Significant Aspects of Fatigue Phenomena and Related Material Failure for Pleated HEPA Filter Media in HEPA Filter Packs during Normal Operations

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Abstract

High Efficiency Particulate Air (HEPA) filters are disposable components that play crucial roles in the reliable operation of nuclear air, or gas treatment systems worldwide. Under certain operating conditions, the properties of the glass-fiber filter medium and the stability of the filter pack can become appreciably degraded - even during what may be characterized, or possibly mis-identified, as being benign service. One possible consequence is that the reliability of filters in their service locations can be reduced significantly, as a result of various combinations of potential factors of adverse influence, one of which is fatigue of the filter medium during time in service.

It has been said that a majority of engineering failures can be attributed to the fatigue of a material ill-selected during an engineering design process, or mal-appropriately processed during product manufacture[1]. Any structure or mechanical component subjected to cyclical loading can fail due to fatigue effects. Toward avoiding fatigue failure, good design practice includes a focus of careful attention upon material performance requirements which not only can be unique to a given design, but also constitute an essential basis upon which design and manufacturing processes rely for the realization of a product that fulfills service life expectations both reliably and economically.

In a case reported during 2010 for normal operations that involved commercial radial-flow HEPA filters at the *Sellafield* nuclear facility in the UK, filter functional failure quickly followed losses of filter medium physical integrity, via rupture of the filter medium related to factors closely associated with fatigue. As reported by the authors, root causes of the failure included malefic flow conditions upstream and within the filters; in combination with filter packs characterized by a physical robustness deficiency and by fabrication materials of questionable quality, or suitability.

The comparatively high aerodynamic forces of quasi-cyclic nature – acting on a radial-flow filter pack of pleats and separators – can be traced to non-uniform, pulsating, and vorticity-laden (rotating, or swirling) air flows inherently characteristic to this pack design at rated volume flow. These unsteady flows, imprinted with patterns of relatively large-scale anisotropic turbulence within the pack, are primarily created by random separations of airflow from trailing surfaces, as high velocity air passes from the smaller inlet throat of the filter into the larger diameter inner cavity of the pack.

It was the repeated failure of nuclear-grade axial-flow HEPA filters in what was then (mistakenly) considered benign service that drove the development of more robust designs in Germany during the mid-1980's. These failures had preceded the typically expected useful service life of approx. 24 months and have since been linked to fatigue of the glass-fiber filter medium. Though their operating conditions were long-assumed to be benign, they have now been recognized as filter maligning, due to the extremely adverse airflow patterns within a specific, single-filter modular housing design, commonly used in parallel-flow configurations during that era. Very strong supporting evidence for the link between failure and fatigue was provided by results for used filters that failed while being individually subjected to high humidity airflows in a test facility at Karlsruhe Nuclear Research Centre; following their approx. 24 successful months of full-term service within these housings.

It would be recommended that due consideration be given to implementing fatigue testing of both filter media specimens and full-scale filters, as an integral part of the HEPA filter design selection and qualification processes. Also recommended would be that the resistance to filter medium fatigue of any pack design lacking rigid pleat separators and reinforcement of the glass-fiber filter medium be most carefully scrutinized and thoroughly vetted - even for proposed applications under the seemingly most benign of projected operating conditions.

Conclusions presented are based upon review of the open literature on HEPA filters and upon unpublished experience with filters in nuclear air treatment systems at Karlsruhe Nuclear Research Centre.

Background

High Efficiency Particulate Air (HEPA) filters are disposable components that play crucial roles in the reliable operation of nuclear air, or gas treatment systems worldwide. Under certain operating conditions, the properties of the glass-fiber filter medium and the stability of the filter pack can become appreciably degraded − even during what may be characterized, or possibly misidentified, as being benign service. One possible consequence is that the reliability of filters in their service locations can be reduced significantly, as a result of various combinations of potential factors of adverse influence − one of which is fatigue of the filter medium during time in service.

It has been said that a majority of engineering failures can be attributed to the fatigue of a material ill-selected during an engineering design process, or mal-appropriately processed during product manufacture(1). Any structure or mechanical component subjected to cyclical loading can fail due to fatigue effects(1). Toward avoiding fatigue failure, good design practices include a focus of careful attention upon material performance requirements which not only can be unique to a given design, but also constitute essential bases upon which design and manufacturing processes rely for the realization of a product that fulfills service life expectations both reliably and economically(2).

It is of some relevance that little notice is taken in ASME's AG-1 Code(3) of the incongruity between the reliability level of filters qualified in an ephemeral, pristine state characterized by a new, clean filter medium and the much lower levels that can be expected of filters in their service locations, once the subsequently particle-loaded filter medium has been subjected to the effects of aging and fatigue. It is also noteworthy that the Code is silent on the specific topic of a resistance-to-fatigue test for design qualification of new filters to prescribed requirements that would ensure performance expectations be met for filters that could be later compromised by fatigue during service. These gaps could have ramifications in practice when the reliable operation of a critical system component (in this case, the HEPA filter) directly depends upon the physical integrity of one of the weakest, most brittle and yet essential materials (the glass-fiber filter medium) to be found within an air cleaning system and that is, moreover, one of the most susceptible to physical degradation within comparatively short time intervals - even during routine filter service.

In a case reported during 2010 for normal operations that involved commercial radial-flow HEPA filters at the *Sellafield* nuclear facility in the UK(4), filter functional failure quickly followed losses of filter medium physical integrity, via rupture of the filter medium related to factors closely associated with facilitation of fatigue processes. As reported by the authors, root causes of the failure included malefic flow conditions upstream and within the filter pack cavities; in combination with filter packs characterized by a physical robustness deficiency and by fabrication materials of questionable quality, or suitability for the application.

The comparatively high aerodynamic forces of quasi-cyclic nature – acting on a radial-flow filter pack of pleats and separators – can be traced to non-uniform, pulsating, and vorticity-laden (rotating, or swirling) air flows(4, 5) inherently characteristic to this pack design at rated volume flow. These unsteady flows, imprinted with patterns of relatively large-scale anisotropic turbulence within the pack cavity, are primarily created by random separations of airflow from trailing surfaces, as relatively high-velocity air passes from the smaller inlet throat of the filter into the larger diameter inner cavity of the pack.

Two primary causes of these adverse flow patterns are the relatively high air velocities at the filter inlet and the typical 90° change in flow direction that takes place within filter housings just upstream of the filter inlet. At design flow, the average air velocities over the cross sectional area normal to the airflow in radial-flow geometries can approx. range from 5-10 times higher than those at the inlet to deep-pleat packs of typical axial-flow filters. Peak local velocities within the airstream are likely to be even higher, by an estimated factor of up to approx. two (2) times the average velocity. Additionally, other contributing factors enhancing the transfer of momentum and energy from the airstreams to the pleated filter medium can include housing vibration, blower-induced pulsations in the airflow and non-uniform, unsteady flow patterns within the ductwork and filter housings just up- or downstream of the filters in their service locations.

It was the repeated failure of nuclear-grade axial-flow HEPA filters in what was then (mistakenly) considered to be benign service that drove the development of more robust designs in Germany during the mid-1980's. These failures had preceded the typically expected useful service life of approx. 24 months and have since been linked to fatigue of the glass-fiber filter medium(6). Though their operating conditions were long-assumed to be benign, they have now been recognized as filter maligning, due to the extremely adverse airflow patterns within a specific, single-filter modular housing design, commonly used in parallel-flow configurations during that era. Very strong supporting evidence for the link between failure and fatigue was provided by results for used filters that failed while being individually subjected to high humidity airflows[6] in a test facility at Karlsruhe Nuclear Research Centre; following their approx. 24 successful months of full-term service within these housings. Failures of new, clean filters of the same manufacturer and design (1000-CFM axial-flow − having deep-pleat packs and separators of aluminum) and tested in the same test facility under similar conditions, exhibited no indication of having been fatigue related[6].

Based upon their comparative lack of mechanical robustness, radial-flow filter designs lacking filter medium reinforcement or rigid separators are typically are among the most susceptible to filter medium fatigue under essentially any flow conditions. This is because their packs are inherently less stable than deeply pleated ones incorporating rigid separators. As pointed out by the authors of the *Sellafield* report, less rigid pleat separators make for looser packs. And loose packs facilitate additional space and degrees of freedom for pleat movement under aerodynamic loads, both of which result in a higher susceptibility to failure via filter medium fatigue − as well as to facilitation of undesirable mechanical interactions between the pleated filter medium and any more-rigid objects located within close proximity. Dimple-pleat filters have demonstrated instances of pack behavior that included pleat oscillation and collapse, prior to failure by rupture of the filter medium at locations of highest stress and fatigue. Furthermore − in comparison to deep-pleat axial-flow designs at the same pressure drop − radial-flow pleat geometries are also handicapped by intrinsically higher stresses and stress gradients within the filter medium, both of which act to considerably accelerate the fatigue process.

The conclusions presented here are based upon review of the open literature on HEPA filters and on fatigue testing, as well as upon unpublished experience with filters in nuclear air treatment systems at Karlsruhe, Germany. They were lent additional support by recognition of relatively high, average inlet air velocities for two proposed radial-flow designs (3000 ft/min: 9 times those of typical axial flow pack designs) and (2200 ft/min: 6.5 times) filter geometries at the design flow rating of 2000 ft^3/min.

The lack of an existing performance qualification standard tailored to address fatigue of conventional HEPA filter media in service poses an additional hurdle to be overcome in the process of validating new filter designs will eventually fulfill reasonable service life expectations both reliably and economically. A challenge for which solution options are also constrained by the necessity of ensuring the long-term performance of new, nuclear-grade filter designs having the recognized potential handicaps summarized above, but not having yet been proven in long-term actual service under a variety of operating conditions.

Thus, it would be most highly recommended that consideration be given to implementing fatigue testing of both filter media specimens and full-scale filters, as an integral part of filter selection and qualification processes. It would also be recommended that the resistance to filter medium fatigue of any radial-flow pack design lacking rigid pleat separators and reinforcement of the glass-fiber filter medium be most carefully scrutinized and thoroughly vetted, even for proposed applications under the seemingly most benign of projected operating conditions. It has been said with merit: Were HEPA filters to be re-invented, it would be essentially inconceivable for reinforcement of the filter medium not to be reflected in mandatory performance requirements for their qualification.

Potential resources to be drawn from might include FC-I subarticles addressing filter medium resistance to flexing; current standards and practices for cleanable HEPA filter media and for pulse-jet cleanable bag house filters; the draft of proposed AG-1 Code section FM; and Mil. Std. 810 p. 514.5. One aim of the latter is to take service life into account via use of a shaker table and a shake-frequency spectrum tailored to closely simulate cumulative worst-case actual vibration conditions that a test object could be expected to encounter during actual service operation.

Introduction

Ventilation and air treatment systems provide for the health safety and the thermal comfort of personnel in facilities that contain hazardous or toxic materials. These systems also prevent the release of contaminated airborne particulate to the surrounding environment. The required high particle-removal efficiencies are made possible by the use of HEPA filters which represent indispensable components in air treatment systems of nuclear facilities globally. One of the most crucial responsibilities incumbent upon a system operator is that of ensuring continuous, high-efficiency particle removal throughout service intervals ending with HEPA filter change-out − which is typically limited by administratively prescribed maximum allowable filter pressure drop or service life. This constitutes a responsibility tending to encompass some rather unique challenges.

Similar to other system components, HEPA filters are expected to perform reliably not only during normal facility operations throughout expected full service lives, but also under possible upset or so-called accident conditions generally of much shorter durations. In some cases, filter units may be called upon to withstand individual or combined challenges of elevated temperature, air velocity, or pressure drop; shock wave impingement; or high air humidity − without performance decreases that would result in a loss of airborne particle confinement. However, even during normal service, their reliability can be compromised by numerous factors of adverse influence that may at times lie outside the direct oversight and immediate control of the system operator.

Unlike most essentially permanent, system components having service lives that approach, or equal the useful life of the system or facility, disposable elements such as HEPA filters are removed from service following much shorter time intervals. For examples: after a prescribed upper limit on pressure drop or time in service is exceeded, or after having failed the aerosol particle challenge of an in-place leak test, or following filter exposure to moisture, or to corrosive gases beyond certain threshold combinations of concentration and time. Were an effective and economic in-place test for filter reliability available, less reliance could be placed upon such administrative guidelines and more upon the reliability test; toward justifiably extending filter service life and thereby helping to keep filter life-cycle costs to a minimum.

As disposable units, conventional HEPA filters are inherently much less mechanically robust than most other system components. Almost no other system component is fabricated from weaker materials than are they – or can degrade during service, to the point of functional failure under routine operating conditions – as can they. As most typically manufactured, they can be characterized as being fragile and having levels of reliability during service limited primarily by the intrinsic characteristics of one inherently weak and brittle constituent; the 0.5-mm thick glass-fiber filter medium.

Conventional (*i. e.*, non-reinforced) filter media of glass fibers represent by several orders of magnitude the weakest material utilized in filter fabrication (s. Fig. 2 in [(6)]); to a degree that makes them susceptible to tearing under relatively small applied forces, beginning with filter manufacture through filter handling, transport, and service. Glass-fiber media are also severely handicapped by a susceptibility to degradations in their material properties; not only due to particle loading and to increasing age and fatigue of the filter medium over time in service, but also via exposure to moisture or corrosive media. Both filter medium strength and water repellency characteristics can be significantly degraded by most of the above factors of influence, as important examples.

An acute drawback to conventional HEPA filters themselves is that only slight localized physical damage to the glass-fiber medium can cause unacceptable decreases in filter removal efficiency − equating to a loss of filter physical integrity via a material failure of the filter medium by small-scale tearing or puncture that precludes the filter from fulfilling its fundamentally intended function.

It is the performance reliability of *plauf*ed (particle loaded, aged, used, and fatigued) filters under adverse operating conditions that can be legitimately questioned, given the lack of an in-place filter reliability test. One extreme technical solution to this issue would be to undertake measures to ensure that the robustness level of *plauf*ed filters approach that of system duct work, toward taking into account possible challenges to filters in their weakest condition by the most adverse operating conditions to be expected at their service locations. A more economically accountable approach to enhancing the reliability of current filter designs would be to implement reinforcement of the filter medium, together with measures to ensure that a minimum acceptable level of filter-pack robustness is sustained throughout filter service life.

Published research results obtained over a period extending from the mid 1950's through the 1980's can be said to have been reasonably well utilized in the continued development of both HEPA filters and the codes and standards that delineate their performance specifications. The realization of numerous improvements in filter performance and reliability can be traced to these investigations.

However, knowledge gained since the 1980's has not yet been fully exploited in ongoing revisions of US codes and standards. Current specifications do not reflect more recently gained knowledge of the modes and mechanisms of filter mechanical failure documented in the open literature and elsewhere for current and proposed designs under a wide range of adverse operating conditions. This information has potential application to further drive filter development and enhance filter performance reliability throughout expected filter service life.

It is apropos to emphasize via repetition that despite intermittent performance advances over the past 60 years, off-the-shelf HEPA filters of any design generally remain not only among the least robust components to be found in the air treatment systems of nuclear facilities, but also retain their ranking of being the most sensitive to the adverse effects of conditions deviating from those of normal or routine operations. In this respect, they constitute the weakest link in a chain of crucial components forming the barriers between contaminated zones and the environment. Underlying reasons include the inherent fragility and brittleness of conventional glass fiber filter media. Another is the sensitivity of filter media to cumulative degradations in material properties caused by pleating, aging, fatigue, elevated temperature, moisture exposure, and particle loading. An additional factor of relevance is the potential loosening of the filter pack that can result from exposure to high air velocities and pressure drop, elevated temperature, and moisture; individually or in combination.

In-place leak test on the basis of aerosol particle penetration, limitations of

Though the in-place leak test is helpful for identifying filters that have already failed in service, mis-application of positive test results for *plauf*ed filters can create a false sense of security that filters will function reliably during subsequent operation; after they have been latently degraded during prior routine service, or preceding moisture exposure. Contrary to a seemingly yet widespread traditional belief: in-place aerosol particle penetration tests provide no measure of service-related degradations in filter robustness and hence no indication of filter reliability, either for any instant or any interval of time.

Basic aspects of the Phenomenon of Fatigue of an Engineering Material – relevant to a typical mechanical design process

"The majority of engineering failures are caused by fatigue. Fatigue failure is defined as the tendency of a material to fracture by means of progressive brittle cracking, under repeated alternating or cyclic stresses of an intensity considerably below the normal (*i. e.*, the initial) *strength. Although the fracture is of a brittle type, it may take some time to propagate, depending on both the intensity and frequency of the stress cycles. Nevertheless, there is very little, if any, warning before failure, if the crack is not noticed. The number of cycles required to cause fatigue failure at a particular peak stress is generally quite large, but it decreases as the stress is increased. For some mild steels, cyclical stresses can be continued indefinitely provided the peak stress (sometimes called fatigue strength) is below the endurance limit value. …*

Fundamental requirements during design and manufacturing for avoiding fatigue failure are different for different cases and should be considered during the design phase." [(1)]

"All structures and mechanical components that are cyclically loaded can fail by fatigue." [(2)]

Relevant independent variables that can affect an engineering material's fatigue life[†] typically include

- the material's classifications with respect to:

  being either an isotropic or an anisotropic material

  exhibiting either brittle or ductile behavior

- the ratio of the maximum (peak) stress value generated by the selected representative cyclic load, divided by the initial ultimate strength of the material

- the absence of; or the type and distribution of non-negligible stress concentrations in the material

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[†] *which is generally quantified by the total number of stressing cycles prior to failure by rupture*.

Fatigue strength has been generically defined to be the number of stress cycles of a specific character that a material specimen can withstand, before failure of a specified nature occurs. The number of cycles required to cause failure decreases as the magnitude of the peak stress value increases. It is also called fatigue limit and is affected by environmental factors such as corrosion[(7)].

Fatigue and its Relevance to HEPA Filters

Fatigue and Related Material Failure for Pleated HEPA Filter Media within Filter Packs during Nuclear Service

Fatigue, which represents a detrimental phenomenon capable of compromising the physical integrity of a pleated glass-fiber medium in a filter pack during transport or service, includes the process by which the ultimate strength of the medium is reduced significantly, over time at locations of highest stress, and under dynamic mechanical loads that generate time-varying stresses having peak values less than the initial ultimate strength of the material in a new condition.

Even in a pristine, un-pleated state, glass-fiber filter media are by nature not only anisotropic but also brittle: elongations at rupture typically lie between 1 and 2% in a new, dry state. Compared to ductile ones, brittle materials characteristically exhibit relatively short fatigue lives. *I. e.*, they become susceptible to crack propagation (or, tearing in the case of fibrous media) and rupture after far fewer loading cycles - under what had initially been otherwise sustainable mechanical loads during the material pre-fatigued state. And unlike more ductile ones, brittle materials are much more apt to fail catastrophically and without advanced warning.

Also of relevance with respect to material fatigue susceptibility is the typical 50% reduction in tensile strength across the ends of the pleats of filter medium, resulting from the pleating process just preceding fabrication of the filter pack (s. Fig. 3 in [(6)]). The resulting random damage to the microstructure along crease lines creates localized, elevated values of stress, referred to as stress concentrations.

Moreover, not only do glass fiber media represent a brittle and anisotropic material substantially degraded in strength by the pleating process, but they are configured in pack geometries handicapped by relatively high, heterogeneous stresses and stress gradients that fluctuate under the dynamic mechanical loadings created by the airflow. In essentially all conventional HEPA-filter pack designs, the flow-induced stresses in the filter medium have maximum values on the pack upstream side at the top and bottom of the pleats where they are embedded in the bonding agent holding the pack to the frame of axial-flow, or to the endcaps of radial-flow filters (s. Fig.'s 5 and 7 in [(6)]).

Thus are created preconditions for the initiation and relatively rapid propagation of fatigue phenomena. The filter medium micro-structure is first damaged by folding during pack fabrication in localized regions along the ends of the pleats and visually identifiable as creases. During service, the maximum stresses and stress gradients of the airflow-induced heterogeneous stress distribution will appear at certain known locations on the up-stream side of the pack. In addition to these non-uniformly distributed stresses, any non-negligible, localized stress concentrations – arising from initial discontinuities within or subsequent damage to the filter medium – can add appreciably to the magnitude of total stress at any spatial coordinate with the filter medium.

Taken all together, these represent an adverse constellation of greatest possible stress arising at locations of lowest material strength, thereby creating ideal conditions for initiation and promotion of fatigue. Since the fatigue process generally proceeds most quickly in a material at the locations of highest stress. Ironically, if not insidiously; the locations at which greatest material strength is called for − toward reliably sustaining the mechanical integrity of the filter medium during service − are the very locations where the highest stresses are accomplishing the most rapid reductions in material strength.

It is also noteworthy that fatigue effects can be greatly exacerbated in cases of filter pack loosening which enables significant pleat lateral movement (flutter) and mechanical interactions with any adjacent, invariably more-rigid, medium maligning elements (separators, screens, or support grills) under the aerodynamic forces of the airflow. With respect to other factors of practical influence; any concurrent degradations of the filter medium due to aging can be expected to further accelerate the fatigue process.

Radial-flow pack geometries

In sharp contrast to their many advantages, a number of distinctly relevant drawbacks to current radial-flow pack designs also exist (s. Fig.'s 1 and 2 in Appendix A). One of these is represented by the intrinsically higher, flow-induced stresses and stress gradients within the filter medium (s. Fig. 3 in [(9)]), that act to accelerate the fatigue process (s. previous subsection). These result from the exceedingly high ratio of pleat length to pleat depth which is equal to approx. eight (8); a factor two to four (2−4) times higher than those permitted in sections FC and FK of AG-1 for axial-flow filters. One countermeasure commonly used to address this is to segment packs along their longitudinal axis, so as to reduce effective pleat length and thereby reduce the magnitude of this critical ratio – and thus the stress and stress gradient levels within the filter medium.

Another significant factor is the exceedingly high average inlet air velocity for representative filter geometries at the design flow rating of 2000 ft^3/min. Specifically: for one design ≅ 3000 ft/min, (or 9 times those of typical axial-flow pack designs) and for another ≅ 2200 ft/min (or 6.5 times). Peak local air velocities are likely to be appreciably higher: by an estimated factor of up to approx. two (2) times the average velocity. Moreover, other factors can contribute to transfer of momentum from the air stream to the pleated filter medium including: filter housing vibration; blower-induced pulsations in the airflow; and non-uniform, unsteady flow patterns within the ductwork and filter housings just up- or downstream of the filters in their service locations.

Both the high stresses at a given pressure drop and the excessively high inlet velocities directly underlie the susceptibility of radial-flow filters to failure resulting from filter medium fatigue. Contributing secondary causes related to filter design and manufacturing can be marginally low initial filter medium strength characteristics, or above average degrees of damage sustained during the pleating process. And with respect to loose filter packs; low pleat density, or a lack of rigid pleat separators, or an initially loose pack.

The first direct linkage of engineering material fatigue to the in-service failure of nuclear-grade radial-flow HEPA filters is to be found within a 2010 report of operational experience at the *Sellafield* nuclear facility in the UK(4). In this case, incipient tearing and subsequent rupture of the filter medium was attributed to a number of underlying factors, including the relatively high, heterogeneously distributed aerodynamic loads on the radial-flow filter pack resulting from the effects of non-uniform (referred to as “streaming” in the report) and vorticity-laden airflows. Three additional contributing factors were also noted: a questionably low filter medium tensile strength, the relatively weak ribbon-type separators, and a deficiency in pack “strength” of the marginal filter design − attributed to a low pleat density. These were all associated with one (Manufacturer A) of two manufacturers.

The authors also reported that the issues with the filters of Manufacturer A were eventually corrected by substituting more rigid "cord" (*string*, in AG-1 terminology) separators for ones of ribbon and increasing the pleat density, both of which would have made for a more robust pack. It should be noted that failure of the filter designs at *Sellafield* occurred despite the (most) likely presence of segmentation along the pack longitudinal axis, typically used to reduce the critical ratio of pleat length to pleat depth.

A third characterization of the airflow within filters of the *Sellafield* system not mentioned by the authors would be that of “quasi-pulsating”; thereby completing the list of detrimental flow conditions to be withstood by a pleated filter medium in a radial-flow geometry as it is subjected to the dynamic loads and energy imparted by a pack-buffeting airstream via momentum transfer.

No mention of any vibration of filter housings appears in the *Sellafield* report. However, the importance of balancing the airflow through filters operated in parallel is explicitly emphasized, toward multiple ends related to good practice in ventilation systems. The more important of these would include minimizing both the overall system pressure drop and the mechanical vibration of ductwork and housings − as well as extending the average service life of filters.

The second linkage of engineering material fatigue to the failure of (prototypical) nuclear-grade radial-flow HEPA filters is to be found in related video films and a 2011 final report of tests carried out at MSU’s Institute of Clean Energy Technologies(8). In this instance, alternating swelling and collapse of pleats, along with their lateral movement, led to tearing of the pleated filter medium at locations associated with fatigue failure of the filter medium. But for the downstream metal grill, the filter packs would most likely have failed in dramatic catastrophic fashion, at a ΔP only slightly higher than that of incipient failure.

Adverse flow conditions within radial-flow filter packs and their potential effects on HEPA filtration efficiency

The maligning flow patterns characteristic of radial-flow pack geometries at filter rated flow also pose a possible undue hurdle to be overcome with regard to meeting in practice the intent of the average filtration velocity of 5 ft/min as specified in AG-1. The maximum average velocity requirement is related to helping ensure that the specified filtration efficiency is met for the most penetrating particle size associated with HEPA filter media. It is traditionally assumed that meeting this specification depends to a great extent upon a smooth flow of particle bearing air at a relatively uniform velocity entering the upstream side of the filter medium.

Given the extremely non-uniform air velocities within the upstream cylindrical cavity of radial-flow filters, this assumption would seem to be somewhat open to question. Potential short-term consequences include the inability of an otherwise HEPA-grade filter medium to meet the maximum allowable penetration for the filter most-penetrating particle diameter. And possibly unexpected longer-term ones, as flow patterns within pleat channels change during particle loading of the medium over filter service life.

Aspects of adverse flow conditions within filter housings and their potential effects on average filter service life and filter change out

In a somewhat analogous vein, if airflows through individual filters within housings become non-uniform to an undue degree, untoward ramifications may ensue. The flow patterns inside some filters within the housing may become significantly more unruly than usual. It is also conceivable that average filter service life could be substantially reduced, or filter change-out unduly complicated by discovery that change-out of complete sets of filters included ones that were not yet fully particle loaded.

Filter pack designs incorporating dimpled or corrugated pleats as pleat separators

The so-called dimple-pleat design is one that depends upon embossment of the filter medium itself to create a profile of bulges or corrugations intended to serve as pleat separators. This means of maintaining pleat spacing in a filter pack is one utilized by one US manufacturer for both axial- and radial-flow filter designs. The acute weakness of the concept is that the resulting pack lacks both a sufficient initial physical rigidity and the capability to retain its (inherently-low) initial robustness throughout service, in comparison to packs having rigid metal separators, for example.

Factors in additional to those noted above can increase the risk of fatigue failure in the dimple-pleat design. Ones that can be inferred from plots of stress in the filter medium for the radial-flow pack geometry are the high magnitudes of stresses and of stress gradients in the pleated filter medium, as compared to deep-pleat axial-flow filters, for example. The high stresses result from the high ratio of pleat length to pleat depth and to a lesser extent the absence of rigid separators. At least one commercial radial-flow design makes use of pack segmentation to reduce this ratio.

At its very best, even based upon less than worst-case assumptions, the dimple-pleat design is currently no more robust (for new filters) than the weakest FC Design Designation No. 4 (axial flow, deep pleat) filter (s. Fig. 2 in[9]) which is susceptible to catastrophic failure − and as of recently must now again be qualified independently of other FC pack geometries . Another drawback is the inherent lack of rigidity characteristic of the dimple-pleat separators (particularly over time in service), which directly contributes to pack loosening followed by pleat collapse and swelling phenomena and the creation of play within which pleats can vibrate laterally under the aerodynamic loads of the airstream. Both swelling and lateral motion (flutter) further exacerbate the already high maximum stresses and stress gradients in the filter medium and significantly accelerate fatigue effects at the locations of highest stress − where failure via mechanical tearing of the filter medium will ultimately begin to occur.

Furthermore, the dimple-pleat design (whether within a radial- or axial-flow pack configuration) is also highly susceptible to catastrophic failure at mechanical loadings only somewhat higher than initial rupture of the filter medium. This is in direct contrast to deep-pleat filters having separators. For the above reasons − in addition to its lack of any record of service history − the dimple-pleat, radial-flow design carries with it an extraordinarily high risk of early failure in service, due to fatigue of the filter medium over time, even under the most benign conditions of operation.

There are a number of similarities between the characteristics of the dimple-pleat design and the radial-flow packs for which failures were reported at *Sellafield*: low filter medium strength, lack of rigid separators, marginally robust filter pack, and susceptibility to catastrophic failure. Though the lack of pack segmentation represents an additional drawback (and dissimilarity) of more recent dimple-pleat prototypes, compared to the *Sellafield* filters.

Axial-flow pack geometries as a comparison baseline for radial-flow geometries

Incidental retrospection related to test results for radial-flow prototypes recently led to belated recognition of a long-overlooked probable root cause of in-service failures of axial-flow filters during the 1970's in Germany and an estimate for an approx. upper limit on the time to failure for that particular fatigue process. Relevant aspects were: 1.) that fatigue of the filter medium led to the failure under what were once thought to be benign operating conditions and 2.) that failure occurred after less than the typical 24 months of filter service life.

Gone unrecognized some 40 years ago was the maleficence of the vorticity-laden, non-uniform, and quasi-pulsating airflows characteristic of the single-filter housings of standardized German modular design, which were typically connected together in parallel flow configurations to build systems. The starkly pack-buffeting airflows were very likely exacerbated by other contributing factors not directly attributable to the housings. Among these were flow pulsations and (possibly) acoustical pressure waves generated by the blowers; them-selves typically of 1960's design vintage and operated at overall system Δp's between 40 and 60 in WC. The blower-induced flow pulsations and acoustic pressure waves likely augmented the adverse effects of poor housing design and further accelerated the filter medium fatigue process to some extent. An additional factor could have been the vibrations of the housings themselves, also created by the dynamics of the air flow - and possibly in part by the acoustic pressure waves. The vibrations in the housing side panels were not only visible and audible, but also palpable to the touch. During system operation, the airflow- and fan-generated, ear-numbing noise adjacent to the housings consisted of a whining, pulsating roar and had sound levels in excess of some 85 dB.

Strong supporting evidence for fatigue as the basis of the filter failures in service was provided by results for initially-intact, used filters that failed while being individually subjected to high humidity airflows in a test facility at Karlsruhe Nuclear Research Centre; following their approx. 24 months of prior, full-term service life within the housings. Failures of new, clean filters of the same manufacturer and design (1000-CFM axial-flow − having deep-pleat packs with metal separators) and tested in the same facility under similar humid-air conditions exhibited no indication of being fatigue related. The burst pressures of the used filters were reduced by a factor of essentially two (2) for the observed failure mode involving tearing of the filter medium at the locations of highest stresses in the pack − and hence locations of greatest fatigue-related reductions in material strength(s. Fig. 3 and explanations below).

There are certain parallels between the experiences at *Sellafield* (radial flow) and in Karlsruhe (axial flow). In both cases, functioning filters were installed in service locations to be operated under what were considered to be essentially innocuous conditions. In both cases, some filters had to be later removed from service unusually early, after having failed in-place leak tests. In both cases, tearing of the filter medium was the factor responsible. In both cases, remedies were implemented to address the issue of in-service filter failure. And in both cases, adverse flow conditions could be implicated in filter failure during routine service.

Minor upgrades to the radial-flow filters of *Sellafield* consisted of improving filter medium strength (presumably), separator rigidity, and pleat density, all of which contributed to enhanced pack robustness. Remedies for the axial-flow filter failures at Karlsruhe consisted of first discontinuing the use of mini-pleat V-panel filters and then developing significantly more robust deep-pleat designs, via a focused and systematic, in-depth, multimillion dollar, six-year process, based upon investigations of the modes and mechanisms of filter failure under a variety of adverse filter operating conditions.

At *Sellafield*, the maligning flow conditions confronting filters in service were recognized early on during the failure investigations. However, fatigue as a factor and destructive airflows as drivers of filter medium fatigue seem to have gone unrecognized for filter failures at Karlsruhe for some 40 years. Only via recent association of failures for axial-flow designs with both the *Sellafield* experience and more recent radial-flow dimple-pleat prototypes, was the connection made. Recognition of the similarities between the adverse flow conditions at *Sellafield* and at Karlsruhe also provided an important clue, as well as additional support for the recognition of fatigue-related failure of the filter medium in axial-flow filter packs.

The Effects of Aging on the Resistance to Fatigue of Pleated HEPA Media within Filter Packs

Aging of filter-unit construction materials is a process of physical and chemical change during which the performance characteristics of the given material are altered with time, most typically in detrimental ways. In the case of a HEPA filter medium, relevant time intervals can include storage under static conditions, stand-by service, and service during dynamic air-treatment system operations, typically over year-long time intervals.

Glass-fiber filter media basically represent a rather unique combination of materials wrought into a porous microstructure consisting of numerous diverse chemical compounds brought together during medium manufacture, in order to create a product of unusually high filtration performance capability. Volatiles and the inherent lack of longer-term chemical stability of the constituent polymeric binder and water repellency agents, explain in part the susceptibility of HEPA-grade media to degradation over relatively short time intervals, as compared to more conventional solid, homogeneous design materials such as metals, concrete, and wood.

The high specific surface areas of glass-fiber HEPA filter media microstructures and of captured fine particles help to facilitate the enhancement of material-degrading chemical reactions and physi-sorptional interactions with ambient gases in contact with the surfaces of the submicron diameter glass fibers, binder, and any captured particles. Somewhat counterintuitively, submicron diameter glass fibers exhibit non-negligible chemical reactivity over extended time intervals with, among others, water vapor, liquid water, and oxygen, even in otherwise chemically benign environments.

It is most likely that resistance to fatigue is one of the several important filter medium characteristics subject to degradation via aging effects, though to a yet unknown extent.

Measures to Counter Fatigue-Related Failure of Pleated HEPA Filter Media within Filter Packs during Nuclear Service

Several means are available to help counteract fatigue-related degradations in filter medium performance. Examples include: reinforcement of the filter medium by glass-fiber scrims or cloths; or by metal screens. The added layer of a reinforcing medium assists in two primary ways. Firstly, it helps carry some of the aerodynamically-induced mechanical loads, thereby reducing the magnitude of the stresses within the filter medium. Secondly, it increases the strength of the composite laminate of the filter medium and its layer(s) of reinforcement. The net result for each is identical within the context of fatigue mitigation. The number of loading cycles is increased prior to rupture of the filter medium and the fatigue life of the filter is thereby extended. One potential challenge to reinforcement lies in ensuring that delamination of the filter medium from the reinforcing layer(s) does not occur in service; otherwise the effectiveness of the reinforcement is essentially negated.

Other fatigue countermeasures include those aimed at increasing pack robustness via the use of rigid pleat separators, or increasing pack density by including more pleats within the pack, while ensuring that the pack is initially tight upon the completion of its fabrication. Segmentation of the pack along its longitudinal axis also represents a means to mitigate fatigue by reducing the magnitude of the stress and stress gradients within the filter medium.

All the above measures can be used to decrease the likelihood of the pack loosening after filter manufacture and of any subsequent accelerated fatigue of the filter medium during transport, handling, and service.

With respect to system operations, reduction of the operating flow of current 2000-cfm filters by one-half could help increase fatigue life by decreasing the unsteady aerodynamic forces transferred to the filter pack by the airstream. Flow guide vanes within housings, just upstream of the filters, or even within the inlet throat or the filter pack could accomplish a similar effect, but may not be significant enough to justify economically.

Codes and Standards for HEPA Filter Qualification as Examples for Prospective Tests to Serve as a Measure of Resistance to Filter Medium Fatigue

It is notable that the AG-1 Code is essentially silent on the topic of a specific resistance-to-fatigue test toward design qualification of new filters to prescribed requirements that would ensure performance expectations be met for filters that could be later compromised by filter medium fatigue during service. This gap is particularly problematic in practice when the reliable operation of a critical system component (the HEPA filter) directly depends upon the physical integrity of one of the weakest and most brittle materials (the glass-fiber filter medium) to be found within an air cleaning system and that is, moreover, one most apt to physically degrade within relatively short time intervals.

The lack of an existing performance qualification standard tailored to address fatigue of conventional HEPA filter media, therefore, poses a hurdle to be overcome in the process of validating that future radial-flow filter designs will eventually fulfill reasonable service life expectations both reliably and economically. A challenge for which options are further constrained by the necessity of ensuring the long-term performance of a new, nuclear-grade filter design having the recognized potential handicaps summarized above and not having been yet proven in long-term actual service under a variety of operating conditions.

Some indirectly related filter tests do currently exist in the AG-1 Code. The resistance to rough handling test is one that somewhat resembles a fatigue test, though it was originally intended to serve as an impact test for simulating severe mechanical jarring of filters during transport and handling. Without some modification though, since it would not be applicable to the purpose, as-is. A precedent-setting example for implementation of the rough handling test in a modified form is embodied by one step in the preconditioning process for the resistance to pressure impulse test in a proposed Code section for high-strength axial-flow filters. A similar, so-called seismic test, typically left to the discretion of the facility owner as an optional requirement in sections FC and FK, has limitations with regard to directly serving as a possible template. Although, as is the case for the currently existing filter resistance to rough handling test of Code section FK, it may have relevant potential for further consideration.

Another option − exemplified by Mil. Std. 810 p. 514.5 − is oriented toward taking full service life into account via use of a shaker table and a shake-frequency spectrum tailored to closely simulate the cumulative, worst-case actual vibration conditions that a test object could be expected to encounter during actual service operation. Some variation of this could be considered for HEPA filter elements.

A pristine glass fiber filter medium having a comparatively high resistance to fatigue will not necessarily retain this quality once it has been pleated and otherwise compromised while being forced into conforming to the relatively compact geometry of a radial-flow filter pack. It is therefore, not inconceivable that both types of fatigue tests could be proposed for incorporation into AG-1 within the foreseeable future. Radial-flow pack geometries – being of the more readily compromised and thus of higher priority – are more apt to be addressed before those of axial-flow ones.

Mandatory Appendix FC-I, of AG-1, for qualification of HEPA filter media includes a test of a medium's flexing characteristics involving drawing specimens around a cylindrical mandrel five (5) times. A list of aspects representing residual physical integrity based upon specimen post-drawn inspection and particle penetration test constitute the test pass/fail criteria. In its current form, the limited number of cycles and the lack of a specified stress level are two aspects that would limit its suitability as a resistance-to-fatigue test.

Conclusions

Toward deeper understanding of fatigue related issues, a useful analogy can be drawn between the fatigue process associated with pleated HEPA filter media and the tactics of ankle-biting carnivorous predators. Both insidiously work to first disable their mark by focusing on more frail, less easily protected, and yet critical points of defense, before finally bringing their target to ground. Non-reinforced HEPA filter media have two primary intrinsic frailties: their mechanical fragility and their brittleness, exacerbated by physical damage during pleating to form the filter pack. The combination of these with operating conditions involving adverse flow conditions and inherently weak pack designs sets the stage for filter medium fatigue processes that can lead to early failure, *i. e*., within time intervals shorter than the service lives that would normally be anticipated or deemed acceptable for HEPA filters under most typical operating conditions.

Conclusions presented are based upon review of the open literature on HEPA filters and on fatigue testing in general, prototype radial-flow filters of the dimple-pleat design, as well as upon unpublished experience with filters in nuclear air treatment systems at Karlsruhe. They were lent additional support by recent recognition of the excessively high, average inlet air velocities for radial-flow filter geometries at a design flow of 2000 ft^3/min.

The lack of an existing performance qualification standard tailored to address fatigue of conventional HEPA filter media poses an additional hurdle to be overcome in the process of validating that filters will eventually fulfill reasonable service life expectations both reliably and economically. A challenge for which design and performance qualification options are also constrained by the obligation to ensure the long-term performance of new, nuclear-grade filter designs having the recognized potential handicaps summarized above and not having been yet proven in long-term actual service under a variety of operating conditions.

It must be noted as being exceptionally significant that the dimple-pleat, radial-flow design carries with it an extraordinarily high risk of early failure in service, due to fatigue of the filter medium over time, even under the most benign presumed conditions of operation. This suggests due skepticism is warranted should this design be drawn into consideration for any nuclear application.

Thus it would be most highly recommended that due consideration be given to implementing fatigue testing of both filter media specimens and full-scale filters, as an integral part of any radial-flow filter design selection and qualification processes. This toward fulfilling the system operator's responsibility for ensuring continuous, high-efficiency particle removal throughout reliably-safe and cost-effective, administratively-set service intervals ending with filter change-out limited by maximum allowable filter pressure drop, or prescribed service lives.

It is also most strongly recommended that the resistance to filter medium fatigue of any pack design lacking rigid pleat separators and reinforcement of the glass-fiber filter medium be most carefully specified and excruciatingly well vetted via stringent qualification, even for proposed applications under the most benign of operating conditions.

Potential resources from which to be drawn might include FC-I subarticles addressing filter medium resistance to flexing, standards and practices for cleanable HEPA filter media(12) and for pulse-jet cleanable bag house filters(13), the draft of proposed AG-1 Code section FM, and Mil. Std. 810 p. 514.5(14). The latter takes full service life into account via use of a shaker table and a shake-frequency spectrum tailored to closely simulate the cumulative worst-case actual vibration conditions that a test object could be expected to encounter during actual service operation.

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Appendix A
Figures

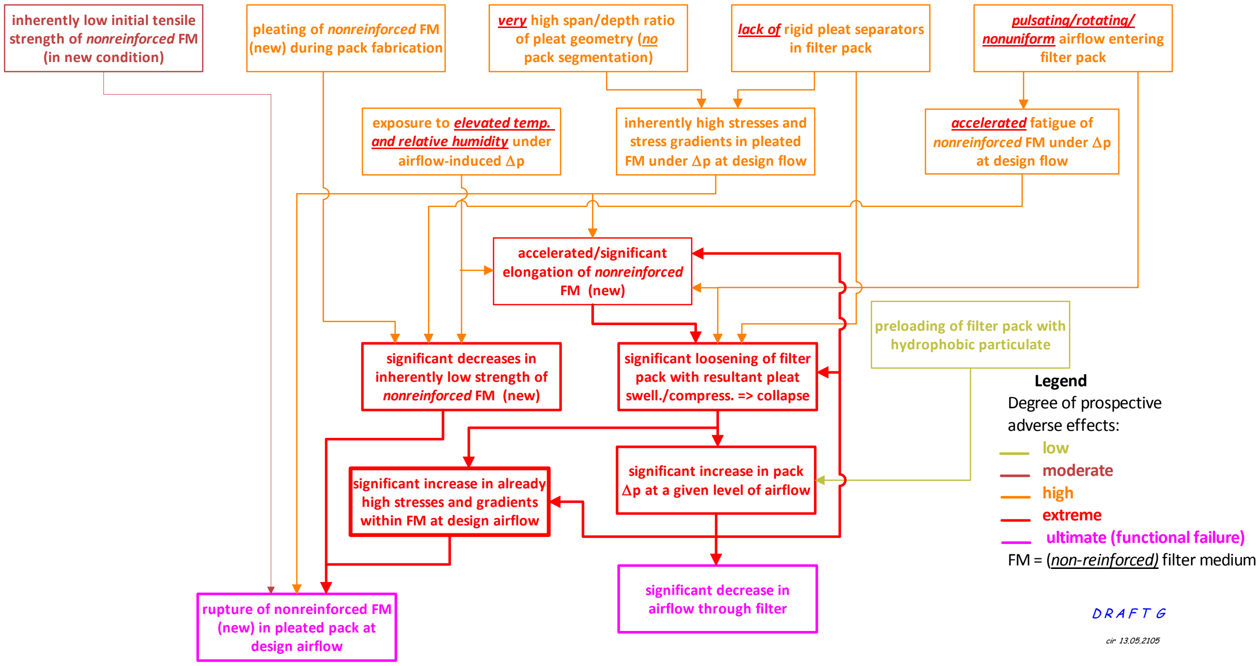

Figure 1: Prospective mechanisms and relationships underlying increases in pressure drop and the tearing of the filter medium in loose or dimple-pleat, radial-flow filter packs in a new, particle-loaded condition (no rigid separators and no reinforcement of glass-fiber filter medium).

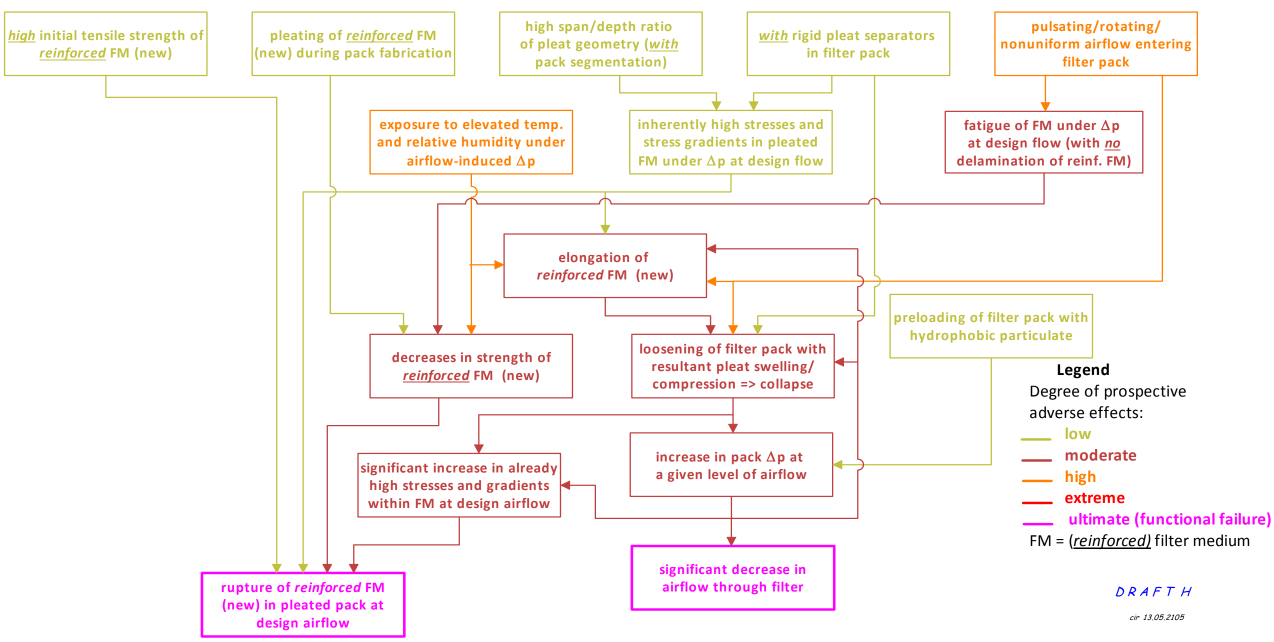

Figure 2: Prospective mechanisms and relationships underlying the increase in pressure drop and the tearing of the filter medium in axial-flow and radial-flow tight filter packs having rigid separators and reinforcement of the glass-fiber filter medium in a new, particle-loaded condition.

(a)

(b)

(c)

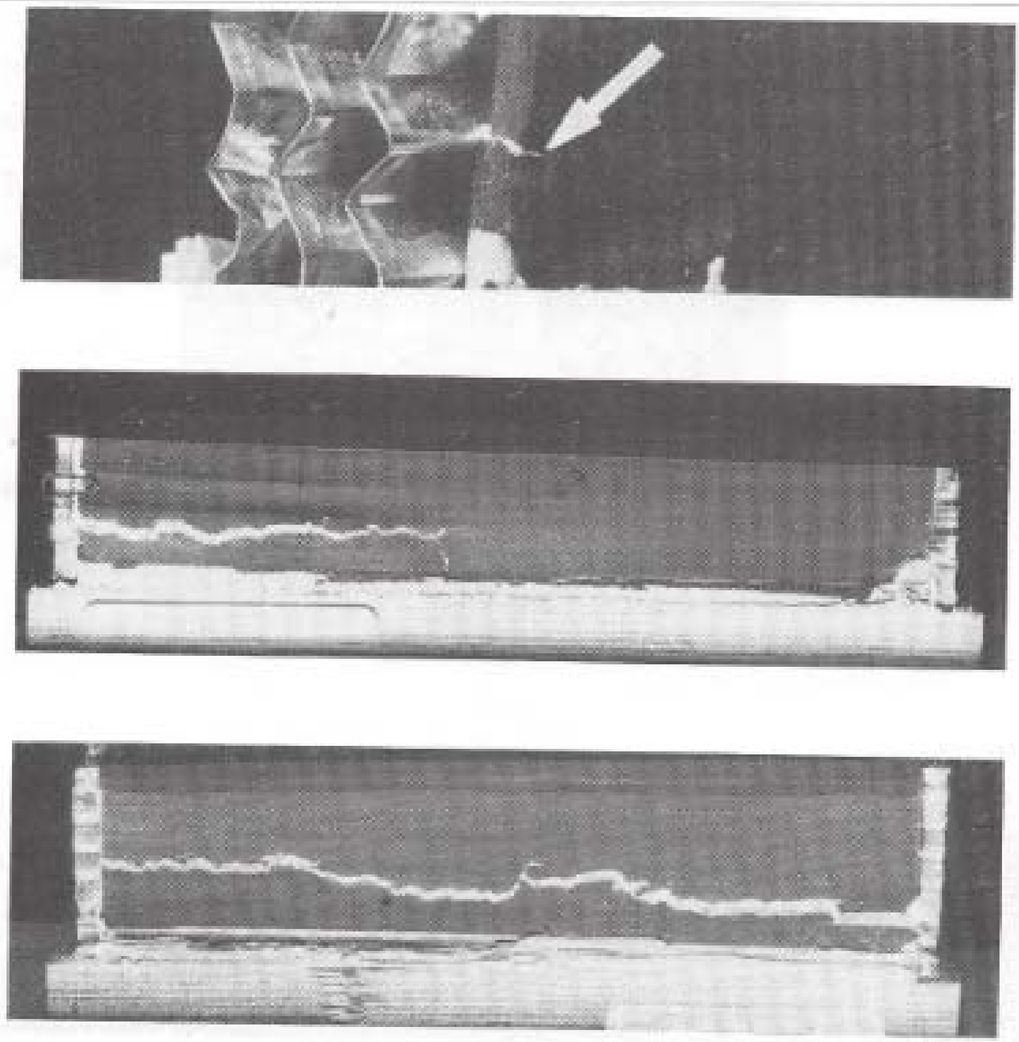

Figure 3: Physically sectioned packs removed from used 24-in x 24-in x 11.5-in axial-flow HEPA filters having an aged, particle-loaded, and fatigued glass-fiber filter medium, following some 24 months of normal service in an air-cleaning system and after subsequent exposure to humid air at design flow of 1000 ft^3/min at Karlsuhe Nuclear Research Centre[10].

Shown are examples of:

(a) tear initiation in the end of a filter medium pleat on the upstream side of the pack; positioned very closely to the location of maximum stress (and hence fatigue),
(b) a tear propagation (left to right in photo) having reached almost half the depth of the pack in moving toward the downstream side of the filter, and
(c) a tear propagation having reached the full depth of the pack after having moved (left to right in photo) toward the downstream side of the filter.

The tear propagation is in the direction of decreasing stress, thereby also implicating pre-high-humidity-test (*i. e.*, in-service) fatigue of the filter medium as a significant failure factor. Tears initiated at the highest stress locations and moved in the direction of decreasing stress values with time. A phenomenon that would not have been possible without a decrease in filter-medium strength prior to and during the exposure to humid airflow.