SAMPLING ISSUES AND THE IN-PLACE LEAK TEST

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Abstract

Sampling manifolds have been accepted as a means of overcoming difficulties with non-homogeneity of the tracer-air stream resulting from series HEPA and series adsorber designs. However, the use of sampling manifolds during the in-place leak test may be an ineffective solution to the problem of non-homogeneity, especially for the measurement of single, point-source leak paths in a laminar flow environment.

1.0 INTRODUCTION

Design of nuclear air and gas treatment systems includes features to assure the uniform treatment of air or gas, at very high efficiency, for the removal of particulate and gaseous forms of radionuclides.

To accomplish this objective, at least three conditions must exist:

1. Minimization of bypass of untreated air or gas, around or through the media
2. Utilization of high efficiency filtration and adsorption media
3. Uniform treatment of air or gas by the system

During the design and pre-installation of the nuclear air and gas treatment system, testing is performed to assure design objectives are met. In addition to pre-installation testing of the housing, HEPA filters are tested at 100% sampling using a 0.3 micrometer, mono-dispersed particulate challenge. This test reveals penetration of the media itself in addition to bypass of the media due to manufacturing imperfections. In addition, a representative sample of adsorbent media is tested in accordance with ASTM D-3803-1989 (1) for methyl iodide efficiency. This test reveals penetration of the media itself in addition to any bypass of the media occurring due to wall effect in the test apparatus or adsorbent packing imperfections. Manufacturing, sampling and laboratory test procedures are calculated to minimize, to the greatest extent possible, imperfections in manufacturing, sampling, or testing that contribute untreated air or gas passing through the system.

With these considerations as background, this paper discusses sampling problems inherent in testing HEPA and adsorber filter banks These tests comprise part of a group collectively known as *In-Place Leak Tests* and serve to evaluate design conditions one and three above. None of the difficulties discussed are new to the industry. This paper is limited to HEPA and adsorber bank testing within the nuclear air and gas treatment housing and does not address other testing issues that may exist on a system basis. Accordingly, this paper will not address issues relating to bypass ducts or system imbalances that might result in unacceptable system performance. Inasmuch as challenge injection and sampling is most often accomplished by accessing inlet and outlet system ductwork, considerations of system ductwork will be discussed within that framework.

2.0 REPRESENTATIVE SAMPLING

Since effective in-place leak tests are dependent upon representative sampling, the subject of sampling and challenge homogeneity is a fundamental concern. Except for the hypothetical one SCFM air treatment system containing a single HEPA filter bank, the testing of nuclear air and gas treatment systems is a sampling endeavor. One hundred percent of the system flow will not pass through our detectors and therefore we must sample. Sampling from a homogeneous challenge mixture of air or gas, our chances of a rigorously performed test are excellent. Sampling from a strongly heterogeneous mixture, our chances are diminished. The degree of uniformity, (homogeneity or degree of mixing) increases our chances of a valid measurement. Alternatively, we are allowed to make certain assumptions, primarily in the area of downstream sample mixing, avoiding altogether the requirement of multiple sampling. Such an assumption considers the fan downstream of the system an ideal mixing device. Depending upon system configuration, even this assumption may not be error free.

On a practical level, a high degree of rigor has not been applied to sampling activities as they are practiced in the field. Since homogeneity or degree of mixing is influenced by Reynold’s number, it is intuitively clear that areas downstream of system turbulence are more likely to be well mixed than areas of laminar flow. Therefore we strive to inject our challenge agent upstream of a turbulent mixing device e.g. a fan in the case of positive pressure systems; upstream of a bend in the ductwork or damper in the case of negative pressure systems. Similarly, we prefer to take our downstream sample at the fan outlet for negative pressure systems, and downstream of duct bends or dampers in the case of positive pressure systems. While we recognize the importance of mixing, our efforts to quantify the degree of mixing are often lacking or fall short of the ideal.

One common error encountered often in the field is the misapplication of the *ten duct diameter* rule of thumb. Often individuals in the field insist on locating a downstream sample port at least ten duct diameters downstream of the point of potential leakage, as though this were a prerequisite to representative sampling. In fact, the ten duct diameter rule is properly applied where laminar flow is desired, i.e. in an effort to obtain a reasonably flat velocity profile during duct velocity measurement. Of course this is the antithesis to the mixing we require for homogeneous sampling.

Another concern often expressed is the notion of sampling particulates in an area of laminar flow *downstream* of a turbulent mixing device, e.g. a fan, damper, duct transition or duct bend. Here the concern questions the validity of sampling in a region of laminar flow and the corollary concern that adequate challenge mixing will no longer be present in such an area of laminar flow. Were the particle size distribution of our test agent not sub-micron, this might be a valid concern, however in the case of HEPA filter and adsorber bank in-place leak testing, once mixed, the challenge is not un-mixed by entry into a region of laminar flow.

Awarness of these issues supports the observation that experienced individuals involved in testing of nuclear air and gas systems are sensitive to the importance of tracer-air mixing both at the inlet and the outlet of the filter bank under test.

What is less commonly understood is the fact that in-place leak tests are routinely performed by combining assumptions concerning mixing, e.g. a change of duct direction provides adequate mixing, and limited measurements of uniformity based on intuitively determined sampling plans. While we purport to measure system efficiencies to 10^{-4}, we accept uncertainties in the test method itself that have not been adequately estimated, presumably accounting for them by safety factors built into the acceptance criteria.

3.0 MULTIPLE SAMPLING AND SAMPLING MANIFOLDS

Difficulties with adequate tracer-air mixing are not absent in systems containing a single bank of HEPA filters or adsorbers. However, such difficulties are assured when HEPA filters or adsorbers appear in series within a single air-cleaning housing.

As a test or design engineer, our response to the critical issue of tracer-air mixing in this case may be to:

1) Enhance mixing
2) Increase the sample point density

From the design side, designing the system for inherently well-mixed areas upstream and downstream of each filter bank is preferable. Designing in the requirement for multiple sampling (manual or manifolds) admits to the limitations of the design and further encourages poor design.

From the perspective of the test engineer, new designs should not subject test personnel to situations requiring the use of compromise techniques to mitigate the consequences of poor design. Many hours have been spent in committee rooms debating whether or not testing methodologies for systems built in accordance with the latest design standards are applicable to earlier designs. Those of us on the testing side of the debate have been concerned with having available a testing standard that accommodates a wide range of existing system configurations rather than a standard developed for the purpose of testing and accepting systems built in accordance with a companion design standard. The 1975 version of ANSI/ASME N510 (2) was silent on this subject however provided a wide range of flexibility, allowing the user to choose as appropriate sections of the standard to fit a particular application. In 1980 the authors of N510 (3) addressed the problem directly, stating that “It is the intent of this standard that it be rigorously applied only to systems designed and built to ANSI N509; however, sections of this standard may be used for technical guidance for testing of non-N509 systems." This flexibility was carried through to the 1989 version of the standard (4). It is this statement on limitations of the standard that makes it possible to test systems that would be considered un-testable by current test methodologies and to avoid regulatory and administrative traps. However, invocation of this limitation places a burden on the test engineer who must rely on a reservoir of experience to assure adequate tests are performed.

The heart of in-place leak testing consists of three parts; uniformly challenging the bank under test, obtaining a representative sample of the upstream challenge concentration and obtaining a representative sample of the downstream concentration. The samples obtained must represent an accurate measure of the concentration in the total system flow rate and results are then presented as percent of system flow rate. It is not surprising that the significant difficulties encountered during field-testing relate to these three elements. All three elements relate directly to a single, seminal variable, the variable of mixing. Evaluation of homogeneity at the sample point, whether upstream or downstream of the bank has been addressed in two ways. First, the air-aerosol mixing test in all versions of N510 and AG-1 (5) is employed to validate uniform mixing of the upstream challenge to the HEPA or adsorber bank to within plus or minus 20%. Dealing with air/aerosol mixing at the downstream sample point has experienced a somewhat more difficult development. The 1975 version of N510 addressed the issue in Section 11 entitled *Multiple Sampling Technique*. While the Section was confusing to some, the intent of the Section was to evaluate air-aerosol mixing at the downstream sample plane and obtain a statistically significant estimate of the system leak rate based on multiple samples. The multiple sampling technique included calculation of the average concentration in the sample plane and calculation of the 95% confidence level of concentration using standard t-values depending on the number of samples taken. An unfortunate pre-requisite requiring elimination of all leaks prior to sampling assured there would be nothing at all to sample.

Section 11 was carried through to the 1980 version of the Standard but eliminated from the 1989 version in favor of manifolds as described in Appendix C and Appendix D of ASME N509-89 (6). Section 10.3 of N510-75 offered the following instruction,

The downstream sample point should be located, if possible, at a point where a single-point, representative sample, representative of the downstream concentration can be taken; this may be a point downstream of the fan or auxiliary blower, or a point downstream of a flow disturbance which will provide adequate mixing of the DOP-air mixture emitting from the filters in the bank. Where it is impossible to obtain an adequate single-point downstream sample; a multiple sampling technique, in accordance with Section 11, is required.

Again, these instructions were carried forward to the 1980 version and subsequently abandoned. It is interesting to note that there is an implication inherent in the instruction that suggests fans and other flow disturbances by virtue of their presence are adequate in themselves to allow proceeding with the test without the need for multiple sampling. The instruction implies that the use of the multiple-sampling technique is required only when such features do not exist.

It is clear that the introduction of the intuitively appealing notion of downstream sampling manifolds has supplanted the multiple-sampling technique described in earlier versions of N510.
The reasons for the move toward temporarily or permanently installed downstream sampling manifolds are varied and stated quite clearly in Appendix C of ASME N509. Manufacturers are receptive to the idea of permanently installed manifolds because it frees up their designs. Manifolds installed by manufacturers generally have one of two purposes. Certain manifolds are installed for the sole purpose of identifying areas within the bank that leak. From my field experience, these manifolds perform reasonably well. Other manifolds are installed for the purpose of quantifying bypass leakage. My experience in the field and in the shop with these devices has been mixed:

1. When installed in laminar flow environments downstream of leak paths with
2. little room between banks, these devices perform poorly.

2. When installed in areas downstream of turbulent flow or at distances from the point-source leak that allow distribution of the leak plume across the sampling plane, they are more successful in assisting in the determination of actual leak.

Unfortunately, manifolds are often considered an adequate remedy for the former condition. At this point it may be useful to consider another technique known as the *Shroud Test,* offered in N510-75 but deleted in N510-80 to overcome system design problems of non-homogeneity. This test consists of using a shroud to cover individual bank areas, usually a single HEPA filter. A properly designed shroud allows for sampling the section total flow at the shroud outlet where the total shroud flow converges in an area significant smaller than the area shrouded, increasing homogeneity. Area by area, leak rate measurements are taken until the entire bank area has been covered. The individual area readings are averaged and the result is a measurement of leak rate where individual leaks are proportioned relative to total system flow. This technique serves as a theoretical basis for a properly designed sampling manifold and highlights the fundamental problem with current sampling manifold design, i.e., reading obtained with conventionally designed sampling manifolds cannot proportion aerosol detected relative to total system flow. *Sampling manifolds are an attempt to perform the shroud test, without capturing concentration information contained within the entire leak plume.* An adequately designed manifold must be able to quantify the concentration integral in the leak plume in terms of concentration/volumetric flow rate in order to allow a meaningful calculation to the upstream concentration that is based on concentration reading/total system flow rate.

The design of *injection* and *sampling* manifolds are often considered together. Section C5.1 of ASME N509-89, Appendix C states:

In general, all the design points mentioned for injecting manifolds apply to sampling manifolds. The main difference is the low reduced concentration of the challenge agent, on the order of a fraction 1000 to 100,000 less. This greatly reduces the problem of aerosol agglomeration and plateout.

However, injection manifolds and sampling manifolds are fundamentally different. The injection manifold is empirically designed to *disperse* aerosol across the upstream face of the filter or adsorber bank by the use of multiple injection points. A salient feature of this process is *control*, i.e. the designer has the ability to control dispersion; in effect, a means of creating artificial mixing. In the case of the sampling manifold, the designer has little control over the physical characteristics of the leak in terms of concentration profile from the leak point to the sample point or where any given individual leak will occur. The only option the designer has, short of introducing turbulence to improve manifold performance, is to increase the number of sample points in the manifold and locate the manifold as far as possible from the potential leak source. While mixing can be simulated using an injection manifold, artificial mixing cannot be simulated using a sampling manifold in a meaningful way that accounts for the population of potential leak paths and their individual character.

While guidance is provided for the design of sampling manifolds in both N509 and AG-1, it is clear that the guidance is incomplete and in some cases misleading. Consider the following statement in Section HA-5800 of AG-1:

Sampling manifolds shall be qualified to demonstrate that they collect a representative sample equivalent to a single-point sample taken at a point at least ten duct diameters downstream of the filters.

Once again we are re-visiting a fundamental confusion between an area suitable for a velocity traverse and an area suitable for single point challenge sampling. In defense of AG-1 and the decision to include allowance for sampling manifolds, referencing manifold performance to a single point sample of *measured homogeneity* is commendable. However, other assumptions built into Appendix HA-D are potentially non-conservative. For example, although there is an effort to produce artificial leak paths that are representative of the population of potential paths and, an effort to account for differences in manifold operation at various flow rates, this effort cannot adequately characterize manifold operation under actual operating conditions. A system with variable flow rate may be tested at each extreme of operation. Manifold operation through the *range* of flow conditions is not evaluated. The result of manifold testing is the production of a test artifact, carefully engineered to produce acceptable results for each test case at the time of testing.. This is not to say that sampling manifolds cannot be and are not designed to operate effectively, some of the time. This *is* to suggest that such an outcome is fortuitous and unpredictable to a degree, depending on the right combination of eddies and dispersion patterns within a fluid medium, the right amount of sampling, at the right place and at the right time. A key design feature not included in current manifold design guidance would require that the sampling rate at each sample orifice be the same, within acceptable limits of variability. It is clear that a sample manifold designed with equal diameter orifices at each sampling point will draw sample according to the differential pressure across each orifice. It is equally clear that orifices closer to the vacuum source will be biased in a positive direction, for the same reason. However, it seems that the object of manifold design is to create a device that appears to work under a given set of conditions, independent of such design considerations. We could rightly call this the *art*, and perhaps the artifact, of manifold design.

Since sampling manifolds are convenient and provide a *clean*, *simple* method of obtaining a downstream sample, they are very attractive to both the manufacturer and end user. However, the goal of the in-place leak test should not be simplicity but rather accuracy; the best accuracy obtainable given system design and within the constraints of other realities, e.g. local dose rates and contamination levels. In certain cases, the uncertainty introduced by the use of manifolds may be a good trade-off considering other conditions that may prevent in-place leak testing altogether. However, the first focus should always be the search for homogeneity rather than a way around designs that make homogeneous, single-point sampling impossible.

4.0 EXPERIENCE WITH SAMPLING MANIFOLDS

The following is an example of data obtained during a shop sampling manifold qualification procedure. Significant effort was expended in the installation of internal housing baffling and adjustment of the sampling manifold pattern in order to achieve these results.

System Description:

Flow Rate: 1000 SCFM
Configuration: HEPA/HEPA

Data: Prior to Manifold Adjustment

Leak Location		%Leak Reference Sample**	%Leak Manifold Sample	% Deviation
a.	Upper right media	.16%	.04%	-75%
b.	Upper left media	.16%	.04%	-75%
c.	Lower right media	.16%	.24%	+50%
d.	Lower left media	.14%	.04%	-71%
e.	Center media	*	*	*
f.	Center gasket to frame	.04%	.04%	0%
g.	Upper left gasket to frame	.16%	.16%	0%
h.	Lower right gasket to frame	.20%	.20%	0%
i.	Upper right frame to housing	.12% .	18%	+50%
j.	Lower left frame to housing	.08%	.08%	0%

* No data taken **Reference sample taken downstream of fan

Data: Post-Adjustment

Leak Location		% Leak Reference Sample	%Leak Manifold Sample	% Deviation
a.	Upper right media	.18%	.16%	-11%
b.	Upper left media	.20%	.20%	0%
c.	Lower right media	.16%	.24%	+50%
d.	Lower left media	.20%	.20%	0%
e.	Center media	1.08%	1.16%	+7.4%
f.	Center gasket to frame	.16%	.16%	0%
g.	Upper left gasket to frame	.44%	.50%	+13%
h.	Lower right gasket to frame	.50%	.56%	+12%
i.	Upper right frame to housing	.064%	.060%	-6.25%
j.	Lower left frame to housing	.070%	.064%	-8.6

The limited success is directly related to the environment in which these adjustments and modifications took place, i.e. a laminar flow environment and demonstrates the difficulties, even under shop conditions, of obtaining adequate results in the absence of turbulent mixing. Baffling in a low velocity, laminar flow region provides some mixing but primarily serves to redirect the leak plume. Therefore, adjustments in baffling may improve results for one leak path, while negatively affecting another. Increasing the number of manifold sample points eliminates the variable introduced by baffling, but at some point, the number of sample points required for satisfactory performance for all leak paths becomes impractical. Finally, the behavior and shape of the leak plume within the housing is not static over time as evidenced by photometer variability experienced during these measurements. Therefore, the results would likely improve if the readings were integrated over a period of time that includes the limits of variability in plume behavior as measured by the photometer.

5.0 TESTS OF MULTIPLE SAMPLING VS. SINGLE POINT SAMPLING AFTER THE FAN

A number of tests were conducted using the NCS filter test training unit (Figure 1). This unit is a small (20 SCFM) housing containing a single 12" X 12" X 6" HEPA filter followed by a 12" X 12" X 2" carbon adsorber. The unit is fitted with a baffle system in the inlet duct to assure homogeneous upstream mixing of the aerosol and a small centrifugal fan contained within the housing, downstream of the carbon filter. The unit has a movable, adjustable bypass leakage path to simulate filter leakage. In addition, traverse ports are located on the side of the system to allow a 49 point traverse of the entire filter face downstream of the adsorber at a distance of approximately one inch from the downstream face of the bank. All aerosol and velocity measurements were taken at this traverse location except for the reference reading that was taken at the fan outlet. Upstream air/aerosol mixing data were taken via a similar traverse, upstream of the HEPA filter bank at a distance of approximately one inch from the bank face. A total of three simulated, point source leak paths were introduced, one at a time, and aerosol measurements were taken at the downstream traverse for each leak path. One complete traverse, consisting of 49 points across an area of approximately one square foot, for each leak location, was performed. One traverse was performed using the 5 point traverse for each of two simulated leaks. One 9 point traverse was performed for one of the simulated leaks. A fourth artificial leak was produced by loosening the system HEPA filter, producing a distributed, multi-point leak path that was tested with a 49 point traverse. Finally, a fifth artificial leak path was produced by again loosening the system HEPA filter. Three, 49 point traverses were performed on this final leak configuration to examine the variability of the multiple sampling technique. The sample point densities used during this experiment are significantly higher than those typically employed for field installations. As an example, a 10,000 SCFM air cleaning unit containing 10 HEPA filters would be tested with a manifold containing approximately 200 – 2000 sample points using the sample point densities used during this experiment. Therefore, the data presented here represents a multiple sampling scheme (or manifold design) that is unlikely to be employed in the field due to the high sample point density. Therefore, the performance of typically installed manifolds on large scale systems will have a much greater chance of missing individual leaks. Aerosol was generated using a single Laskin nozzle and detected using an Air Techniques, Inc. TDA-2GN. Due to non-homogeneity downstream of the leak point within the housing, a data range for each sample point was recorded and the average tabulated. All readings are expressed in percent leak, with the TDA-2GN referenced to 100% at the inlet concentration. A single set of velocity readings were taken at the downstream face of the carbon adsorber and a single set of air/aerosol readings were taken upstream of the HEPA filter bank. Data are presented in Tables 1-11.

6.0 AS A PRACTICAL MATTER

Since series HEPA and adsorber banks contained within a single housing are more prone to test error when tested individually using manifold or multiple sampling, it is good practice to perform an integrated leak test from inlet to outlet, i.e. to series leak test the HEPA and adsorber banks at the conclusion of individual bank tests. This, combined with visual inspection and bank differential pressure data provides assurance that potential errors associated with manifold or multiple sample testing have not resulted in unacceptable bypass that can be more easily detected in an area of homogeneity. Obviously, this test will not provide information on the leak characteristics of each individual bank but it does provide a “sanity check” at the conclusion of the individual bank tests.

7.0 SOURCES OF ERROR IN THE IN-PLACE LEAK TEST

Calculation of leak rate is performed in accordance with the following calculation:

$L = (Cd/Cu)100$

where: L = Mechanical Leak
Cd=Challenge Concentration Downstream
Cu=Challenge Concentration Upstream

Some identified sources of error are:

1. Stability of the Upstream Concentration
   Stability of the Downstream Concentration
2. Homogeneity of the Upstream Concentration
   Homogeneity of the Downstream Concentration
3. Control of Aerosol Particle Size Distribution (HEPA)
4. Phase Delays in sample detection due to variable detector flow rate and variable sample line length or bore
5. Linearity of the particle detector
6. Linearity of the tracer gas detector
7. Errors in mathematical treatment of data when extrapolating to time zero

1. Stability of aerosol injection may contribute error to the overall leak test results, depending on the frequency of generator variation, the timing of the upstream and downstream sampling, and the type of generator used. For example, my experience has shown that air-operated, Laskin nozzle generators offer greater stability than thermal generators. In both cases, the stability of the compressed air or nitrogen source may contribute to overall stability. Estimated error +/-5%.

2. Based on acceptance criteria for air-aerosol mixing, the acceptable variation is +/-20%. Note: Measurement of air-aerosol mixing is assumed to be valid for tracer-air mixing for the adsorber stage.

3. Deviations in particle size distribution for a properly generated aerosol are not considered to be a significant source of error.

4. Phase delays in sample detection are controllable by using sample lines upstream and downstream of equal length and bore.

5. Linearity of the particle detector, based on manufacturer data is approximately +/- 1% of full scale.

6. Linearity of the halide detector, based on manufacturer data is approximately +/-1% of full scale.

7. The effect of mathematical treatment in time zero plots when employed depends on the suitability of the regression used to fit the data. No estimate of the error associated with time zero plotting is available at this time; however, this source of error can be significant.

From the above, it is evident that a significant source of error in the test method is aerosol homogeneity at the upstream and downstream sample locations. Within allowable acceptance criteria for the Air/Aerosol Mixing Test of +/- 20%, the effect of this variability alone can result in a potential test error of:

Upstream reading:

High:	120
Low:	80
Average:	100

Downstream Reading:

High:	.06
Low:	.04
Average:	.05

Calculated Leak:

High:	.08%
Low:	.03%

Actual:	.05+/-.03%

8.0 CONCLUSIONS AND RECOMMENDATIONS:

Data obtained during manifold qualification and multiple sampling tests presented in Tables 1-8 indicate that even with a very high sample point density of 49 sample points per square foot of bank area, results deviate from the reference value obtained downstream of the fan by –21% to +47% with single, point-source leaks. This variation is dependent on a number of factors, including leak location and air current patterns specific to the system under test. Decreasing the number of sample points to 9 and then five produced a deviation from the reference value of –48% to +43%, depending on the location of the leak. These data suggest that sampling manifolds may be ineffective in measuring integrated system leak rates from point-source leak locations when used in a laminar flow environment, even at very high sample point densities. Table 7 presents local velocity distribution data internal to housing and is not suitable for calculation of system flow rate. Data obtained during manifold qualification tests in the shop show similar difficulties though attempts were made to mix the downstream aerosol by baffling in the laminar flow environment. A system integrated leak test from inlet to outlet should be performed at the conclusion of individual bank leak testing. Table 9 presents interesting, though not unexpected results. Rather than leakage from a single point source, leakage in this case was generalized around the perimeter of the filter, since loosening the filter-clamping device produced the leakage, resulting in a distributed leak source. This, coupled with high sample point density resulted in an excellent multi-point sample and integrated leak test results. Tables 10A, 10B and 10C present data from three sequential multiple sampling tests performed with a single distributed leak source (loose filter) providing a measure of variability of the multiple sampling technique during these experiments. Table 11 summarizes data from these three tables.

From the above results, it is clear that the predominant source of error in the in-place leak test is homogeneity of the sampled tracer-air source upstream and downstream of the filter bank under test. Sampling manifolds used in laminar flow environments should be viewed with caution and the designer experiencing problems qualifying manifolds in accordance with current manifold design recommendations should not be unduly surprised. Where designers are successful in converging flow within the housing, producing turbulence and mixing, manifolds may be useful with varying degrees of this preconditioning. Designers should consider placing series banks in separate housings, incorporating mixing devices in the transition duct between housings. While this may be viewed as a step backward in terms of design, it is certainly a step forward in terms of testability. Sampling manifolds, when used, should be qualified across the entire range of operation, not simply at low flow rate and high flow rate. Manifold design should incorporate orifices sized to assure balanced sampling. If sampling manifolds are used, a system integrated leak test from inlet to outlet should be performed at the conclusion of individual bank leak testing. Other sources of error identified in Section 7 are beyond the scope of this paper and will be the subject of future work.

REFERENCES

(1) ASTM D 3803-1989, *Standard Test Method for Nuclear Grade Activated Carbon*
(2) ANSI N510-1975, *Testing of Nuclear Air-Cleaning Systems*
(3) ANSI/ASME N510-1980, *Testing of Nuclear Air-Cleaning Systems*
(4) ASME N510-1989, *Testing of Nuclear Air Treatment Systems*
(5) ASME AG-1-2003, *Code on Nuclear Air and Gas Treatment*
(6) ASME N509-1989, *Nuclear Power Plant Air-Cleaning Units and Components*

TABLE 1
(%LEAK)
49 POINT SAMPLE TRAVERSE

Traverse Point	1.5"	3.0"	4.5"	6.0"	7.5"	9.0"	10.5"
1.5"	.23	.24	.39	.69	.36	1.56	.84
3.0"	.37	.21	.28	.55	.55	.31	.47
4.5"	.27	.22	.52	.27	.13	.45	.56
6.0"	.27	.23	.35	.20	.22	.29	.25
7.5"	.26	.20	.18	.15	.21	.27	.24
9.0"	.19	.21	.17	.15	.19	.35	.31
10.5"	.21	.31	.18	.18	.23	.33	.31

REFERENCE LEAK @ FAN OUTLET: 0.42%

AVERAGE LEAK (MULTIPLE SAMPLE): 0.33%

DEVIATION FROM REFERENCE VALUE: -21%

Leak Location

TABLE 2
(%LEAK)
49 POINT SAMPLE TRAVERSE

Traverse Point	**1.5"**	**3.0"**	**4.5"**	**6.0"**	**7.5"**	**9.0"**	**10.5"**
1.5"	.27	.21	.17	.15	.11	.19	.29
3.0"	.27	.21	.14	.16	.17	.17	.28
4.5"	.25	.13	.10	.14	.10	.19	.20
6.0"	.56	.31	.23	.18	.10	.08	.16
7.5”	1.7	1.4	1.72	.74	.45	.36	.16
9.0"	2.88	2.10	.80	.78	.53	.25	.25
10.5"	.78	2.05	.71	.60	.23	.22	.21

REFERENCE LEAK @ FAN OUTLET: 0.34%

AVERAGE LEAK (MULTIPLE SAMPLE): 0.50%

DEVIATION FROM REFERENCE VALUE: +47%

Leak Location

TABLE 3
(%LEAK)
49 POINT SAMPLE TRAVERSE

Traverse Point	**1.5"**	**3.0"**	**4.5"**	**6.0"**	**7.5"**	**9.0"**	**10.5"**
1.5"	.18	.15	.10	.13	.11	.14	.16
3.0"	.45	.16	.10	3.48	1.80	.58	.18
4.5"	.44	.31	.39	.66	.48	.29	.13
6.0"	.36	.21	.18	.22	.18	.16	.14
7.5"	.19	.15	.16	.15	.13	.20	.18
9.0"	.15	.17	.12	.07	.17	.24	.18
10.5"	.18	.19	.14	.14	.17	.30	.23

REFERENCE LEAK @ FAN OUTLET: **0.32%**

AVERAGE LEAK (MULTIPLE SAMPLE): **0.31%**

DEVIATION FROM REFERENCE VALUE: **-3%**

Leak Location

TABLE 4
(%LEAK)
FIVE POINT SAMPLE TRAVERSE

Traverse Point	1.5"	3.0"	4.5"	6.0"	7.5"	9.0"	10.5"
1.5"							
3.0"	.25						2.09
4.5"							
6.0"				.20			
7.5”							
9.0"	.11						.30
10.5"							

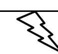
REFERENCE LEAK @ FAN OUTLET: **0.42%**

AVERAGE LEAK (MULTIPLE SAMPLE): **0.60%**

DEVIATION FROM REFERENCE VALUE: **+43%**

Leak Location

TABLE 5
(%LEAK)
FIVE POINT SAMPLE TRAVERSE

Traverse Point	**1.5"**	**3.0"**	**4.5"**	**6.0"**	**7.5"**	**9.0"**	**10.5"**
1.5"							
3.0"	.19						.20
4.5"							
6.0"				.14			
7.5”							
9.0"	.15						.18
10.5"							

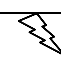
REFERENCE LEAK @ FAN OUTLET: 0.33%

AVERAGE LEAK (MULTIPLE SAMPLE): 0. 17%

DEVIATION FROM REFERENCE VALUE: -48%

 Leak Location

TABLE 6
(%LEAK)
NINE POINT SAMPLE TRAVERSE

Traverse Point	**1.5"**	**3.0"**	**4.5"**	**6.0"**	**7.5"**	**9.0"**	**10.5"**
1.5"							
3.0"	.17			.17			.17
4.5"							
6.0"	.21			.17			.16
7.5"							
9.0"	.14			.14			.23
10.5"							

REFERENCE LEAK @ FAN OUTLET: 0.33%

AVERAGE LEAK (MULTIPLE SAMPLE): 0. 17%

DEVIATION FROM REFERENCE VALUE: -48%

 Leak Location

TABLE 7
VELOCITY DISTRIBUTION
STANDARD FEET/MINUTE
49 POINT TRAVERSE

Traverse Point	**1.5"**	**3.0"**	**4.5"**	**6.0"**	**7.5"**	**9.0"**	**10.5"**
1.5"	81	32	24	36	80	95	56
3.0"	97	62	52	36	42	60	73
4.5"	81	29	32	45	105	96	117
6.0"	59	35	44	47	173	152	73
7.5”	53	56	55	95	155	194	163
9.0"	73	37	26	26	39	81	98
10.5"	54	34	39	36	45	42	63

FAN

TABLE 8
CHALLENGE AIR/AEROSOL MIXING
49 POINT SAMPLE TRAVERSE

Traverse Point	1.5"	3.0"	4.5"	6.0"	7.5"	9.0"	10.5"
1.5"	100	102	102	100	106	103	100
3.0"	107	100	101	100	102	104	100
4.5"	103	100	106	105	101	100	100
6.0"	100	101	103	100	101	104	100
7.5"	109	103	100	107	102	100	103
9.0"	103	100	102	100	104	102	102
10.5"	103	102	101	100	100	100	105

AVERAGE CONCENTRATION: 102 +/-2

TABLE 9
% LEAK
49 POINT SAMPLE TRAVERSE

Traverse Point	1.5"	3.0"	4.5"	6.0"	7.5"	9.0"	10.5"
1.5"	3.28	3.21	2.92	3.47	7.69	3.92	3.02
3.0"	3.49	2.43	3.29	3.39	3.55	4.52	7.07
4.5"	1.80	2.69	2.61	2.65	2.87	7.10	9.74
6.0"	3.88	4.27	3.48	3.15	4.26	9.51	11.19
7.5”	7.03	5.80	5.89	6.65	9.95	12.03	11.80
9.0"	8.30	8.01	8.30	8.53	9.90	8.93	11.6[illegible]
10.5"	7.62	7.66	8.70	9.55	10.06	10.05	9.24

REFERENCE LEAK @ FAN OUTLET: 6.23%

AVERAGE LEAK (MULTIPLE SAMPLE): 6.32%

DEVIATION FROM REFERENCE VALUE: +1.60%

Leak Location

Loose Filter

TABLE 10-A
%LEAK
49 POINT SAMPLE TRAVERSE

Traverse Point	1.5"	3.0"	4.5"	6.0"	7.5"	9.0"	10.5"
1.5"	2.00	1.50	1.20	0.93	1.28	1.60	2.13
3.0"	2.05	1.75	0.90	1.00	1.30	2.05	2.00
4.5"	1.75	1.40	1.07	1.20	1.30	2.05	2.59
6.0"	1.80	2.95	1.55	1.80	2.60	4.00	2.65
7.5"	2.35	2.35	5.10	5.75	4.80	7.40	4.95
9.0"	2.55	2.40	2.80	3.65	5.55	4.45	2.05
10.5"	3.10	3.65	3.45	4.65	5.05	4.65	4.30

REFERENCE LEAK @ FAN OUTLET: **2.69%**

AVERAGE LEAK (MULTIPLE SAMPLE): **2.76%**

DEVIATION FROM REFERENCE VALUE: **+2.60%**

Leak Location

Loose Filter

TABLE 10-B
%LEAK
49 POINT SAMPLE TRAVERSE

Traverse Point	1.5"	3.0"	4.5"	6.0"	7.5"	9.0"	10.5"
1.5"	2.35	2.40	1.85	1.55	1.25	1.95	2.85
3.0"	2.30	1.80	1.95	1.40	1.95	2.55	2.40
4.5"	1.95	1.85	1.65	1.15	1.70	2.55	2.95
6.0"	1.90	1.80	1.80	1.80	1.80	2.45	2.75
7.5"	2.40	2.25	2.30	2.95	3.80	4.90	5.35
9.0"	2.35	2.50	3.20	3.95	3.20	3.60	4.45
10.5"	2.55	3.35	3.50	3.50	4.35	4.30	4.05

REFERENCE LEAK @ FAN OUTLET: 2.78%

AVERAGE LEAK (MULTIPLE SAMPLE): 2.64%

DEVIATION FROM REFERENCE VALUE: -5.04%

Leak Location

Loose Filter

TABLE 10-C
%LEAK
49 POINT SAMPLE TRAVERSE

Traverse Point	1.5"	3.0"	4.5"	6.0"	7.5"	9.0"	10.5"
1.5"	2.25	2.00	1.70	1.50	1.30	1.90	2.45
3.0"	2.20	2.00	1.55	1.30	1.50	2.50	3.05
4.5"	2.20	1.95	1.15	1.10	1.25	2.25	2.55
6.0"	2.05	1.70	1.80	1.55	1.50	2.10	3.15
7.5"	2.25	2.00	3.30	3.30	3.60	5.40	4.80
9.0"	2.80	2.65	2.65	3.25	3.05	2.95	3.05
10.5"	2.75	3.30	3.50	3.70	4.05	4.00	3.25

REFERENCE LEAK @ FAN OUTLET: **2.55%**

AVERAGE LEAK (MULTIPLE SAMPLE): **2.51%**

DEVIATION FROM REFERENCE VALUE: **-1.6%**

Leak Location

Loose Filter

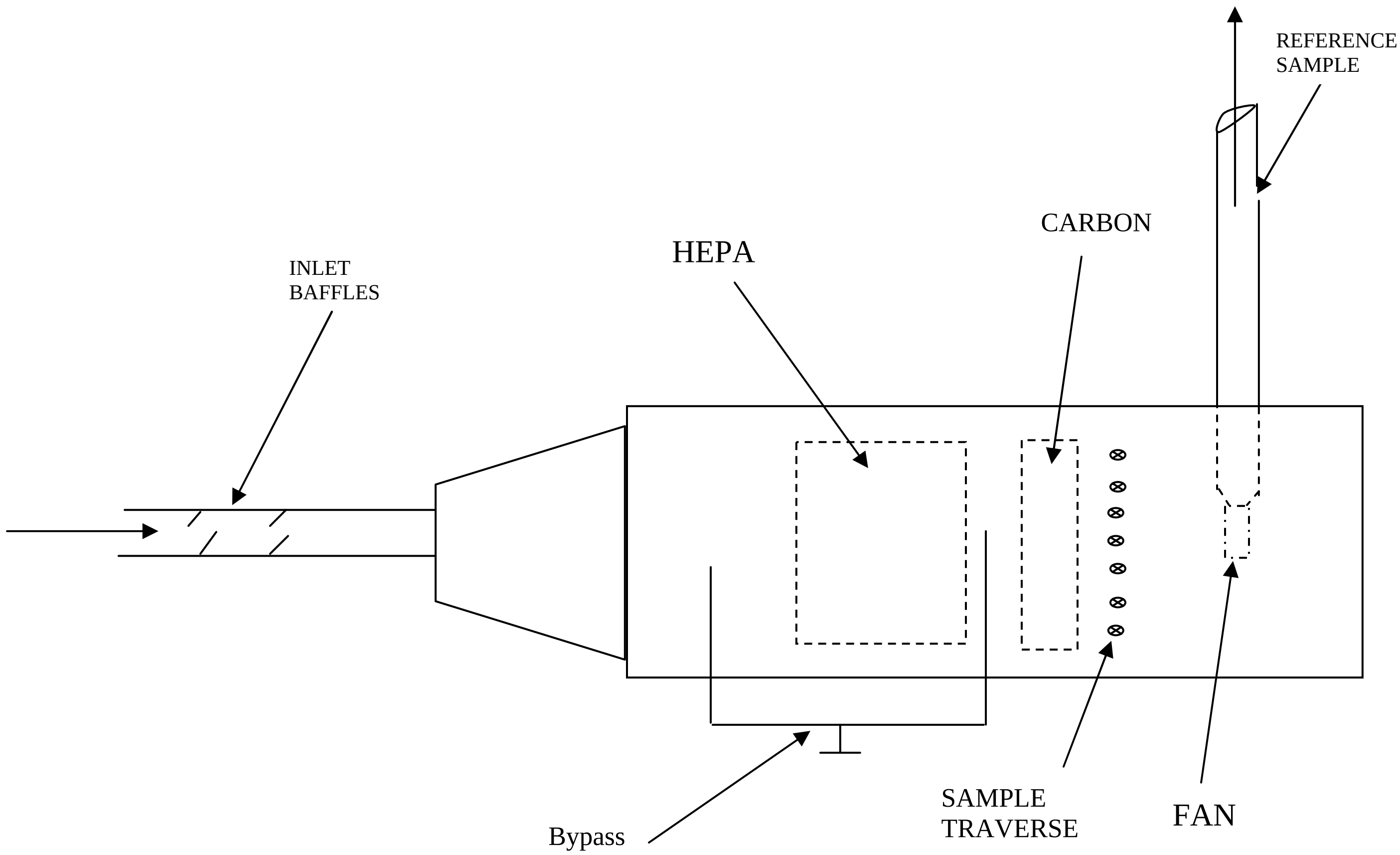
TABLE 11
Summary Tables 10A-10C

% Leak Multiple Sampling	% Leak Reference Location
2.76	2.69
2.64	2.78
2.51	2.55

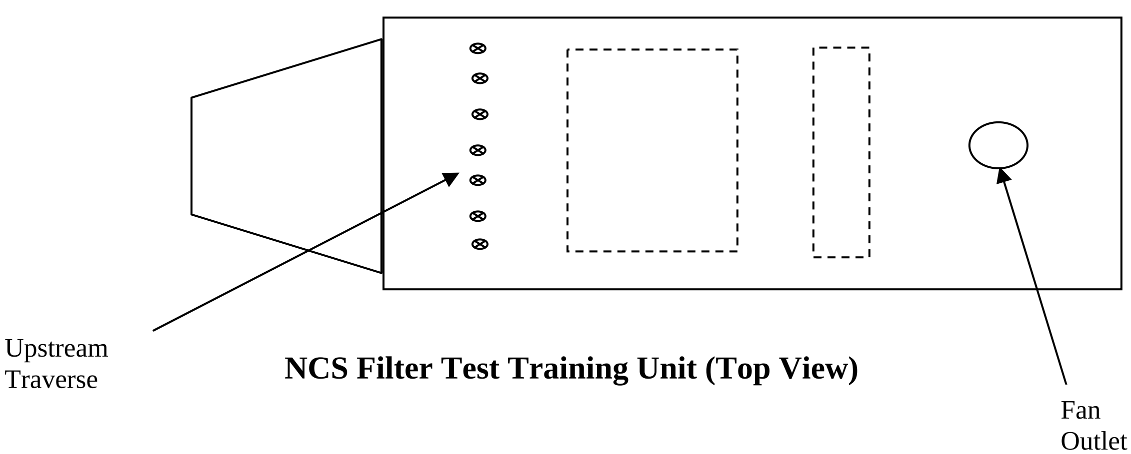
$\bar{X}$ = 2.64 +/- .13

$\bar{X}$ = 2.67 +/- .12

Figure 1



NCS Filter Test Training Unit (Side View)



NCS Filter Test Training Unit (Top View)