ASME AG-1 and Verifying HEPA Filter Performance Envelope

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ABSTRACT
This paper provides a reflective look at activities and infrastructure employed in qualifying ASME AG-1 HEPA filters. This review also considers infrastructure for evaluating performance envelopes and qualifying HEPA filters for code sections FC, FM, FI, FK, and FO. Service life considerations of Section FC fibrous glass HEPA filters are included. Code revisions and new sections for filter designs with advanced performance capabilities require qualification test methodologies for a wider and more aggressive range of test conditions. Above all else, performance verification of qualified ASME AG-1 HEPA filters are subject to ASME NQA-1 requirements.

INTRODUCTION

Credited HEPA filters must be considered "can't fail" components of safety significant or safety class ventilation systems (SSVS or SCVS). HEPA filters employing conventional fibrous glass media are inherently subject to damage by moisture, elevated temperature, and a variety of additional challenge conditions. Code sections have been added or are under development to include a variety of more robust media along with filter geometries other than rectangular axial flow designs. Ultimately, more robust designs must be evaluated (qualified) to an expanded set of challenge conditions and may be tailored to exposures of the specific application (e.g. ceramic or metal media filters).

The ASME AG-1 code [1] has an international reputation and is specifically identified for use by individual states and US federal agencies. However, it is instructive to recognize that ASME's publishing of AG-1 was delayed for a year in order to first publish their NQA-1 code [2] for nuclear quality assurance. Delaying publication of AG-1 should be understood as emphasizing AG-1's dependence on NQA-1 for quality assured fabrication and qualification of products such as credited HEPA filters.

Facility design considerations for SSVS or SCVS include identifying, characterizing, and controlling off-gas composition upstream of credited HEPA filters. Control technologies are evaluated individually and collectively to verify performance capabilities. Testing includes evaluation ranging from "normal" to "design basis" conditions. Additionally, routine inspection/maintenance coupled with observance of service life and verification of filter performance are included in facility management programs.

FILTER QUALIFICATION

ASME AG-1 HEPA filters used as credited components are subject to quality assured requirements. This is provided by evaluating the performance under a range of qualification testing activities. All aspects of testing, from design of testing infrastructure, selection and use of measurement and test equipment, automated computational software, etc. are subject to NQA-1 requirements.

A committee sponsored by the Department of Energy (DOE) reviewed the qualification testing of HEPA filters in 2008-2010 and made a number of findings and recommendations: (1) the industry practice of production tests on HEPA filter media on every batch should be considered for the AG-1 code to ensure the media meets the qualification requirements between the 5 year qualifications, (2) the practice of qualifying filter models by a composite of subcomponents from different qualified filters should be documented in AG-1, (3) the inconsistency between the AG-1 Code requirement for qualification every 5 years and the UL practice of inspections rather than tests should be addressed, (4) the statistical nature of the qualification failure should be incorporated into AG-1, especially for the overpressure tests, where the failure rate can be 20% for a qualified filter, and (5) the qualification test results should be made available to the users of the HEPA filters [3]. These findings are still valid today. Other researchers have pointed out deficiencies in the ASME AG-1 Code such as the UL practice of not complying with the requirement for qualification every 5 years and also the failure of the resistance to pressure test for not detecting pleat collapse in certain filters and the consequent flow restrictions at differential pressures less than 10 inches WC [4].

What is currently identified as HEPA filtering capability was initially developed for protecting soldiers by the Germans prior to World War II [5]. They incorporated fine asbestos fibers to reduce the most penetrating particle size. The US Army became custodian of this “classified” technology. The Army’s infrastructure and testing capability developed for evaluating HEPA filters is now housed at the Edgewood Chemical and Biological Center (ECBC). It is clear, in retrospect, that ECBC possessed the essential infrastructure and expertise for evaluating HEPA filters when AG-1 was published in 1985.

The Underwriters Laboratory (UL) facilities provide testing infrastructure for two qualification tests required by AG-1 Section FC: the heated air test and the NFPA spot flame test. These two tests are specified in the standard UL-586 [6]. Thus, ECBC and UL were used to provide testing expertise and infrastructure for qualifying the majority of Section FC’s requirements.

ASME NQA-1 requires the subject facilities to maintain a qualified supplier list (QSL) for vendors supplying NQA-1 services or products. Unfortunately, neither the UL nor the ECBC can be qualified to NQA-1. While this is certainly understandable based on expertise and historical activities, it is an inconsistency for manufacturers of media and filters. The ECBC does provide manufacturers a certificate of conformance and maintains a website listing items that have been issued certificates of conformance. In contrast, DOE’s Filter Test Facility in Baltimore, MD is subject to NQA-1 and is subject to periodic audits [7].

It is appropriate to revisit and reevaluate infrastructure used to conduct the individual qualification tests. For example, the resistance to pressure test in AG-1 Section FC-5140 and FK-5140 was intended to identify filter failures following exposure to 10 inches water column in humid air for one hour. The test has been successful in identifying failures such as torn media from the lower filter efficiency in the post exposure measurements. However, recent studies have shown that there is a second failure mode where some HEPA filters also fail due to pleat collapse of separatorless filters at slightly elevated temperature and moisture conditions [4,8]. The pleat collapse can occur rapidly leading to high differential pressures (greater than 10 inches WG) along with media rupture, severely impacting safety of the ventilation system. This led DOE to issue a safety warning [9]. This important failure mode should be incorporated into either the resistance to pressure test or a separate qualification test.

Improvements rough handling test are also needed to address problems with the current practice and make improvements to provide more information from testing other than pass/fail endpoints. The rough handling test specified in ASME AG-1, Section FC-5130 and Section FK-5130 uses a machine that employs a set of axles fitted with eccentric cams rotated at a prescribed rate to elevate and drop the platen or base to which a filter has been affixed. Design specifications are available and test stands are routinely manufactured by the user or outsourced. Lifting and dropping of the platen and adhered filter is loud and the whole assembly is prone to “wander” across the floor unless bolted in place. Mechanical failures can and do occur such as burning the electrical motor wiring, shearing of keys that index gears on the rotating axles or deforming a key causing the axles to rotate out of phase with each other, invalidating the test.

The biggest deficiency of the rough handling test is the lack of data. The test infrastructure was originally developed to determine carbon channeling in gas filters during shipping and handling but was later used for HEPA filters replicating damage from shipping and handling [5]. A note in Section 8.2.4 of the Nuclear Air Cleaning Handbook states that that the rough handling test does not actually test the HEPA filter in its shipping container and thus does not test for shipping damage. Figure 8.2 in Section 8.2.4 shows a HEPA filter tested in its shipping carton, but neither the original US military standard [10] nor the ASME AG-1 code requires the HEPA filter to be tested in its shipping container.

A filter is firmly attached to the platform, lifted and dropped for the designated timed period, then tested for post-stress filtering efficiency. Rough handling is basically a pass-fail filtering efficiency test with no data collected for other purposes. There is no characterization of timing of the lift-drop sequence to determine forces applied to the test filter.

The rough handling machine can be modified to represent a variety of different exposure conditions including handling and transportation. Pneumatically driven pistons under each of the four corners of the test platen can be controlled by a computer set of frequency, amplitude, and phase for each of the pistons. This flexibility coupled with accelerometers on each corner of the platform can provide data more capable of characterizing stresses generated by simulated transportation and accidents including earthquakes. A modified design of the rough handling machine can also be used to test sealing surfaces by a filter and housing combination for a variety of normal and accident conditions. The challenged housing and filter would then be connected to flexible up and down stream ductwork for testing filter efficiency following a simulated handling, transportation, or seismic test.

ECBC also performs ASME AG-1 Section FC-5140 resistance to pressure test for HEPA filters. This is routinely referred to as the wet overpressure test. Testing infrastructure consists of (a) an open-faced housing containing the filter in which a sufficient air flow is passed through the filter to generate 10 inches WC differential pressure across the filter for 1 hour with (b) a spray nozzle that generates 1 lb/min. of water droplets upstream of the test filter. However, neither the standoff distance from the spray nozzle to the test filter, nor the particle size distribution is specified by code or by procedure. In 2013 the ECBC moved the water spray nozzle closer to the test HEPA filter to mitigate the large amount of spray that fell to the bottom of the test duct prior to reaching the HEPA filter. This change in nozzle position resulted in the failure of a manufacturer to qualify a HEPA filter and a formal inquiry [11] was submitted to the ASME committee questioning experimental details such as nozzle position, air flow rate, uniformity of spray against the HEPA filter, and droplet size distribution. Following a review, the nozzle was moved back to its original position, but no changes were made to the code section.

The objective of the AG-1 resistance to pressure test is to demonstrate the ability of wet, pleated fibrous glass HEPA media to survive for one hour at a differential pressure of 10 inches water column. The test stand uses a magnehelic gauge for monitoring differential pressure and volumetric flow rate through the filter is controlled manually by fan speed.

The resistance to pressure test needs to have additional specification of spray dispersion across the face of the filter, characterization of spray droplet size, and uniformity of spray dispersion across the face of the test filter as outlined in the ASME AG-1 Inquiry 13-1316 (2013) [11]. A preliminary study was conducted at Mississippi State University (MSU) to look at the issues relating to water sprays on radial HEPA filters, but insufficient data was collected to recommend changes to the AG-1 Code [12]. Technologies currently exist for both rough handling and wet overpressure tests to characterize specific challenge factors (e.g., g-forces associated with the rough handling and over pressure tests and media damage associated with water droplet size, velocity, and number density of droplets impacting the leading edges of pleated media).

Testing infrastructure used to qualify ASME AG-1 Section FC filters was state of technology when developed in the 1950s and early 1960's [10,13]. It is important to acknowledge the wisdom and ingenuity that crafted the methodology and testing infrastructure currently used. However, it is equally important to acknowledge that if initial test stands had been developed more recently, the testing infrastructure and data collected would look vastly different.

New filter designs employing more robust media developed by Lydall Inc. [14] have been commercially available in Europe since 1986 [15,16] and have been demonstrated in the US by American manufacturers since 1992 [17], but the first HEPA filter using this high-strength medium (Lydall 3398-L2W) that also met the requirements in ASME AG-1 and was installed in a US nuclear facility did not occur until 2017 [18]. The high-strength filter developed by the Porvair Filtration Group [18] for Bechtel National Inc. (BNI) for use in the waste treatment plant (WTP) in Hanford, WA, was largely based on ASME AG-1 Section FK. Tests at MSU showed the filter can withstand 50 inches WC in a particle loading test in addition to passing the overpressure test at ECBC for Section FK-5140 to 10 inches WC for 1 hour. Initially, the early prototype high-strength filters tested at MSU were exposed to a constant differential pressure of 225 inches WC (8.13 psi) by flowing a polymer-water solution through the filter for one hour. This resistance to pressure test was modeled after the AG-1 resistance to pressure test [19,20]. The resistance to liquid pressure test was later replaced with a particle loading test to 50 inches WC. MSU did not use the Code Section FM for qualifying the Porvair filter because the code section was not yet published, did not address radial-flow filters and did not have a test apparatus for conducting resistance to constant pressure tests at 225 inches WC for one hour.

Section FM of the AG-1 Code was developed for specifying the design, performance and qualification of axial-flow HEPA filters using the Lydall high strength HEPA media [21-23] and is approved for publication in the next AG-1 edition in 2023. The resistance to pressure impulse test in Section FM evolved from a series of experimental test apparatuses that could generate sufficiently high differential pressures [25,26]. The initial studies showed that generating high filter differential pressures with water flow systems were much better (less expensive and smaller equipment size) than air flow systems, but the water flow system still required unacceptable highwater flow rates [25,26]. A series of improved designs was developed and evaluated based on creating an impulse with a slug of water since the impulse creates the much higher pressure drop than possible with a constant water flow [21-23]. The pressure pulse is a practical solution for obtaining high differential pressures using water. The potential high-pressure hazard for HEPA filters in the WTP was the application of the full fan pressure on the HEPA filters; consequently, the qualifying test required a constant differential pressure of 225 inches WC. Previous filter test systems used transient air pressure pulses to challenge HEPA filters to simulate filter challenge for tornados and shocks [26].

Other high strength HEPA filters were being developed based on steel fiber medium [27,28] and based on ceramic fiber medium [29]. These filters have their individual AG-1 code sections under development: Section FI for metal filters including metal HEPA filters and Section FO for ceramic HEPA filters. The development of these new standards is dependent on new methodologies and test equipment to qualify the filters for resistance to a range of temperatures, pressures, and environmental conditions such as moisture, chemicals, thermal shock and particle loading. Both FI and FO sections use the MSU high temperature air flow test system that can accommodate the test requirements for metal and ceramic HEPA filters at temperatures of 750 °F for 1 hour [19,20,30]. The MSU filter test systems greatly exceed the capability of existing HEPA filter test systems. For example, the MSU resistance to liquid pressure system can test metal, ceramic and reinforced glass fiber HEPA filters or representative filter components at constant pressure up to 225 inches WC for the prescribed one hour. Similarly, the MSU resistance to temperature test system can expose metal, ceramic and reinforced glass fiber HEPA filters or representative components to constant temperatures of 750 °F for one hour at flow rates up to 200 cfm and high differential pressures up to 10 psi [30]. High-strength glass fiber HEPA filters with lower differential pressure can use the conventional ECBC or UL test equipment as was done with the BNI filters including the Porvair filter [18].

These high-strength glass fiber HEPA filters also have high temperature resistance as do the metal and ceramic fiber HEPA filters. Tests in the United Kingdom show that high strength glass fiber HEPA filters exposed to air flow at 932 °F (500°C) and 30 inches WC of differential pressure for 10 minutes showed no structural damage and retained an efficiency greater than 99.9% [31]. In AG-1 resistance to temperature tests, high-strength glass fiber HEPA filters exposed to 750 °F for 5 minutes still maintained the 99.97% efficiency and also even after the same filter was then subjected to the resistance to pressure test at 10 inches WC for one hour [32]. Thus, the reinforced glass fiber HEPA filter can be considered in the similar class as metal and ceramic fiber HEPA filters. Of course, at even higher temperatures, the melting point of the filter material must be considered where ceramics are better than steel, which is better than glass.

Both MSU test systems will undoubtedly require modifications with increased use of these test systems. For example, the polyethylene glycol (PEG) used to increase the viscosity of the water was found to precipitate from the solution during the filter tests and required extensive flushing of clean water prior to drying and testing for filter efficiency. Although reducing the concentration of PEG would eliminate the problem, this would reduce the fluid viscosity and require increased liquid flow and larger pumps to achieve the high-pressure differential. An optimization study would be needed to resolve the precipitation issue in the MSU resistance to liquid pressure test system.

ASME AG-1 addresses air filtration applications for filtering efficiencies other than HEPA's 99.97% removal efficiency of 0.3 micrometer particles. Regardless of the application, even prefilters selected must function reliability and meet or exceed performance requirements. The more difficult the unit operation upstream of credited filters, the more vital the need to ensure function necessary to protect the credited filters.

FILTER SERVICE LIFE

HEPA filter service life has been an important topic for several years within the AG-1 community in the US as well as in other countries: the primary issues dealt with aging effects of filters in level B storage and in service and the lack of an approved aging test; secondary issues dealt with changes in manufacturing methods - whether planned or accidental- and changes in filter materials and filter designs.

Historically, the policy for HEPA filter replacement in US nuclear facilities was determined by each organization. Typically, HEPA filters are replaced due to age, failure of an in-place leak test, or a prescribed pressure drop limit (typically 4 inches WC). The selection of 4 inches WC for replacement is a compromise between long service life and the need for residual particle loading capacity in case of accidents assuming the filter is functional at 10 inches WC. Some facilities also replace HEPA filters to limit radioactive material trapped on the filter for either operator safety or waste disposal classifications [33].

The motivation for establishing an age limit for HEPA is to provide assurance that the filter will perform its intended function during both normal and upset conditions. The ASME AG-1 Code requires that HEPA filters pass the filter qualification tests of resistance to pressure, resistance to rough handling, resistance to temperature, and spot flame. Media are qualified by tests including tensile strength, water repellency, and media flexing to ensure that HEPA filters are sufficiently robust to perform their safety function. Measuring the annual filter leak test and filter pressure drop is important, but these measurements will not ensure the filter is sufficiently strong to survive high differential pressures, excessive moisture, or high temperatures and smoke from fires. The concern is that the required HEPA strength, as measured with the AG-1 qualification tests, deteriorates over time even when in storage [34]. Although many researchers discussed potential non-destructive measurements to measure HEPA filter strength (e.g. strain gauges for media tensile strength) no studies have been conducted.

The general approach used to investigate age deterioration of HEPA filters was to conduct tests on used HEPA filters and samples of the filter media [34-37]. Most of the studies were conducted on the filter medium from the aged filters; however, the studies by Johnson et al (1988) and Gilbert et al (1994) also included a few tests on the filters [34,36]. The aged filters and filter media used in these studies ranged from new to 21 years. These studies were analyzed to try to establish a maximum service life for HEPA filters initially for use at Lawrence Livermore National Laboratory [33] and were later incorporated into the Nuclear Air Cleaning Handbook as Appendix C [5]. The recommended age limits of 10 years for installations in dry conditions and 5 years for installations in potentially wet conditions were primarily based on experimental tensile strength and water repellency measurements of the medium taken from the aged HEPA filters using the AG-1 procedures in Section FN. These tests were conducted at the Rocky Flats Filter Test Facility prior to decommissioning in which they had the full suite of AG-1 media and filter qualification test equipment. The volume of HEPA filters used at Rocky Flats justified infrastructure used by a qualification product laboratory (QPL) as well as a filter test facility (FTF). Rocky Flats ordered truckloads of HEPA filters directly from manufacturers, qualified each lot, and processed each filter through filter test facility procedures.

Additional tests were also conducted to determine the degradation of the acrylic binder that is added to bind the glass fibers into a filter mat during the manufacture of the filter media [34]. A thermogravimetic analyzer (TA Instruments, New Castle, DE) was used to determine the amount of acrylic binder in the filter medium samples. The test results confirmed that filter media with increased binder had proportionately increased tensile strength. AG-1 tests for resistance to pressure and for resistance to heated air were conducted on three 1,000 cfm Type A HEPA filters and showed the filter with the low binder content failed the test whereas the one with higher binder did not. The low binder content in the media and filter correlated with multiple HEPA failures at the Rocky Flats Plant, which was also the motivation for conducting this filter age study [34]. Such variations in filter media binder complicate the study of filter aging when testing production filters from different years. In addition to the planned and unintended changes in filter media composition, the large scatter of experimental data in these filter age studies suggests that laboratory studies of accelerated aging would yield more accurate results. However, if the accelerated aging laboratory studies are intended to provide a more accurate determination of useful HEPA filter lifetime for nuclear facilities, then these tests would have to be correlated to actual field aging data to validate the laboratory tests. If the accelerated aging tests are intended for improving the performance of HEPA filters or extending their relative life, then correlations with field aging data is not needed.

AG-1 project teams and the full committee have discussed and debated service life of HEPA filters since the original guidance was added to DOE's Nuclear Air Cleaning Handbook. Over a decade ago this ongoing discussion began framing the issue in terms of two segments – ***storage*** under level B conditions and ***in-service*** life. This redefinition of service life has been particularly championed by members of the Nuclear HVAC User Group (NHUG).

NHUG members encouraged a new HEPA filter aging study and began actively identifying aged AG-1 Section FC HEPA filters in support of the effort. They solicitated filters that had been in storage for 10 years or more without being placed into service. NHUG also searched for filters in service for 10 or more years in applications free from radiological contamination. An initial set of thirteen “aged” filters were provided to the Institute for Clean Energy Technology at Mississippi State University for an aging study comparing in service versus aged filters that had remained in storage. These filters were used in an initial aged filter study developing methodology and procedures for qualifying media and laboratory instrumentation. This included evaluating samples of media from those and other aged filters received from DOE facilities that had been in held storage unused for more than ten years [38]. An additional paper providing results of further research is also presented during this year’s conference.

Service life guidelines based on laboratory data such as discussed above can be provided in code or regulatory documents such as the Nuclear Air Cleaning Handbook. However, guidance based on these types of data will almost always be conservatively biased and based on worst case considerations. Using the combination of filters that have remained in storage or used in a variety of service applications to benchmark aging effects neglects changes in formulations used in media manufacturing between periods of qualification. It also ignores the possibility of nonlinear degradation of binders, water repellency and other components.

MSU’s recent studies of aged filters taken from various nuclear facilities show the scatter in data that is large and is similar to that in previous studies [38]. This is not surprising considering the large variation in exposure conditions and also the variability in materials and production methods and designs for different HEPA filters. In contrast, the scatter in data can be greatly reduced by conducting artificial aging of new media under a variety of conditions including temperature, humidity, acid gases, oxidizers, and can provide greater confidence in how storage conditions affect filters in storage. However, because detailed information of field exposure conditions and filter manufacturing variability and are not known, the laboratory results may differ from the field data. Additionally, the expanded suite of test results provides information facilities can use to enhance effectiveness of monitoring and managing in-service filters.

DOE’s established service guidelines for nuclear facilities are not the only such on-going deliberations. Offgases from the wide range of processes involved in domestic nuclear facilities tend to be unique to the facility. Certainly, there are common control considerations, but it is unreasonable to expect in service aging of HEPA filters to be uniform across the breadth of applications. Certainly, aging studies to determine the effects of exposures can assist in both management efforts to enhance safety and reducing unexpected failures.

Oversight/guidance for nuclear facilities in the United Kingdom have also recently reconsidered the service life of HEPA filters, and the recent British approach has been expanded to provide flexibility. There is a stated filter service life similar to the US version, but UK guidelines offer individual facilities the opportunity to expand the service life beyond the federal limit. Each facility can build a case for the extension based on detailed knowledge of the process including control systems, monitoring, and inspections to ensure proper function.

Facilities have a much fuller understanding of how system unit operations function, their reliability, how best to monitor performance, and how to mitigate risks that damage credited HEPA filters during off-normal periods of operation. Engineering considerations coupled with enhanced monitoring, inspection of system functions, and data collection can be incorporated into a petition to expand service life.

Ultimately, the question becomes "who will take responsibility for establishing the age limit." Clearly, a uniform standard has to incorporate the most sensitive case. This emphasizes very conservative times. However, a mechanism allowing each entity to provide a basis for extension may be an alternate companion to a standard service life. If facilities can be provided the opportunity to take responsibility for a site-specific version, then engineering, operational, monitoring, and record keeping essential to meet regulatory requirements must conform to regulatory entity requirements.

It is prudent for the AG-1 committee to at least interface with DOE to consider methodology presented by UK attendees and their approach to extending service life of HEPA filters. It is DOE's and NRC's responsibility to establish a conservative service life for HEPA filters used by facilities under their oversight. However, partnering with regulatory oversight entities to develop methodology by which individual facilities can incorporate system engineering, operational monitoring, and filter inspections to petition service life extension can at least be investigated.

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