ASME AG-1 HEPA Filter Media Velocity

Gerard Garcia
Bechtel National Incorporated
Richland, Washington

Abstract

The ASME AG-1 required maximum HEPA filter media velocity is 5 feet per minute (1). As will be shown below, modern filter media and construction methods make 5 feet per minute an overly conservative value that is not necessary to achieve the level of performance required by ASME AG-1. To better understand these requirements, selected references in the literature were assessed in the context of how the current ASME AG-1 filter media velocity requirement was established. A recommendation is provided suggesting that a media velocity requirement is not required if it were replaced by a performance requirement for most penetrating particle size and particle loading test.

Introduction

ASME AG-1 HEPA filter performance is based on efficiency for a given particle size. The HEPA filter must exhibit a maximum penetration of 0.03% when tested with an aerosol of essentially monodispersed 0.3-micrometer diameter test aerosol particles (2). This requirement drives the filter manufacturer to optimize the filter media design to achieve the required maximum penetration. The filter manufacturer can optimize the filter media design to meet this requirement by manipulating the glass fiber paper composition and overall filter construction so that the total aerosol penetration through the filter media, frame, and gasket are not greater than 0.03% of upstream concentration.

Filtration theory explains how the HEPA filter manufacturer meets this penetration requirement. HEPA filter media does not act like a strainer, where particles that are too large to pass through the open spaces are trapped, and particles smaller than the open spaces pass through. Rather, particles are primarily trapped in the filter media by diffusion, inertial impact, and interception. Particle capture is subject to fiber diameter, fiber spacing, fiber cross-section, media thickness, and media velocity. For a given filter media velocity, aerosol penetration will be at maximum for the most penetrating particle size, and then aerosol penetration decreases for particles smaller or larger than the most penetrating particle size as shown in Figure 1. For a given particle size and filter media type, aerosol penetration will increase as media velocity is increased as shown in Figure 2.

Figure 1 and Figure 2 show that media velocity is an aspect of filter design. However, there is nothing new about the relationship between aerosol penetration, particle size, and media velocity. The longstanding specification for HEPA filter media velocity is 10.5 feet per minute and it dates back to the Department of Defense Military Specifications for gas masks. This same filter media velocity criterion still exists today in ASME AG-1, FC-I-3210.

A relatively recent constraint imposed on the filter manufacturer is the 5 feet per minute media velocity indicated in ASME AG-1, FC-4110 (b). As will be shown below, this newer constraint is an overly conservative value that is not necessary to achieve the ASME AG-1 required level of performance.

Brief History of HEPA Filter Media Velocity

The first standard to mention 5 feet per minute appears to be an Oak Ridge National Laboratory document titled Design, Construction, and Testing of High-Efficiency Air Filtration Systems for Nuclear Applications by C. A. Burchsted and A. B. Fuller. This document was published in January 1970 and was given Oak Ridge National Laboratory document number ORNL-NSIC-65. A sample specification in Appendix A of this document indicates the following for airflow velocity through the filter medium: 5 fpm ± 20% when operated at manufacturer's rated capacity (3). In ORNL-NSIC-65, Figure 2.5, it states: Normal flow rate, at manufacturer's rated filter capacity, is *approximately* 5 fpm (3).

Six years after the publication of ORNL-NSIC-65, its successor was introduced as ERDA-76. ERDA-76 still includes a sample specification for a HEPA filter, but it no longer includes airflow velocity through the filter medium. In ERDA-76, Figure 2.8, it states: Normal flow rate, at manufacturer's rated filter capacity, is *approximately* 5 fpm (4). There are two points of concern with the ORNL-NSIC-65 Figure 2.5 and ERDA-76 Figure 2.8. First, note that the indicated flow rate is only an approximation. Secondly, note that both of these figures are from a Mine Safety Appliances Company bulletin.

There are two likely sources of influence for ORNL-NSIC-65 Figure 2.5 and ERDA-76 Figure 2.8. The first source for these figures appears to be a Mine Safety Application (MSA) Company technical report that discusses penetration versus media velocity curves. The MSA Company collected HEPA filter test data and published the results in a technical report (Reference 5) for the 14th ERDA Air Cleaning Conference in 1976. The second source appears to be the American Association for Contamination Control HEPA filter standard. The MSA report refers to this standard for the filter medium recommended velocity. This standard will be discussed later in this discussion.

The MSA report, titled HEPA Filter Performance Comparative Study, analyzed particle size penetration for five HEPA filter types at media flowrates ranging from 3 feet per minute to 28 feet per minute using homogeneous 0.56, 0.40, 0.30, and 0.16 micron diameter DOP particles. The curves in ERDA-76 Figure 2.8 are based on the same particle sizes with one exception. The only difference between the MSA and ERDA data is at the smallest particle size. MSA shows data for the 0.16-micron particle and ERDA shows data for the 0.10-micron particle. Since the MSA report was published in the same time frame as ERDA-76, and since the input data resembles the ERDA-76 curves, it appears that the MSA data is a source for ERDA-76 Figure 2.8.

Interestingly, the MSA filter media velocities were 6, 5.5, and 5.3 feet per minute when tested at the manufacturer's rated filter capacity for three of the five filter types tested. The point here is that HEPA filters were being manufactured with media velocities greater than 5 feet per minute. The MSA report goes on to state: No comparative tests were conducted on the various filter medium because virtually all filter paper is manufactured with glass fibers which have the same spectrum of fiber diameters and lengths. Consequently, most filter medium should show the same general particle penetration characteristics (5).

To state that, "… all filter paper is manufactured with glass fibers which have the same spectrum of fiber diameters and lengths (5)" is inaccurate. In fact, the opposite is true. Filter papers are manufactured with different fiber diameters as required to achieve the desired filtration efficiency. Filterable particle size depends directly on fiber diameter and filter construction. Further, this statement leads to a conclusion in the report that is incomplete and relevant to the time when this MSA report was written. The last of three conclusions in the MSA report states: Particle collection efficiency for glass fiber HEPA medium in the range tested drops significantly when the filter medium velocity exceeds 5 FPM (5). This statement is true, but it is not the whole story because particle collection efficiency will eventually increase at higher velocities. The MSA report also does not mention that there is a clear decrease in the most penetrating particle size as media velocity increases as illustrated in Figure 2.

Filtration theory says that particle collection efficiency decreases with increasing media velocity up to a point and then collection efficiency begins to increase as velocity increases. This is demonstrated in Characteristics of Air Filter Media Used for Monitoring Airborne Radioactivity (6). This Naval Research Laboratory (NRL) technical report characterizes penetration of 0.3 micron particles as a function of several air velocities for many filter media types. Penetration data for MSA filter media type 1106B is provided in the NRL report. The NRL report shows that penetration for the MSA filter media increases to a maximum at about 30 centimeters per second, but as the flow rate is further increased, penetration decreases progressively as predicted by filtration theory.

The MSA report states: One can observe from the family of curves that if the filter medium velocity exceeds the AACC CS-1T recommended velocity of 5 FPM, particle penetration increases significantly (5). AACC CS-1T is a reference to the American Association for Contamination Control HEPA filter standard. It is obvious from the above statement that the AACC media velocity *recommendation* influenced the results of the MSA report. However, the media velocity *recommendation* in the AACC HEPA filter standard is relevant to the source data collected at the time to generate such a recommendation. As will be shown below, there is new source data that appears to point to a different conclusion. The AACC published the first HEPA filter standard outside the government in May 1968. This first publication was designated AACC CS-1T ("T" for tentative) and it was titled "HEPA Filters." The AACC later became the Institute of Environmental Sciences (IES).

In November 1983, the IES published IES-RP-CC-001-83-T. In January 1986, the IES published IES-RP-CC-001-86, "Recommended Practice for HEPA Filters" and it superseded both IES-RP-CC-001-83-T and AACC CS-1T. The 5 feet per minute media velocity in AACC CS-1T carried over to IES-RP-CC-001-83-T and then to IES-RP-CC-001-86. In 1993, the IES published IES-RP-CC001.3, "HEPA and ULPA Filters" which superseded IES-RP-CC-001-86. The most significant change to IES-RP-CC-001-86 is the deletion of the 5 feet per minute media velocity requirement.

Ironically, the IES initially recommended 5 feet per minute media velocity and indirectly influenced the media velocity requirement in ERDA-76, but now it no longer cites this requirement. It is ironic because it will be shown later how the ERDA-76 media velocity requirements cascaded into ASME AG-1. To get a complete history of the evolution of nuclear air cleaning standards, see <u>Review of HEPA Filtration Test Standards and Their Applications to Nuclear Applications</u> by Jacox in the literature for the 22nd DOE/NRC Nuclear Air Cleaning and Treatment Conference (7). Table 1 also provides a chronology of the 5 feet per minute media velocity requirement in the documents indicated in this paper.

The test results from the MSA report are shown in Figure 3. This figure shows particle size penetration curves for various media velocities. There are three items of interest in this figure. The first item of interest is the curve for 0.3 microns that crosses the 5 feet per minute media velocity line at 99.97% efficiency. The second item of interest is the arrow on Figure 3 that points to the 5 feet per minute media velocity line with the note that states, "Recommended Filter Media Velocity." This note is similar to what now appears in ERDA-76. Thirdly, note how the curves shown in Figure 3 compare to the penetration versus airflow velocity curves shown in the new Nuclear Air Cleaning Handbook (8). The curves from the new Nuclear Air Cleaning Handbook are shown in Figure 4.

The difference between the MSA curves shown in Figure 3 and the new Nuclear Air Cleaning Handbook curves shown in Figure 4 is approximately 30 years of filter media research and development. Modern filter media and construction methods make the curves shown in Figure 3 and in ERDA-76 obsolete. The filter media used to create Nuclear Air Cleaning Handbook data shows that the ASME AG-1 definition for a nuclear grade HEPA filter (i.e., 99.97% efficient at 0.3 microns) can be achieved at media velocities up to 10.5 feet per minute. Figure 4 also shows that 99.97% of the most penetrating particle size (MPPS) can be filtered at a velocity of 6 feet per minute. The curves in Figure 4 are further substantiated by the HEPA filter test data found in References 9, 10, 11, and 12.

Reference 9 by Lifshutz and Pierce shows penetration curves for HEPA filter media at 1.0, 1.2, 1.8, 2.5, 3.5, and 5.35 centimeters per seconds (i.e., 2.0, 2.4, 3.5, 4.9, 6.9, and 10.5 feet per minute respectively). The penetration for the test HEPA filter media is less than 0.01% for all velocities for the 0.3 micron aerosol particle.

Reference 10 by Pierce provides a summary table of test data for penetration of HEPA filter media at 10.5 feet per minute (the standard test velocity for media), and at 5 feet per minute. The summary table in Reference 10 shows a maximum penetration of 0.03% for the 0.3 micron aerosol particle at 10.5 feet per minute.

Reference 11 by Cambo provides test data for Lydall Grade 3398 filter media for eight different velocities ranging from 1 to 10 feet per minute. The filter penetration for the Lydall Grade 3398 filter media is less than 0.03% for the 0.3 micron aerosol particle at all velocities.

Reference 12 by VanOsdell et al. provides test results for Lydall Grade 213 filter media. The test results for the Lydall Grade 213 filter media in Reference 12 show that the ASME AG-1 definition of a HEPA filter can be achieved for velocities ranging from 0.5 to 20 centimeters per second (1 to 39 feet per minute). The test results also show that the penetration of the most penetrating particle size is less than 0.01%. In other words, the filtration efficiency is greater than 99.99% for the most penetrating particle size for this filter paper. Reference 12 test results for Lydall Grade 252 filter media are even better.

Reference 9, 10, 11, and 12 show agreement with the penetration versus airflow velocity curves shown in Figure 4 from the Nuclear Air Cleaning Handbook (8). In other words, independent HEPA filter test results show that modern filter media and construction methods make the curves shown in Figure 3 obsolete.

After ERDA-76, the next standard to reference 5 feet per minute media velocity was DOE Standard NE F3-45. However, it was carried over from ERDA-76 without any reference to it being an approximation. DOE Standard NE F3-45 was the predecessor to DOE-STD-3020.

DOE-STD-3020-97, Article 5.2.3, now states: The total effective media area provided within the filter pack shall be such that face velocity shall not exceed 5.0 ft/min (1.52 m/min) at the rated airflow (13). Again, the reference to it being an approximation has been omitted.

The 5 feet per minute media velocity requirement in DOE-STD-3020-97 was carried over to ASME AG-1 by a recommendation from a senior member of the ASME AG-1 Committee on Nuclear Air and Gas Treatment. Table 1 provides a chronology showing how the 5 feet per minute media velocity requirement cascaded from AACC CS-1T to ASME AG-1-2003. The addition of the 5 feet per minute media velocity requirement to ASME AG-1-2003 has created confusion with regard to methods for specifying the collection efficiency of HEPA filters. It is also imposing unnecessary limitations on ASME AG-1 Section FC for HEPA filters and Section FK for special HEPA filters. ASME AG-1 was the first nuclear air treatment code to cite this filter media velocity requirement.

ASME N509 and ASME N510 are both predecessors to ASME AG-1. Neither of these codes includes reference to 5 feet per minute media velocity. However, in ASME N509, it does state that: Glass fiber media shall conform to the requirements of Military Specification MIL-F-51079 (14).

Military Specification MIL-F-51068 is the longstanding Department of Defense HEPA filter specification and is titled Filters, Particulate (High-Efficiency Fire Resistant). MIL-F-51068, Article 3.2.5 states: Unless otherwise specified in the contract or purchase order, the filter medium shall conform to MIL-F-51079. Military Specification MIL-F-51079 is the longstanding Department of Defense HEPA filter media specification and is titled Filter Medium, Fire-Resistant, High Efficiency.

MIL-F-51079, Article 3.2.1 states: The pressure drop across the medium shall not exceed 40 millimeters of water (1.57-inches WC) with ambient temperature airflow through the medium at a minimum velocity of 320 centimeters per minute (10.5 feet per minute), when tested in accordance with 4.2.4.1 (15). Military Specification MIL-F-51079, Article 4.2.4.1 states: Three test specimens shall be tested for airflow resistance and DOP smoke penetration at a flow rate of 32 liters per minute using the Q127 DOP Filter Testing Penetrometer. The exposed test area of the specimens is 100 square centimeters (15). After converting the above values to US customary units, and dividing flowrate by media area, it can be shown that the media velocity requirement is 10.5 feet per minute. Military Specification MIL-F-51079 was cancelled in 1998. The December 1998 cancellation notice states: "MIL-F-51079D, dated 14 March 1985, with Interim Amendment 1, dated 17 February 1988, is hereby cancelled. Further acquisitions should refer to Appendix FC-I of American Society of Mechanical Engineers (ASME) AG-1 Code on Nuclear Air and Gas Treatment." In ASME AG-1-2003, Appendix FC-I, the required media velocity is 10 feet per minute.

Alternate Performance Specifications

This selection of literature references demonstrates that modern filter media and construction methods make 5 feet per minute an overly conservative value that is not necessary to achieve the level of performance required by ASME AG-1. As it stands, the ASME AG-1 media velocity requirement is by chance serving to provide a factor of safety for the filter design. One conclusion to be drawn is that ASME AG-1 should redefine what is necessary to achieve the level of performance required for modern filter media and construction methods – not leaving the physical integrity of the modern filter to chance. Alternate performance specifications should be considered to address normal filter loading and include a factor of safety for accident scenarios.

Ideally, the alternate performance requirement would address normal operating conditions, taking into consideration the most penetrating particle size for various media velocities, and also provide a benchmark whereby upset conditions could be taken into consideration for specific applications. Filter manufacturers already produce these forms of performance data, namely, penetration versus particle size curves and particle-loading performance curves. Incidentally, these alternate filter media performance requirements are being considered for inclusion in the DOE HEPA filter standard currently being revised.

DOE HEPA Filter Standard Revisions

DOE committed to revising four DOE Technical Standards relating to HEPA filters in a November 2004 letter to the Defense Nuclear Facilities Safety Board. Revision of the first of these DOE standards, DOE-STD-3020-97, Specification for HEPA Filters Used by DOE Contractors, is to be completed by December 2005.

The DOE Office of Quality Assurance Programs (EH-31) is leading the effort to revise the four DOE standards. DOE is using a team of HEPA filter subject matter experts to perform a comprehensive review of the DOE standards and incorporate information from the Nuclear Air Cleaning Handbook, DOE-HDBK-1169-2003, applicable national consensus standards, and information gathered from various past assessments of DOE HEPA filtration systems. The EH-31 staff held the first team meeting in March 2005 at the DOE offices in Germantown, Maryland. A subject matter expert on this DOE team, who is a distinguished author of many technical papers on nuclear air and gas treatment, has been tasked with providing documentation and a technical basis for the alternate performance requirements described below.

The first alternate performance requirement may take the form of a filter media specification that ensures that percent penetration for the most penetrating particle size is below 0.03% for all media velocities. If the manufacturer's filter media is capturing the most penetrating particle size with a percent penetration less than 0.03%, then the filtration efficiency for all other particle sizes will be greater than 99.97%.

The second alternate performance requirement may take the form of a specification for particle mass loading per some fraction of rated filter airflow up to a maximum allowable differential pressure. For example, the specification could state: "At rated airflow the filter shall be capable of holding 50 grams of test dust for each 100 cubic feet per minute of airflow when loaded to 6 inches WC differential pressure based on a test dust load rate of 2.5 grams per minute."

The goal of this specification should be to create a benchmark particle loading curve against which all HEPA filter applications can be measured and include a margin of safety. The benchmark particle-loading curve could be based on differential pressure divided by velocity (i.e., $\Delta P/V$) along the ordinate and the mass of the benchmark test dust in grams along the abscissa. If the benchmark test dust uses $\Delta P/V$ along the ordinate, the primary influence of airflow velocity is removed. This agrees with Darcy's Law, which predicts that $\Delta P/V$ is a constant independent of airflow rate as reported and further qualified by Bergman et al. in Reference 16.

The acceptance criterion for this requirement will mandate that all points along the manufacturer's particle loading performance curve will have to be less than the benchmark particle loading performance curve. If the test dust has a characteristic particle size less than 0.3 microns, then this specification can provide a safety margin by bounding the service for specific HEPA filter applications. The test dust aerosol parameters, such as particle size, density, shape, and electrical charge, will be influential in determining the benchmark. Initially, sodium chloride and carbon black aerosols are being considered.

If the new DOE standard is published with the alternate performance requirements indicated above, it would constitute an important step toward creating a performance-based specification for air cleaning codes and standards. The salient characteristics of DOE-STD-3020-2005 will be collection efficiency at the efficiency minimum and performance parameters for nominal volume flow. Thus, this DOE standard will make a vital contribution to eliminating a confusing multiplicity of methods for specifying the collection efficiency of HEPA filters.

Particle loading capacity of a HEPA filter is directly related to aerosol particle size and environmental conditions upstream of the HEPA filter. It is also directly related to fiber diameter, fiber spacing, fiber cross-section, and media thickness used to fabricate the filter media. Particle loading capacity is indirectly related to media velocity and increases as media velocity increases. Therefore, there is an economic consequence of allowing higher and higher media velocities. Since media velocity (i.e., flow rate divided by media area) is the same for a newly installed HEPA filter and for a HEPA filter just prior to filter change-out, this shows that media velocity is not a characteristic of filter performance. Therefore, media velocity should not be relied on as a measure of performance. To arbitrarily set a maximum allowable media velocity, without reference to most penetrating particle size or loading capacity, in large measure removes the incentive from the filter manufacturer to select the best filter media for a given application.

Recommendation

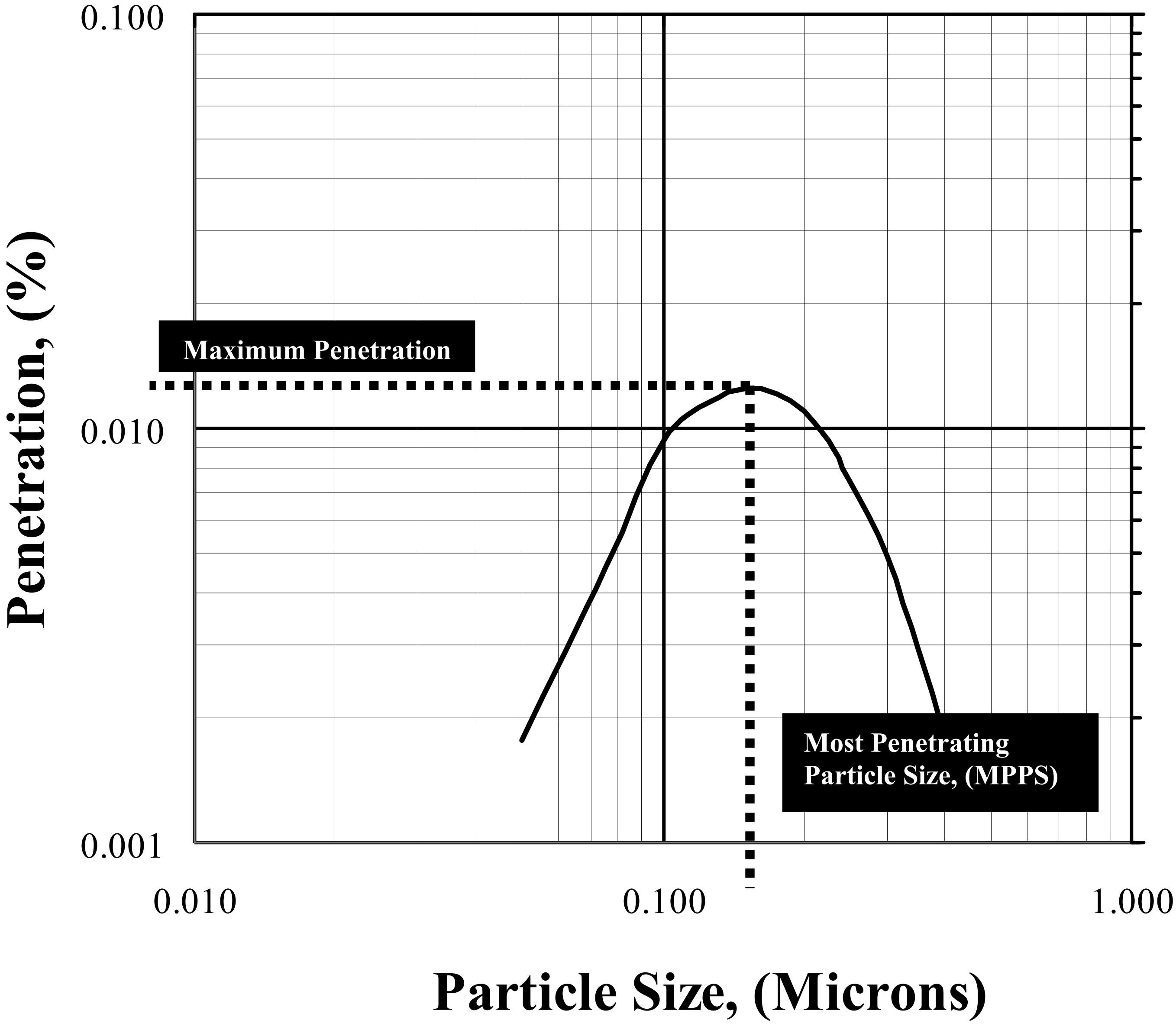
If the ASME AG-1 media velocity requirement were relaxed or eliminated, alternate filter performance requirements must be specified to ensure the safety of the confinement system for the operating life of the filter. Using the alternate filter performance requirements described above could incentivize filter manufacturers to minimize the resultant filter pressure drop while achieving the required filter efficiency and particle loading capacity. This approach could create a more competitive filter market while providing the margin of safety required for nuclear applications. Therefore, consideration should be given to replacing the ASME AG-1 media velocity requirement with the alternate performance requirements indicated above.

Conclusion

This selection of literature references demonstrates that modern filter media and construction methods make 5 feet per minute an overly conservative value that is not necessary to achieve the level of performance required by ASME AG-1. The literature shows that the source document for 5 feet per minute (i.e., Institute of Environmental Sciences, IES-RP-CC001.3) has deleted this requirement. Imposing this relatively recent code requirement (i.e., relative to the longstanding Department of Defense military specification) is a more limiting criterion than either the ASME AG-1 filter efficiency or air resistance requirements.

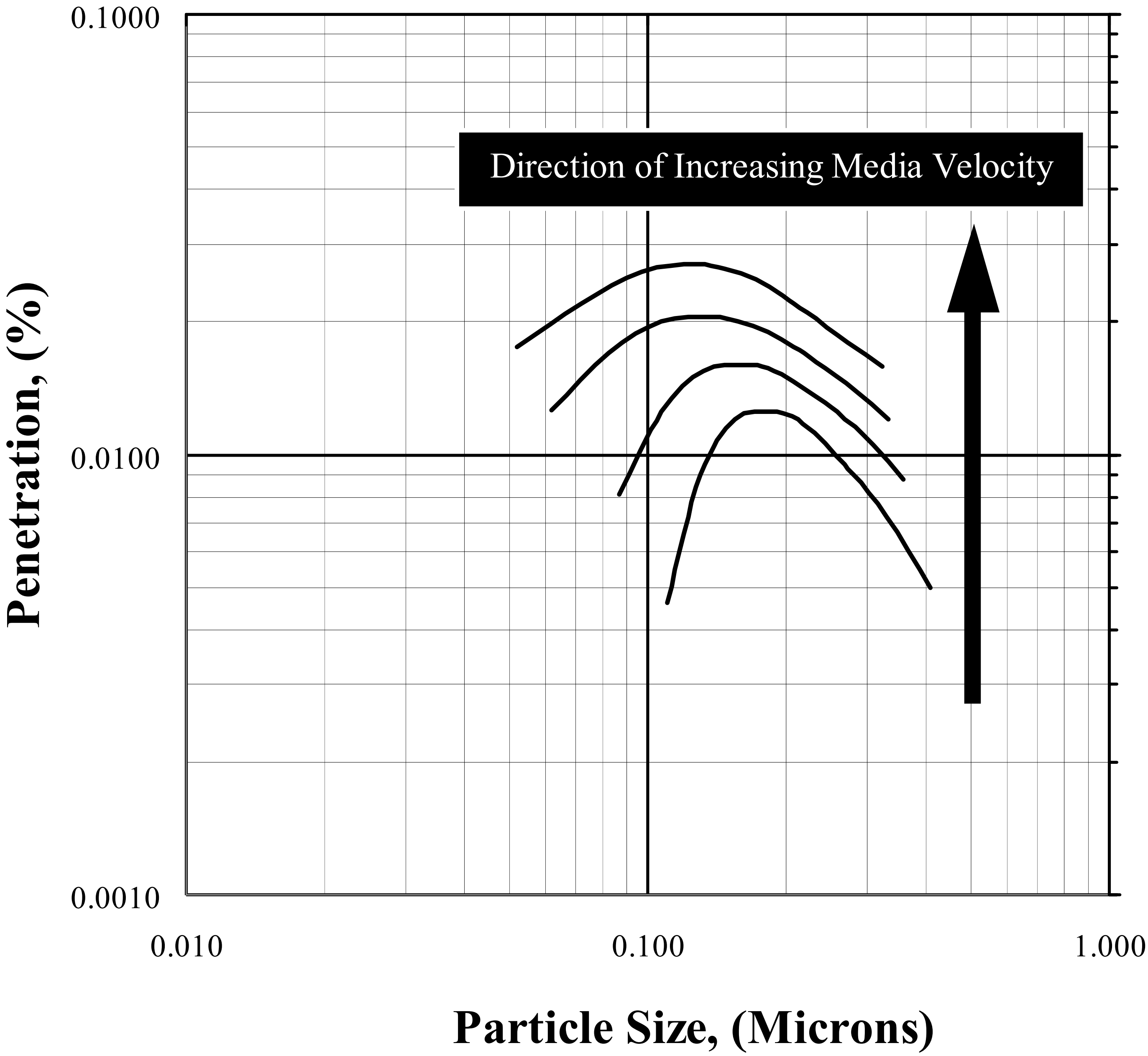
Filter penetration and air resistance are properties that can be validated by qualification tests. Media velocity is not a characteristic of filter performance and is not measured directly, but is determined by dividing the volume flowrate by the exposed filter media. This can lead to errors. By revising the codes and standards to require penetration versus particle size curves and particle loading performance curves, the ASME AG-1 media velocity requirement of 5 feet per minute can be replaced.

Figure 1



0.100
0.010
0.001
0.010
0.100
1.000
Penetration, (%)
Maximum Penetration
Most Penetrating
Particle Size, (MPPS)
Particle Size, (Microns)

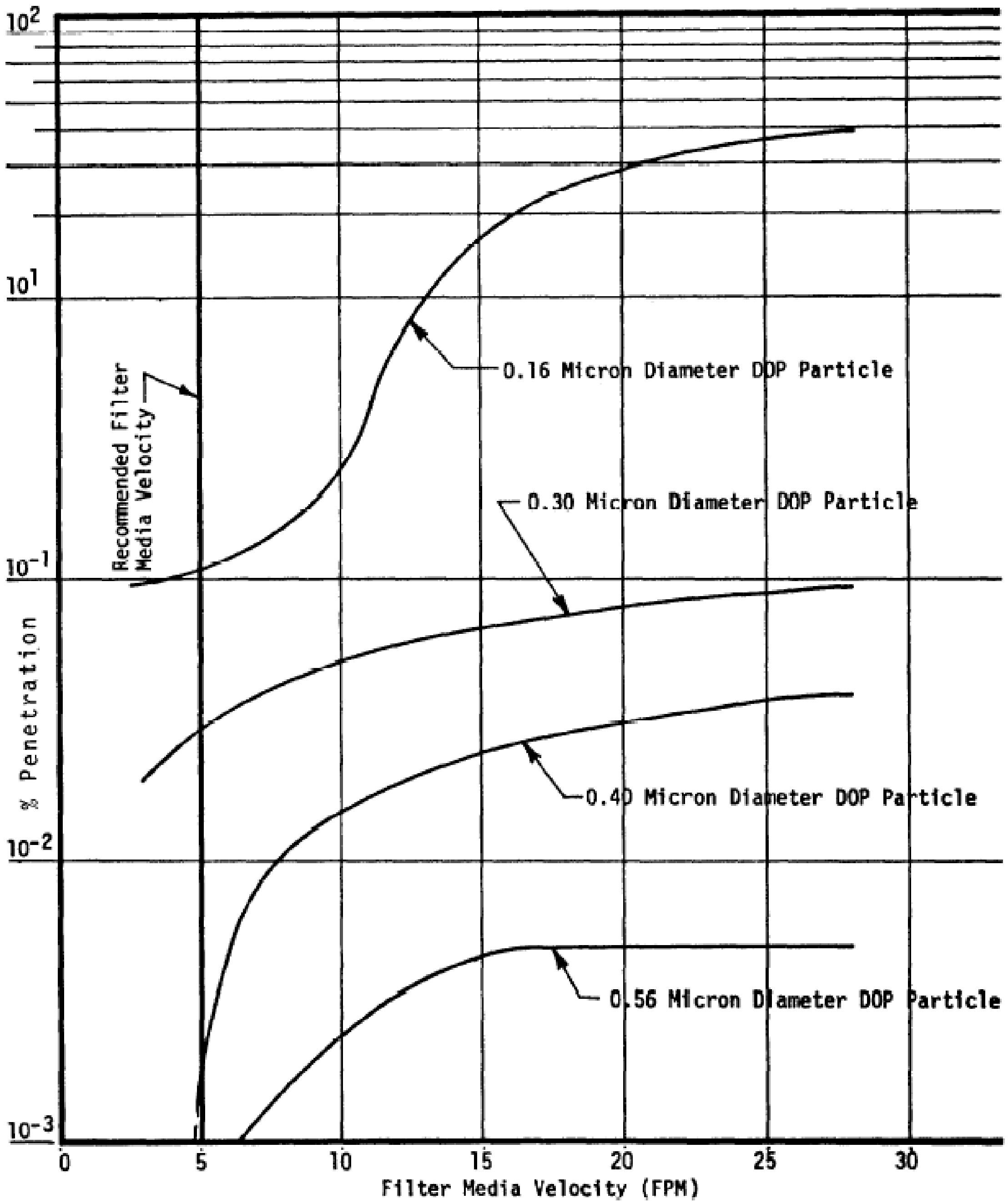
Figure 2



0.1000
0.0100
0.0010
0.010
0.100
1.000
Penetration, (%)
Particle Size, (Microns)
Direction of Increasing Media Velocity

Figure 3

Particle Size Penetration Curves



Source: HEPA Filter Performance Comparative Study, C. A. Gunn and D. M. Eaton, 14th ERDA Air Cleaning Conference, Figure 12, Page 659.

Figure 4

Particle Size Penetration Curves

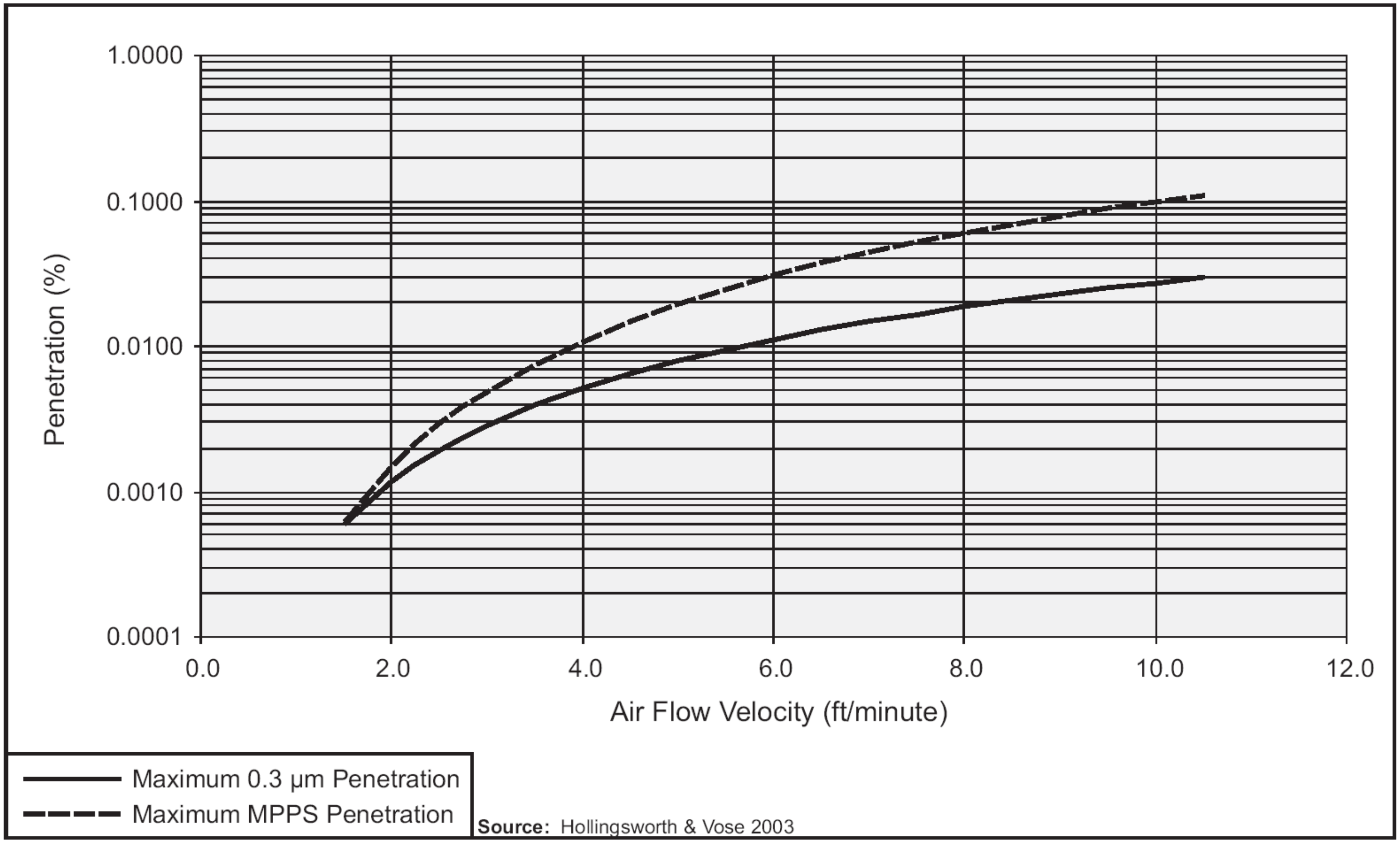


Table 1			
Organization	**Document Number and Document Title**	**Year Of Publication**	**Filter Media Velocity Criteria**
American Association for Contamination Control	AACC CS-1T, HEPA Filters	1968	Recommended 5 FPM
Oak Ridge National Laboratory	ORNL-NSIC-65, Design, Construction, and Testing of High-Efficiency Air Filtration Systems for Nuclear Applications	1970	Approximately 5 FPM
Oak Ridge National Laboratory	ERDA-76, Nuclear Air Cleaning Handbook	1976	Approximately 5 FPM
Institute of Environmental Sciences	IES-RP-CC-001-83-T, HEPA Filters	1983	5 FPM
Institute of Environmental Sciences	IES-RP-CC-001-86, HEPA Filters	1986	5 FPM
DOE	NE F3-45	1987	5 FPM
Institute of Environmental Sciences	IES-RP-CC001.3, HEPA and ULPA Filters	1993	No Requirement
DOE	DOE-STD-3020-97, Specification for HEPA Filters used by DOE Contractors	1997	5 FPM Maximum
ASME	ASME AG-1-1997, Nuclear Code on Nuclear Air and Gas Treatment	1997	5 FPM Maximum
ASME	ASME AG-1-2003, Nuclear Code on Nuclear Air and Gas Treatment	2003	5 FPM Maximum
DOE	DOE-HDBK-1169, Nuclear Air Cleaning Handbook	2003	No Requirement

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3. Burchsted, C. A. and Fuller A. B., Design, Construction, and Testing of High-Efficiency Air Filtration Systems for Nuclear Applications, ORNL-NSIC-65, Oak Ridge National Laboratory, Oak Ridge, TN, January 1970.
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11. Cambo, W., Lydall Filtration/Separation Group, Lydall Grade 3398 filter media data, facsimile, October 7, 2003.
12. VanOsdell, D. W., et al., Experimental Study of Submicrometer and Ultrafine Particle Penetration and Pressure Drop for High Efficiency Filters, Aerosol Science and Technology, Volume 12, Number 4, 1990, pages 911-925.
13. DOE Standard, DOE-STD-3020-97, Specification for HEPA Filters Used by DOE Contractors, January 1997.
14. ASME N509-1989, Nuclear Power Plant Air-Cleaning Units and Components, Article 5.1, ASME New York 10017-2392, 1989.
15. Military Specification, MIL-F-51079D, Filter Medium, Fire-Resistant, High-Efficiency, March 14, 1985.
16. Bergman, W., et al., Enhanced Filtration Program at LLL – A Progress Report, 15th DOE Air Cleaning Conference, page 1085.