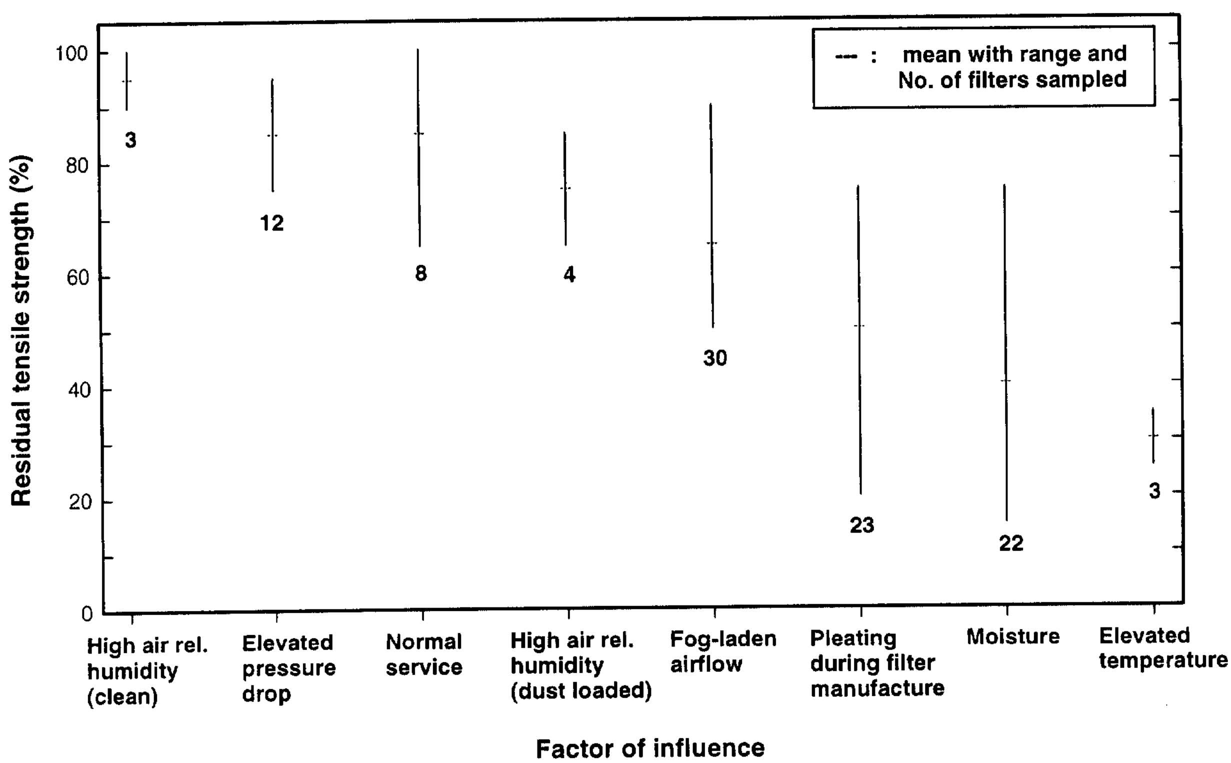

Figure 2: Comparison of the residual ultimate tensile strengths for non-reinforced, conventional HEPA filter media of nuclear grade, resulting from various factors of influence.

Suggested approaches toward eliminating the risk of filter-unit mechanical failure during normal operations and reducing it during other than normal operations

It is to be expected that glass-fiber filter media will continue to play a dominant role in nuclear applications for the midterm future. Moderate cost, high filtration efficiency, low flow resistance and density, reasonable degree of chemical inertness, fair resistance to radiation, elevated temperature, and fire constitute a set of characteristics that other materials cannot presently match. Similarly, the deep-pleat design with separators has proven itself superior in strength to separatorless and mini-pleat designs under most operating conditions. Hence, it has been assumed that the filter-unit design of the following discussion is one characterized by deep pleats, separators and a glass fiber medium. An additional premise is that the prevention of filter structural failure in humid airflow generated solely by the system blower needs to be absolutely ensured. Though the following recommendations focus on guaranteeing filter-unit reliability during exposure to moisture at pressure drops up to the blower maximum, their implementation would also increase reliability under more adverse operating conditions.

With the shortcomings of current deep-pleat filter-unit designs identified, solutions for addressing them can be proposed. For instance, increasing the initial tensile strength of the filter medium and its residual strength under pertinent adverse conditions should have the highest priority. To minimize mechanical interaction between the filter medium and separators, filter pack tightness and stability need to be ensured, particularly under relevant adverse conditions. The concept of a factor of safety for filter-unit mechanical strength needs to be implemented.

Calculation of a safety factor requires knowledge of two values. One is a measure of minimum filter mechanical strength for a given set of operating conditions as compiled by Bergman et al. [27], for example. The other, a measure of the maximum conceivable mechanical loading under the same conditions, possibly obtained from computer simulations, preferably ones verified experimentally. The ideal safety factor would be based upon values for the most adverse conditions anticipated. In practice, however, the economics of enhancing the strength of this weakest of all air-cleaning system components to the level of other ACS components would be prohibitive for the most adverse conditions. This is primarily due to the need for periodic filter-unit disposal. Only for nondisposable, or reusable components, or those with extremely long service lives could the greatly increased costs be justified.

At a bare minimum the safety factor could then, for instance, more advisably be one based upon the maximum pressure drop of the air-cleaning system blower and a proof strength for filter units in a wet condition. A proof strength that should be demonstrated after extended exposure of filter units to elevated temperature, as a separate part of a multi-step test sequence that comprises a qualification test process for nuclear-grade filter units. This should essentially eliminate the risk of filter-unit mechanical failure during normal operations and reduce it during other than normal operations. One overseas high-strength filter design, for example, has a demonstrated safety factor of 1.5 for new units under extended exposure to fog at design flow, after sustaining 23 h at 120 °C in still air [10]. This is based upon a typical maximum blower pressure drop of 10 kPa and a filter burst strength > 15 kPa when wet [7].

The above approaches fall into the category of counter-measures aimed at mitigating the adverse effects of moisture. An additional measure, aimed at preventing moisture exposure in power plant ACS's, would involve specifying droplet separator and air heater performance characteristics in detail. This should be based upon experimentally-verified, combined effectiveness of droplet separators and heaters in protecting aged, dust-loaded filters from condensing steam under the transient temperature and flow conditions that simulate a severe LOCA.

The importance of experimental verification is emphasized by two sets of preliminary test results reported for aged, dust-loaded filter media. One indicated that increasing temperatures above 20 °C can, for at least one dust type, shift the relative humidity, at which moisture-induced, peak filter pressure drops occur, to values below 70% RH [7]. In such cases the intended protection offered by heaters in limiting air relative humidity to < 70% could be viewed as ineffectual. A second data set demonstrated proportionally greater increases in pressure drop with decreasing values of constant airflows at lower than design levels [20]. Given filter units of sufficiently high burst strength, such increases in pressure drop could become irrelevant with respect to filter mechanical failure. The potential ramifications of decreased airflows and resultant redistribution of air-cleaning system pressure drops would, however, remain to be evaluated.

Selected recommendations for augmenting current US codes and standards

Prerequisite to any implementation of the above suggested approaches in actual practice would be revisions to existing codes, standards, and regulatory guidelines. Based upon known failure modes and mechanisms and the authors' interpretation of them, consideration should be given to adding the following functions to specifications presently lacking them. These relate, for the most part, to typical requirements in current documents considered to be in need of change or augmentation.

Filter medium specifications should

- reflect the large differences (1 to 2 orders of magnitude) between typically low tensile strength values of unreinforced, glass-fiber filter media and those of the other filter construction materials
- adequately reflect the potentially adverse and cumulative effects of pleating, aging, fatigue, elevated temperature, and moisture exposure on filter medium tensile strength
- reflect the commercial availability of filter media reinforced with a scrim or cloth of glass fiber
- require a minimum tensile strength in a folded condition
- require a minimum tensile strength in a wet condition.

Filter-unit specifications should

- require that the allowable continuous, peak operating temperature be indicated on the filter label
- require the same test filter units to sustain as many of the stipulated qualification tests as possible

- include extended static exposure of filter units to a temperature at the upper limit of the design range of operation; in order to induce artificial aging effects in the form of accelerated off-gassing of volatiles from the filter medium, the adhesive/sealant, the gasket, and the frame

- include a resistance to overpressure test that simulates the magnitude of the mechanical loadings that the wet, fatigued filter medium of aged, dust-loaded filter packs could have to sustain without damage under normal operating conditions: this to be performed after the extended static exposure of filter units to a temperature at the upper limit of the design range of operation

- include stipulations of adhesive/sealant performance, e.g., nonflammability, thermal stability, and resistance to: shrinkage, relaxation, cracking, and moisture effects

- include a resistance to overpressure test that simulates the magnitude of the mechanical loadings that the wet, aged adhesive/sealant of aged, dust-loaded filter packs could have to sustain without damage under normal operating conditions: this to be performed after the extended static exposure of filter units to a temperature at the upper limit of the design range of operation

- include stipulation of a minimum value for a factor of safety: at the very least, one based upon the maximum pressure drop of the air-cleaning system blower and a proof strength of filter units in a wet condition; after extended static exposure of filter units to a temperature at the upper limit of the design range of operation

- include a stipulation for deep-pleat pack tightness in a new condition such as [33] does

- address the potential loosening of deep-pleat filter packs that can result from exposure to moisture, high air velocities, or elevated temperature.

<u>Droplet separator and air heater</u> specifications should

- stipulate droplet separator and air heater performance characteristics in detail; based upon the experimentally-verified, <u>combined</u> effectiveness of droplet separators and heaters in protecting aged, dust-loaded filters from condensing steam under the transient temperature and flow conditions that simulate a severe LOCA.

Conclusions

Published research results obtained during a period extending from the mid 1950's through the 1970's appear to have been extensively utilized in the development of contemporary codes and standards. The realization of numerous improvements in filter-unit performance and reliability can be traced to these early investigations. However, knowledge gained since then does not appear to have been fully exploited in revisions of codes and standards specifying filter-unit performance. Current specifications in the United States do not reflect more recently gained knowledge of the modes and mechanisms of filter- unit mechanical failure documented in the open literature for a wide range of adverse operating conditions. This information has potential application for further improving filter reliability.

Despite some 30 years of performance advances, conventional HEPA filter units remain not only among the least robust components to be found in a nuclear air cleaning system, but also the most sensitive to the adverse effects of conditions deviating from those of normal operation. In this respect, they constitute the weakest link in a chain of crucial components forming the barriers between contaminated zones and the environment. One reason for this is the inherent fragility of conventional glass fiber filter media. Another is the sensitivity of unreinforced media to cumulative reductions in strength properties caused by pleating, aging, fatigue, elevated temperature, and moisture exposure. A third factor is the loosening of the filter pack that can result from exposure to high air velocities, temperature, and moisture.

Further enhancement of filter reliability will realistically be achieved only by increasing performance specifications in codes and standards to levels that are both technically feasible and economically justified. This process, however, needs to begin at the initiative of regulatory entities, which carry the ultimate responsibility for ensuring public health and safety. Meeting more stringent standards will have to entail cooperation and coordination on the part of both filter users and manufacturers working together with representatives of codes and standards organizations. The final step, optimizing the design and minimizing the cost of filter units that meet upgraded standards, can only be left to manufacturers and the free market.

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Gaseous Effluent Treatment in Nuclear Installations;
Graham & Trotman, London, 1986.

Appendix

Table I: Typical ultimate tensile strength and elongation at rupture for the construction materials of nuclear grade HEPA filter units in a new, dry condition at room temperature [7].

Filter-unit component (material)	Thickness (mm)	Ultimate tensile strength (kN/m²)	Ultimate tensile strength (kN/m)	Elongation at rupture (%)
Filter medium (conventional glass fiber)	0.5	$2 \cdot 10^3$	1	1.5
Filter medium (glass fiber reinforced with glass fiber cloth)	0.55	$3.2 \cdot 10^4$	16	2.0
Separators (aluminum)	0.035	$1.4 \cdot 10^5$	6	4
Gasket (neoprene foam)	6	$6 \cdot 10^4$	360	400
Adhesive/sealant (solid polyurethane)	5	$1.4 \cdot 10^5$	700	1000
Frame (plywood)	19	$5 \cdot 10^4$	950	0.5

Table II: The influence of various factors on the residual tensile strength of new[1], glass fiber, HEPA filter media of nuclear grade, in the machine direction at room temperature[2] (7).

Factor of Influence	Residual Tensile Strength (%) Average value	Range of values	Quantity of Filter Units Sampled
Elevated temperature (after 1 h @ 250 °C)	30	25 - 35	3
Moisture (after 1 h soak @ p_{abs} = 5 kPa, specimens wet)	40	15 - 75	22
Pleating during filter-unit manufacture	50	20 - 75	23
Fog-laden airflow (up to burst pressure of filter, specimens dry)	65	50 - 90	30
High air rel. humidity (after 1 h @ 99% RH) dust loaded (used)	75	65 - 85	4
clean	95	90 - 100	3
Normal service (after approx. 24 months, used)	85	65 - 100	8
Elevated pressure drop (after 3 s at approx. 20 kPa)	85	75 - 95	12

[1] except where noted with (used).
[2] except for tests at 250 °C.

Table III: The influence of various factors on the residual elongation at rupture of new[1] glass-fiber, nuclear-grade HEPA filter media in the machine direction at room temperature[2] (7).

Factor of Influence	Residual Elongation at Rupture (%) Average value	Range of values	Quantity of Filter Units Sampled
Pleating during filter-unit manufacture	40	20 - 60	23
Elevated temperature (after 1 h @ 250° C)	45	35 - 55	3
Elevated pressure drop (after 3 s at approx. 20 kPa)	80	45 - 95	12
Moisture (after 1 h soak @ p_{abs} = 5 kPa, specimens wet)	85	45 - 160	22
High air rel. humidity (after 1 h @ 99% RH) clean	90	85 - 90	3
dust loaded (used)	95	90 - 100	4
Fog laden airflow (up to burst pressure of filter, specimens dry)	105	60 - 150	30
Normal service (after approx. 24 months, used)	110	85 - 125	8

[1] except where noted with (used).
[2] except for tests at 250 °C.

DISCUSSION

BERGMAN: HEPA filters in the US have to pass qualification tests: a heated air test for five minutes at 700°F, an over pressure test for one hour at 10in.w., and a vibration test. Could you share with us some of your thoughts about these specifications and what you might recommend for improved qualification tests?

RICKETTS: I would not at all want to disparage the current qualification tests. Most of them (I can only think of one exception) involve testing different filters during the qualification process for the different challenges. In other words, you do not take the same filter that you put through the heated air test and run it through the resistance to over pressure test, which involves exposing filters to a pressure drop of 10in.w. and to a flow of fine droplets or fog. I think our primary recommendation, to answer your question in as short a time as possible, would be to test the same filter units under as many of these challenges as possible during the qualification process. I hope most of you were there yesterday when Dr. Bergman showed us another horror story with a blowout of filters following a fire and fire suppression measures taken at Rocky Flats in, I believe, 1980. This was a case where the same filters were exposed simultaneously not only to high temperature but also moisture and a high pressure drop caused by the moisture essentially clogging the filter medium. As I recall, there were four stages of filters in the air cleaning system, the first three stages were taken out completely, and the fourth stage was severely damaged. I think this provides an example of why some of these qualification tests might need to be reconsidered.

SCRIPSICK: I agree with this line of logic. I think Bergman and the people at Rocky Flats have done some sequential exposure tests on the same filter. What is needed, and we have to be careful in stating this, is simultaneous exposures. That is what can occur in the field, airflow resistance and heated air. I want to acknowledge that the United States has done its fair share in terms of nuclear air cleaning. Its technology is being used world wide now, so you can't fault the researchers here. I think you were very careful in the beginning of your talk to say that.

RICKETTS: I too think they have made enormous contributions, without which we would not be where we are today.

SCRIPSICK: This country is in a nuclear power reactor lull of a decade or so long. We are now behind the wave in nuclear power research. Although the DOE, as the manager from Hanford indicated, is knocking down our facilities, there is still a need for research. It should have been funded a number of years ago so the country could have gotten the most utility out of the research. Doing it now, I think it is still needed but it will be less useful.

FIRST: Because you did not mention it, I assume you did not get around to testing minipleat filters or separatorless filters. Based on what you already know, what would be your opinion regarding the relative safety of these alternative manufacturing methods? I also wonder about the difference between a six inch deep filter and a twelve inch deep filter. Would the deeper filter be more stable? I think your challenge is well stated, we have to be challenged to look at alternative methods of construction and materials to overcome the deficiencies which you have pointed out. I realize I am asking you for an opinion, but if you are willing to give it, I would appreciate your comments.

RICKETTS: I am willing to answer your first question concerning the minipleat design and the separatorless design. Both designs are a very big improvement, or have the potential for being a big improvement, as far as dust holding capacity goes. It is my personal opinion that one of their advantages is not high strength. I think you will find, if you go to the literature, that deep pleat filters with separators do have a higher burst strength under most conditions of operation than the other two designs. I can recall approximately twenty years ago when the work in Germany first began, that prototype minipleat filters were tested and could not match the burst strength of the conventional deep pleat filters even when reinforced. We have stress models available now that tell us that the deeper the pleat, the stronger the filter. Pack depth is in the denominator of the stress term and I believe it is squared, so the larger the depth squared, the lower the stress is for a given pressure drop. I think that very well explains cautions that I recall running across in the literature many years ago from Mr. Burchstead saying please avoid the six inch pack depth because of its susceptibility to catastrophic failure, the whole pack would bulge out at very low pressure drops.

ADAMS: Did you look at the products of several manufacturers or did you restrict your investigation to just one manufacturer? A second question is, are there specific guidelines that you would say need to be changed, possibly by the regulatory agencies?

RICKETTS: Let me answer your second question first. I think you will find a whole list of recommendations in our preprint, more detail than anyone may want to read, but we took the liberty, anyway. Your first question had to do with how many manufacturers. Were you looking for brand names?

ADAMS: I do not know. I know there are several manufacturers of that filter design. Did you find similar findings in all of them, or in just one?

RICKETTS: In general, the results for filters from various manufacturers were similar. Naturally, there was a range that correlated primarily with filter medium tensile strength. Not all manufacturers use the same filter medium. To put this work in a little better context, I presented a summary of knowledge that goes back over the last fifteen or twenty years of testing filters under adverse operating conditions such as tornadoes; conditions that simulate loss of coolant accidents and so on.

PORCO: To build on Dennis Adams' questions, were all the filters you tested built and qualified to MIL-F-51068, to N-509, or to any current standards? Did they go through a QA Station? Do you have a baseline for comparison?

RICKETTS: Most of the results upon which these conclusions are based were for filters from European manufacturers and tested in Europe. To answer your questions specifically, no, they did not go through the qualification process. They were very, very similar in design to American filters. We have tested a few American filters under tornado conditions. Under those conditions the differences between the European brands and the American brands were insignificant.

PORCO: The reason I bring this up is that I know US manufacturers' nuclear grade filters look very similar to commercial grade filters, but their performance and the strength are quite different due to manufacturing methods and materials.

RICKETTS: In Europe there is also a grade of filter referred to as nuclear grade. It also has to be much, much higher quality than run of the mill filters used in non-contaminated applications. Just to go one step further, I think it has to do with the tensile strength of the filter medium. That is in essence what we feel needs to be changed.

PORCO: I agree with you. Your slide was very interesting.

SCRIPSICK: One of the things that flies in the face of your premise that the medium is very weak is that we have had filters in place in this country for thirty years in some instances. They are still performing and they pass the in-place test. If the medium is now very weak (and I do not think there is any doubt about that) they have had an awful lot of exposure. This seems to go counter to what you are saying. Could you expound on that?

RICKETTS: I assume that any filter that has been in service for more than five years is probably in a second, third, maybe even a fourth stage in a train. It has not been loaded with much particulate and its pressure drop is probably going to be very close to its new pressure drop. For that reason, it probably hasn't been fatigued to the extent that a filter in the first stage has because first stage filters are changed out much more frequently. That would be my thought.

SCRIPSICK: Are you saying that it is not just long term exposure to low differential pressure or sudden new differential pressure but that the stress really multiplies at higher differential pressures?

RICKETTS: I can tell you it is probably approximately linear, but we do not have firm evidence. We certainly have some strong circumstantial evidence that indicates there is a fatiguing effect at the locations of highest stress in a filter pack and that location is typically at the top of the pleat, close to the adhesive, or at the bottom of the pleat, close to the adhesive.

SCRIPSICK: Would you think it would be proportional to pressure drop times time, the pressure exposure? With a thirty year filter, is there a time component?

RICKETTS: I have no basis to give you an answer on that, I can only speculate and I am not sure that would be useful.

BERGMAN: About eight years ago there was a paper published in which Jim Johnson and several other people from Livermore took third or fourth stage HEPA filters from our plutonium building. These filters were clean, and that is why we used them to assess performance. They ruptured at thirteen inches of water. We took new filters out of the box that had just been sitting at warehouses. We had published in either the last Proceedings or the Proceedings before that these filters that had been sitting in the warehouse had at least one half the strength of a brand new filter. So this is to counter the thought that if you do not have any challenge, these filters are going to be fine, and that is not true. These filters deteriorate from day one and it is unfortunate that Tim Sing from Evanite Fibers isn't here. He informed us that glass fibers themselves begin aging from the minute they are produced and some industries require glass fiber manufacturers to package the fibers in a hermetically sealed bag so they effectively stop this aging process.