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PHASE I
PILOT AIR CONVEYANCE SYSTEM DESIGN, CLEANING, AND CHARACTERIZATION

by

Douglas W. VanOsdell and Karin K. Foarde
Center for Engineering and Environmental Technology
Research Triangle Institute
Research Triangle Park, NC 27709
EPA Cooperative Agreement CR822870-0-1

and

Roy Fortmann
Acurex Environmental Corporation
Research Triangle Park, NC 27709
EPA Contract 68-D4-0005 WA 2-030

EPA Project Officer: Russell N. Kulp
U. S. Environmental Protection Agency
National Risk Management Research Laboratory
Air Pollution Prevention and Control Division
Research Triangle Park, NC 27711

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16. ABSTRACT The report gives results of a project to develop and refine surface and airborne contamination measurement techniques that can be used to evaluate air conveyance system (ACS) cleaning. (NOTE: ACS cleaning is advertized to homeowners as a service having a number of benefits, including the improvement of indoor air quality. Because ACS cleaning includes many procedures applied to many different duct systems, evaluation has been difficult, and the effectiveness of ACS cleaning has not been adequately measured.) The research was in support of a field study to be conducted later. To this end, a pilot air conveyance system (PACS), using full-size residential heating and air-conditioning (HAC) equipment, was constructed and operated to provide a controlled, artificially soiled, ACS environment. The PACS consisted of ducts, an HAC unit, a dust mixing room, and instrument room, and a dust generation and injection system. Three types of duct systems were evaluated with the proposed measurement methods under soiled and unsoiled conditions. Each duct system was then cleaned by professional ACS cleaners and reevaluated. As a result of the pilot study, the surface contamination measurement methods were evaluated over a range of conditions and improved. The significance of acquired results in an actual residence was not determined.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Particles	Pollution Control	13B
Measurement		Stationary Sources	14G
Ducts		Air Conveyance Systems	13K
Heating Equipment		Indoor Air Quality	13A
Air Conditioning Equipment		Heating and Air-Conditioning (HAC) Systems	11G
Dust			

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NOTICE

FOREWORD

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ABSTRACT

Air conveyance system (ACS) cleaning is advertised to home owners as a service having a number of benefits, including the improvement of indoor air quality. Because ACS cleaning includes many procedures applied to many different duct systems, evaluation of these claims has been difficult and the effectiveness of ACS cleaning has not been adequately measured.

The objective of this project was to develop and refine surface and airborne contamination measurement techniques that could be used to evaluate ACS cleaning. The research was in support of a field study to be conducted later. To this end, a pilot air conveyance system (PACS) using full-size residential heating and air conditioning (HAC) equipment was constructed and operated to provide a controlled, artificially-soiled, ACS environment. The PACS consisted of ducts, an HAC unit, a dust/mixing room, an instrument room, and a dust generation and injection system. Each of three types of duct systems was evaluated with the proposed measurement methods when new, soiled by injecting previously collected duct dust, cleaned by professional ACS cleaners, then evaluated again.

As a result of the pilot study, the ACS cleaning evaluation measurement methods were applied over a range of conditions and improved. Surface contamination (microbial and total dust) measurement methods and visual inspection showed that the pilot unit was effectively cleaned by the ACS cleaning methods applied during this study. Submicron and larger particle counts were reduced following ACS cleaning and respirable particle mass was reduced for two of the three duct systems. The significance of these results in an actual residence was not determined.

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1.0 INTRODUCTION

1.1 Background and Overview

Commonly referred to as “duct cleaning”, ACS cleaning is advertised to homeowners as a service capable of preventing and possibly mitigating indoor air quality (IAQ) problems as well as improving system efficiency. It is a broadly defined service, with a wide range of cleaning apparatus used by different contractors and different parts of the system cleaned using different equipment. ACS cleaning includes the cleaning of all air-side components of a ventilation system: air handler, heat exchanger, humidifier, blower, and duct system (NADCA, 1992). Many combinations of cleaning procedures could be used on any given system and there are many types of systems. In general, residential ACS cleaning is intended to remove solid material and is not specifically directed at condensed or adsorbed gases. Following cleaning, ACS cleaning contractors may also coat the internal surfaces of damaged or biocontaminated fibrous insulation with aftermarket polymeric coatings as part of their service, and may also treat the ACS with biocides. Because the use of coatings and biocides on biocontaminated duct materials has not been tested and is not recommended (EPA, 1991), neither were evaluated during this research project.

The effectiveness of ACS cleaning could be evaluated in a number of ways: visually by inspection, measurement of residual dust using various measures, measurement of indoor air quality improvement following ACS cleaning, and measurement of improvements in air flow and energy efficiency. Visual inspection has shown that ACS cleaning generally removes substantial fractions of the dust in an ACS. The only published residual dust measurement method is that of NADCA Standard 1992-01, used to evaluate nonporous surfaces. By this definition, an adequately cleaned surface is visibly clean and when sampled following Standard 1992-01, is found to retain less than < 1 mg debris collected/100 cm^2 (0.1 g/m^2). There is no analogous standard for porous surfaces. Initial development of the surface sampling methods included a literature review and the development of several alternative sampling techniques, only the best of which were tested and further developed during the pilot unit research.

Adequate published research data are not available to support the IAQ improvement claims sometimes attributed to ACS cleaning contractors, and the data that are available are difficult to interpret. Ahmad, Tansel, and Mitrani (1994) found a reduction in total supermicrometer particles (measured with an optical particle counter) and in bioaerosol concentrations following ACS cleaning, but no change in submicrometer particle concentrations. Particle concentrations in the homes were found to be higher during cleaning than before or after. The authors felt that their study was not general enough to justify broadly applicable conclusions, and recommended that their results be considered as case studies. Fugler and Auger (1994) found that cleaning did not impact the levels of circulating dust in residences and, in at least one instance, a dust cloud was liberated after cleaning.

ACS cleaning, at least for relatively dirty ventilation systems, is thought to improve the energy efficiency of HVAC systems (Carl and Smilie, 1991). Again, few data are available and some conflicting reports have been published. Fugler and Auger (1994) reported finding no improvement in fan pressure drop or duct flow rate. Fellman (1994) points out some limitations of the work reported by Fugler and Auger.

A research program was undertaken by the U.S. EPA to investigate the application of ACS cleaning to residences. The overall research program included separate, coordinated projects conducted by the Research Triangle Institute (RTI) and Acurex Environmental Corporation (Acurex), with ACS cleaning support being provided by the National Air Duct Cleaners Association (NADCA). In addition, program review and comments were provided by the North American Insulation Manufacturers Association (NAIMA) and the American Society for Cleaning and Restoration (ASCR). The overall research program includes the following:

> <u>Phase I: Pilot Air Conveyance System Design, Characterization, and Operation</u> to develop test methods for field evaluation of ACS cleaning with respect to both cleanliness on the ducts and ventilation surfaces and the IAQ in the building being studied; and
>
> <u>Phase II, Field Investigation of ACS Cleaning</u> in 9 local residences as a pilot study to evaluate ACS cleaning and its effect on residential IAQ, and energy usage.

This report covers Phase I, PACS development, characterization, and operation, and the results of Phase II of the research are reported by Fortmann et al. (1996).

1.2 Objectives

The overall objectives of the Air Pollution Prevention and Control Division's (APPCD) Air Duct Cleaning Program are to determine when and how to clean ACS, evaluate how effective such cleaning is, and determine the impact of ACS cleaning on indoor air quality. A two-phase research program was undertaken to develop evaluation methods to achieve these objectives. First, a pilot study (Phase I) was used to develop the measurement methods. The specific objectives of Phase I were to develop and operate a PACS as a test bed suitable for the application of ACS cleaning to allow:

- Development and testing of proposed ACS cleaning evaluation methods, and
- Comparison of indoor air quality (IAQ) instrumentation, intended for use in the field, under controlled conditions that were also as realistic as possible.

Data obtained in the pilot system were used to develop ACS cleaning field evaluation methods and helped the interpretation of the results obtained during a field study (Phase II), which was undertaken as a pilot study to evaluate ACS cleaning in actual field use.

1.3 Phase I Project Activities

The Phase I research was a cooperative effort, led by RTI, with participation by personnel from APPCD/EPA, Acurex, and air duct cleaning professional organizations (NADCA and ASCR.) The initial project activity was review of a conceptual design by all participant at several workshops. This process resulted in the selection of 3 duct materials and associated construction techniques that were to be studied during Phase I: bare galvanized sheet metal, sheet metal with fibrous glass duct liner (FDL), and fiberglass duct board (FDB). In the opinion of the participants, these are the 3 principal duct materials used in the United States.

The PACS was constructed at RTI and checked-out in early December 1995. The workplan contemplated conducting the research over several months, while the actual research period was only about 1 month from beginning the first duct cleaning operation to completion of the third duct system test. This occurred because the research was a cooperative effort that included contributions from EPA, Acurex, and NADCA as well as RTI, and the EPA furloughs that occurred in late 1995 and early 1996 delayed the project start and compressed the schedule. In the end, all measurements and duct cleaning were conducted on the PACS between April 22, 1996 and May 24, 1996. This schedule compression did not adversely affect the overall research program, but did prevent some non-critical measurements from being taken as the duct systems were changed-out, soiled, and conditioned over short time spans.

The Phase I project described in this report included the following activities:

- Work/QA Plan Preparation
- PACS Design
- Design Review
- Equipment Specification
- Construction
- Checkout, and
- PACS Operation
- Field Method Development

The research results are summarized and conclusions drawn in Section 2 of this report. Recommendations are given in Section 3. Section 4 provides a description of the experimental apparatus and methods, and Section 5 describes the experimental procedures used to conduct the research. Section 6 contains a presentation and detailed discussion of the results, and Section 7 a discussion of project data quality assurance. References are provided in Section 8.

2.0 SUMMARY AND CONCLUSIONS

Overall, the PACS was successful as a test bed for sampling method development. That is, dust could be injected, conditioned, and the system cleaned such that the PACS was a reasonable laboratory surrogate for a residential ACS. Operated for only short periods, as was true of this work, it was not suitable for biocontaminant studies because active growth was not present. Specific conclusions from this research are summarized below:

1. Previously collected duct dust can be mechanically dispersed into a duct system and conditioned at high humidity to provide a realistic challenge to conventional ACS cleaning techniques. The dust deposit was clearly artificial, but, in the opinion of experienced ACS cleaning practitioners, had a reasonable distribution in the duct system and adhesion to the duct walls.
2. A pilot ventilation system can be used to investigate some aspects of ACS cleaning under controlled conditions and provide results that may be applicable to field ACS cleaning.
3. The medium volume dust sampler (MVDS), when fitted with a brush on the nozzle, was shown to be suitable for collection of dust from bare galvanized steel, FDL, and foil liner surfaces of ACS components. Conditioned dust could not be effectively removed with the nozzle only. Collection efficiency of the MVDS with the brush was higher than the MVDS with a slotted nozzle or the NADCA Vacuum Test Method.
4. Neither the MVDS with the slotted nozzle nor with the brush were suitable for collection of dust from FDB. The brush dislodged a substantial amount of fibrous material from new FDB. The nozzle did not effectively remove dust deposited on the fibrous surface. Accurate measurements of dust on FDB surfaces can not be made with the vacuum methods used in this study.
5. Dust loading on bare galvanized steel duct surfaces that were cleaned were less than 0.02 g/m^2 (0.2 $mg/100\ cm^2$) when measured with the NADCA Vacuum Test Method, meeting the NADCA Standard 1992-01 criterion for verifying cleaning effectiveness. Collocated measurements with the MVDS-brush were 0.26, 0.37, and 0.36 g/m^2 at the three locations. The mass loadings were 26, 37, and 18 times higher than the NADCA results,

demonstrating the low collection efficiency of the NADCA Vacuum Test method.

6 Overall, microbial contamination was low in the PACS because no active growth was taking place. For microbial sampling of dust deposited on the surface of various fibrous glass and galvanized metal surfaces, the vacuum method provided more consistently reliable results that the surface swab technique. It was particularly superior on the fibrous materials.

7. Measurements of dust levels on surfaces of various ACS components at multiple locations demonstrated that the deposition of dust in the system was highly variable. Deposition patterns varied between the three systems. The highest deposits in the supply ducts occurred in the bare galvanized duct system.

8. The amount of dust measured on new ACS components prior to soiling in the PACS was comparable to post-cleaning measurement results. That is, background dust levels on "clean" FDL, flexible duct surfaces, the foil liner in the air handler, and the cooling coil were similar to the amount of residual dust that could be collected after ACS cleaning.

9. The amount of residual dust collected with the MVDS-brush from galvanized steel duct, FDL, flexible duct, foil liner, and cooling coil surfaces after cleaning ranged from 0.14 to 0.49 g/m^2 (1.4 to 4.9 $mg/100\ cm^2$). Visually, this level of dust deposit on the surface appeared as a thin film of dust. These results suggest that the criterion for determining that surfaces have been effectively cleaned (in a manner comparable to NADCA 1992-01) should be about 0.5 g/m^2 when an efficient sampling method is used.

10. Both the results of the post-cleaning dust sampling and visual inspection indicated that the ACS components could be cleaned effectively by the methods used in this study.

11. Concentrations of airborne particles in the $> 0.5\ \mu m$ size fraction measured with a laser particle monitor were lower in the instrumentation room after ACS cleaning for all 3 systems tested. This may have been caused by the ACS cleaning, but may also have been caused by changes in the particle concentrations of the infiltrating air from outside the PACS. The decrease was not large, in any case.

12. Average $PM_{2.5}$ and PM_{10} mass levels in 24-hr integrated samples ranged from 1.7 to 11.8 $\mu g/m^3$ in the instrumentation room during these tests. In the tests with the galvanized steel duct and FDB systems, $PM_{2.5}$ and PM_{10} concentrations were lower after ACS

cleaning. Because of a large variation in the particle concentrations in the instrumentation room prior to cleaning of the FDL system, collection of a single integrated sample prior to cleaning would likely result in an incorrect assessment of the impact of ACS cleaning on indoor air quality. The tests demonstrated the importance of collecting multiple integrated samples and the need to measure particle concentrations for extended pre- and post-cleaning periods.

13. Fibers were not detected at levels greater than 0.001 fiber/cm^3 in air samples collected in the instrumentation room during tests with bare galvanized steel duct, FDL, or FDB. Fibers also were not detected with a Fibrous Aerosol Monitor operated during the first two tests.

14. A brief pulse of particles was released when the galvanized ACS was brought back in service following cleaning. This phenomenon was detected by both the bioaerosol and optical particle samplers. For the bioaerosol sampler in the galvanized ACS, about 80% of the total bioaerosol was sampled in the first 15 minutes of the hour-long test and about 2% in the final 15 minutes. The optical particle counters detected an hours-long pulse of particles. The other duct systems did not produce a clear pulse when restarted after cleaning.

15. Results from the tests in the PACS identified problems with the LAS-X Aerosol Spectrometer data logging hardware that were corrected prior to the field study. Information was collected during the tests that was used to refine methods and protocols that were used in the field study.

16. While not a focus of the study, as the research progressed it became apparent that ACS construction quality was an important variable in both PACS operation and in the "cleanability" of an ACS. While poor construction practices did not interfere with this study, which focused on methods development and not measurements, they did affect the performance of the ACS and the ease and thoroughness with which it could be cleaned.

    With regard to the duct itself, the unlined galvanized duct installed in the PACS had no apparent construction flaws. The butt-joints between sections in the FDL system had been sprayed with duct liner adhesive but were not sealed with a mastic. A small piece of liner near the return air inlet was found to be loose when inspected prior to cleaning. The cut edges in the FDB system did not appear to be sealed and were not coated. These construction details, while not in accordance with applicable construction standards, were flaws that the duct cleaning professionals considered to be very common.

In addition to duct quality shortcomings, the air handler, though it was in "as received" condition, was not perfectly sealed and coil bypass and leaks occurred at several points.

3.0 RECOMMENDATIONS

The following recommendations arise as a result of the research described in this report:

1. The MVDS with brush should be used to sample dust mass deposited on surfaces during the Phase II field study.
2. Surface microbial contamination on porous materials should be sampled with a vacuum method rather than a swab method to ensure collection of sample in depth from the material.
3. If fiberglass duct board ACS cleaning is to be evaluated, a suitable surface sampling method will need to be developed.
4. NADCA Standard 1992-01 should only be used as intended. For research purposes, a sampling method comparable to the MVDS with brush should be used with a clean surface dust mass target of approximately 0.5 g/m^2 to verify cleaning effectiveness.
5. Additional research is needed to understand all the parameters involved in obtaining a suitable ACS dust deposit. This would include both studies of dust in ACS and dust generation techniques. In this study, dust adhesion was found to be increased through exposure to high relative humidity (>90%), but the phenomena was not investigated quantitatively. The dust dispersion technique used during this research should have provided a reasonable large particle dust source but may have provided fewer small particles in the challenge than are normally present. However, little information is available concerning the size and character of the dust circulating in an ACS. In addition, the amount and distribution of the dust in a residential ACS must be evaluated through a field study to allow the formation of realistic ACS dust deposits in pilot units.
6. ACS dust properties must be investigated and an more reliable dust source found before research can be conducted over an extended period. The present work utilized duct dust from a single area of the country, but the amount available was relatively small and of unknown variability. Collection and mixing of a very large quantity of duct dust would be one approach. However, an artificial dust would have many advantages for such a

research program.

7. For continued research, the lessons learned from this work should be incorporated into the study protocols of future field research.
8. The study of biocontamination in an ACS must be conducted over longer time periods than were available to the present research so that active microbial growth can become established in the ACS. Accomplishing this would present some risk of exposure for those working in the vicinity unless the PACS was redesigned for containment to prevent exposure, and may be impractical. Such studies are needed, and use of smaller biocontamination study apparatus is thus recommended.
9. Biocides, encapsulants, and sealants are all used in residential ACS cleaning in attempts to control biocontamination without replacing duct work. The usefulness of these practices and their potential threats to residents have not been determined and should be investigated.
10. The instrument room appeared to have potential for indoor air particle instrument comparison. However, opening the door compromised the fine particle data through contamination from the laboratory. More useful data could be obtained through remote data logging and instrument servicing.
11. Additional study is required to determine whether FDB sheds fibers into the ACS such that the fibers increase the airborne fiber concentrations indoors. The scope of this research was too limited to draw conclusions.

4.0 APPARATUS AND METHODS

4.1 System Design, Specification, and Construction

4.1.1 Pilot Air Conveyance System Design Concept.

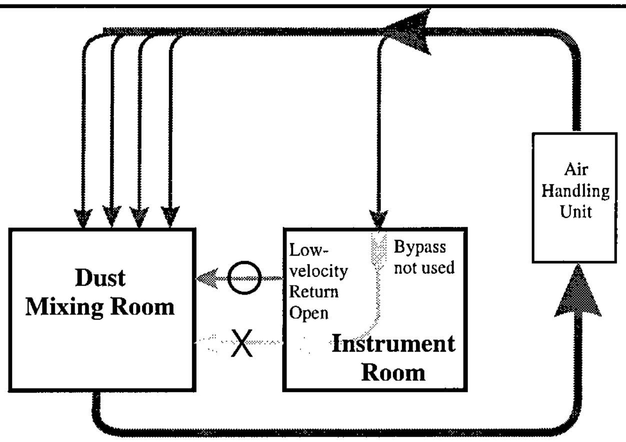
4.1.1.1 Overview. To accomplish the project goals, a PACS was developed to allow artificial soiling of ACS components using a reasonable (defined later) test aerosol. The pilot system included commercially available components expected to accumulate dust in varying degrees (e.g. bends, diffusers, registers, grills, blowers, heat exchangers, expansions, contractions, regions of surface irregularity, and dampers) and was designed to allow application of all aspects of the proposed evaluation method with the exception of evaluation of IAQ in the residences, including pre- and post-cleaning inspections and evaluations. The equipment was all scaled for a small residential air handler at 5.28 kW (1.5 tons) of refrigeration capacity.

To the extent practical, the PACS was constructed of modules to simplify cleaning and allow substitution of new test components. Standard, commercially-available HAC equipment was used when possible. The PACS consisted of the following systems: 1) supply and return ventilation ducts, 2) air handling unit (AHU) including air conditioning coil and heat exchanger, 3) dust mixing room, 4) instrument room, and 5) dust generation system. As shown schematically in Figure 1, the PACS was operated in two modes:

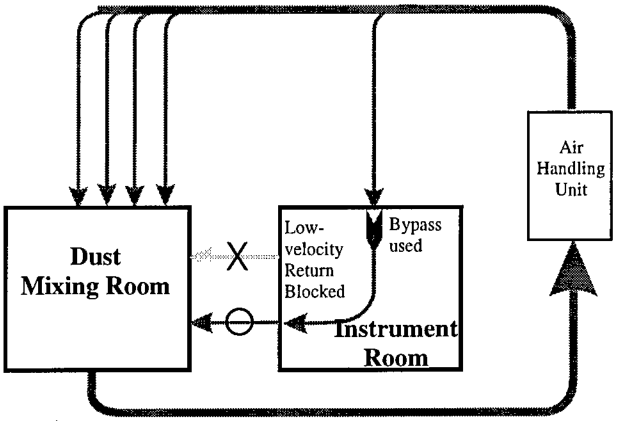
- normal operation with flow into both rooms, and
- bypass of the instrument room during dust injection.

So that evaluation methods could be developed for the three major duct materials, completely separate PACS duct systems were constructed of the three duct materials commonly utilized in residential HAC. A new air handler was installed for each duct type. Each completely new system was then utilized in the PACS in separate tests as described below.

The laboratory within which the PACS was constructed had a roughly 3.7 m (12 ft) ceiling height. It was air-conditioned laboratory space maintained at approximately 24°C (75°F) under temperature control and without humidity control. All components of the PACS, including the air conditioner condenser, were located within the laboratory.



Normal PACS Operating Mode



PACS Bypass Mode used during Dust Injection

Figure 1. Schematic showing PACS operational modes.

4.1.1.2 Design Reviews. The PACS design was reviewed internally and externally. Design review meetings with representatives of interested industrial associations were held at RTI on December 8, 1994 and at EPA on February 13, 1995. A third review with NAIMA was presented in Washington, DC, on March 3, 1995. A special review to consider fiberglass materials was held with NAIMA at RTI on April 13, 1996. Ideas presented by the reviewers were incorporated into the design and the final design parameters for the pilot system are given in Table 1.

The primary operational goal for the PACS was to achieve an ACS dust deposit that was a reasonable challenge for residential ACS cleaning systems and that provided a reasonable test bed of test methods and protocols proposed for the field study. Because residential heating and

Table 1. PACS Design Parameters

Temperature	Thermostat control to 16 to 27°C (60 - 80°F) in instrument room.
Relative Humidity	Humidifier output set to hold about 50% in room with AHU on in normal operation.
Room Pressure	Positive to laboratory. Measured in room.
Air Circulation Rate:	As provided by AHU blower [approximately 0.33 m^3/s (700 cfm.)]
Infiltration Rate	Limited by tight construction.
AHU Design	Commercial equipment sized for total load of about 5.3 kW (1.5 tons).
Duct System Design	Sized for total flow. Material varied for experimental purposes.
Duct Construction	System 1 - galvanized steel. System 2 - fibrous glass duct liner in galvanized steel. System 3 - fiberglass duct board. All systems were constructed in accordance with SMACNA and NAIMA standards.
Register locations	Included floor, ceiling, and sidewall.
Test Dust	Previously collected ACS dust, re-dispersed for experiment.

air conditioning (HAC) systems vary greatly between installations, accumulate "dirt" over years of operation while in both heating and cooling modes, and the sources and kinds of duct "dirt" vary greatly, the PACS may not duplicate actual field conditions but provides a reasonable representation. Normal operating parameters (temperature, humidity, pressure) of the pilot unit were not considered critical because they vary greatly in the field. They were maintained within commonly encountered ranges. As discussed further below, humidity was raised for a conditioning period to achieve the important goal of an adhering dust deposit.

All the design and experimental discussions and reviews were accumulated in a Work/QA Plan for the Phase I Research (RTI, 1995), which was transmitted to all participating and reviewing parties.

4.1.2 Duct Systems

4.1.2.1 Objectives and Design. The duct system was designed so that it could be constructed by a local air conditioning contractor from commercially available components. The overall design and duct routing allowed fair access to all the duct and ventilation system components. As in actual duct systems, some components were more accessible than others so that the ACS cleaning and the ACS cleaning field evaluation methods could be tested in physically awkward situations. Though not typical of residential construction, bolted flanges with foam gaskets were used on the duct sections where possible to give improved access (if required experimentally) and to reduce assembly/disassembly times.

4.1.2.2 Apparatus. During the test program, the main supply and return trunks of the PACS duct systems were constructed of:

1) bare galvanized steel with exterior insulation,
2) fibrous glass lined galvanized steel, and
3) fiberglass duct board.

Figure 2 gives an elevation view of the PACS duct systems and sample ports, all of which had the same inside dimensions and sample location designations. The galvanized steel used was chosen by the contractor as appropriate for the duct size. It was beaded every 30.5 cm (12 in.) for strength. The FDL was specified to be the most common material used (as recommended by NAIMA), which is acrylic polymer faced, 1 in. thick, and has a density of 1.5 lb/ft^3. Examples are CertainTeed Ultralite 150, Owens-Corning Aeroflex Plus 150, or Schuller Permacote Linacoustic Standard. The choice of material was made by the duct contractor. The FDB used

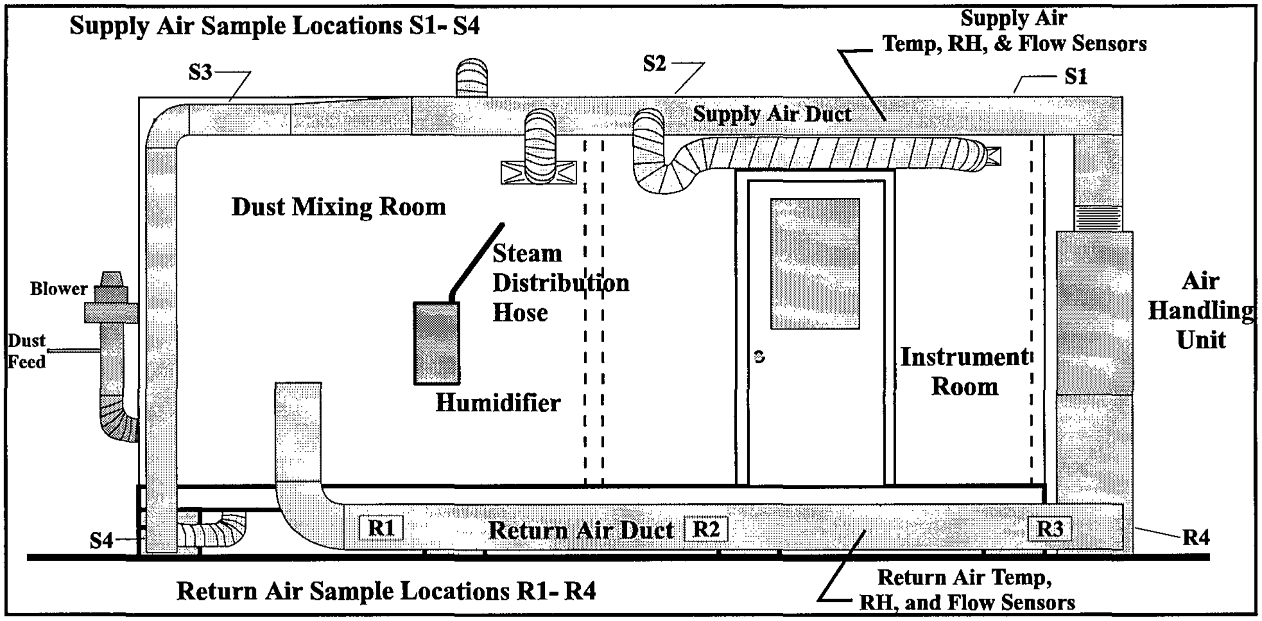


Figure 2. Elevation of PACS showing features of duct systems.

was also the most common variety, known a standard unfaced, 1 in. thick EI-475 material. Examples are CertainTeed Ultraduct, Knauf Air Duct Board EI-475, Owens-Corning 475 FRK Fiberglass, or Schuller Microaire 475. Again, the duct contractor chose the particular brand used.

Each return duct had internal dimensions of 30.5 cm high by 20.3 cm wide (12 by 8 in.). A return air grille was placed at the entry from the mixing room. So the dust in the mixing room would move throughout the ACS, no return air filter was used. The duct was connected to the return air plenum at the base of the air handler. All return air ducts had the same internal dimensions.

At the top of the air handler, the supply trunk duct attached to a flexible connector on the AHU. Each supply trunk had internal dimensions of 25.4 cm wide by 30.5 cm high (10 by 12 in.) for most of its length, then was reduced to 30.5 cm high by 20.3 cm wide (12 by 8 in.). As with the return, each of the three duct systems had the same internal dimensions.

All connections to supply registers were made with 15.2 cm (6 in.) diameter flexible duct. The flexible ducts were attached to the take-off collars and supply registers with a double mechanical connection using duct ties. Take-offs were sealed to the galvanized ducts with duct sealant. The FDB system was sealed with tape.

4.1.3 Air Handling Unit

4.1.3.1 Objectives and Design. The design guidelines were for an AHU that was a commercial unitary system with a direct expansion (DX) coil and heat exchanger installed. New AHUs were installed for each pilot duct system so any residual dust from a used AHU would not confound the duct dust measurements. The air conditioner (A/C) evaporator in the AHU was challenged by the sensible and latent loads provided by the baseboard heaters and humidifier in the mixing room. No cooling loads were provided to exercise the auxillary heater that was installed in the AHU. It was in the air stream only to collect dust and require cleaning.

4.1.3.2 Apparatus. The AHU used was a Heil Model BA3018QK heat pump, which is a 52.8 kW (1.5 ton) refrigeration capacity unit operating at 0.32 m^3/s (680 cfm). The fan was placed in a draw-through position. Within the unit, the rectangular coil, with 6 fins/cm (15 fins/in.) was installed diagonally across the air handler. The AHU was supported about 1 m (3 ft) above the floor on a angle iron stand and operated in upflow.

4.1.4 Dust Mixing Room

4.1.4.1 Objectives and Design. As shown in Figures 1 and 2, the PACS includes two rooms - the dust mixing room and the instrument room. The dust mixing room, which was the only room used while injecting dust, had the following design objectives:

- to serve as the "house" whose ducts had to be cleaned,
- to provide a mixing and settling volume for the test aerosol while soiling the PACS,
- to provide a load for the HAC system, and
- to provide thermal and humidification capacitance to smooth operation.

The dust mixing room contained heaters and a humidifier to provide the sensible and latent loads for the air conditioning system. They were controlled to cause the A/C to be cycled by the thermostat 4 to 6 times an hour.

4.2.4.2 Apparatus.

Figure 3 shows interior details of the dust mixing room, which was approximately 2.44 m high by 2.44 m deep by 3.05 m wide (8 x 8 x 10 ft), with a volume of 18.2 m^3 (640 ft^3). During PACS operation, all air from the AHU was passed through the mixing room, so the ventilation rate in the room was much higher than commonly encountered in individual rooms in residences. As intended, this high ventilation rate coupled with the mixing fan appeared to effectively disperse the test aerosol (during loading) and the injected steam from the humidifier.

The room was built with conventional residential construction materials following construction practices that minimize infiltration. The wall panels were installed with foam tape behind the seams and the electrical and instrumentation cut-outs were sealed with caulk. The wall panels were removable to allow design modifications when required.

The heaters were conventional baseboard heaters, each 1.2 m long with a rated maximum output of approximately 1 kW. They were controlled by individual thermostats on each heater unit and all three were limited by an overall heater thermostat mounted on the wall of the room.

Additional mixing was provided within the dust mixing room by a ceiling mounted moisture resistant fan. It was controlled by a speed controller mounted outside the dust mixing room. The fan was normally on at a medium speed to disperse the steam from the humidifier.

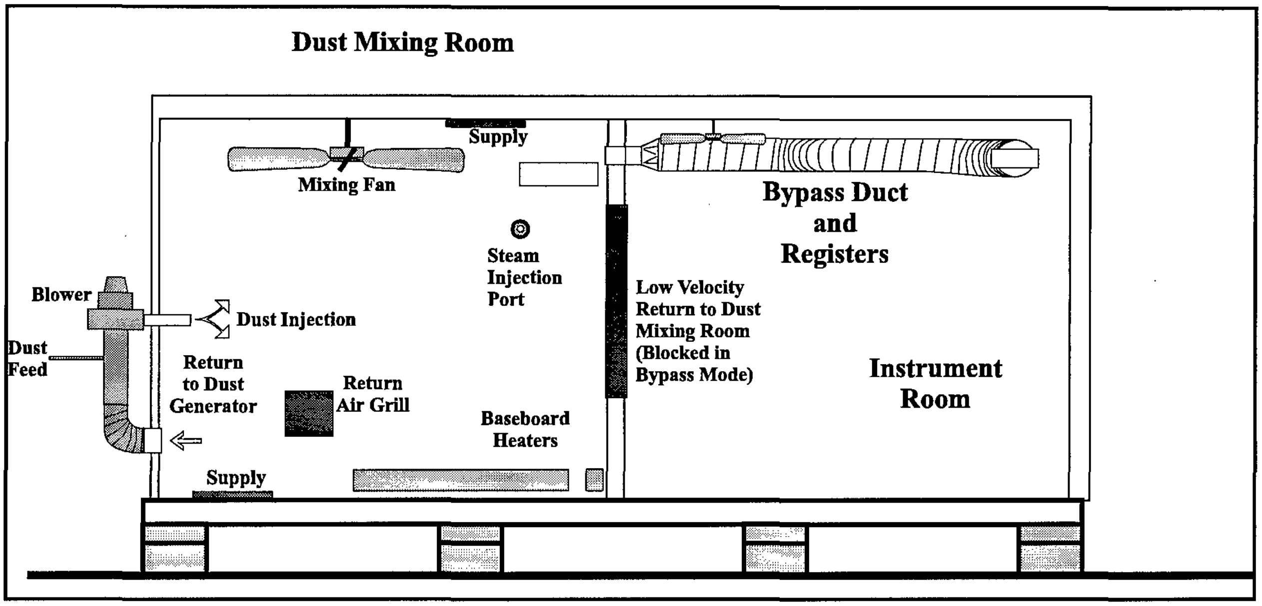


Figure 3. Interior elevation of PACS showing construction detail.

The electronic steam humidifier had a capacity of 12 gallons/day at 115 VAC. Steam was directed into the mixing room through a remote steam pipe from the humidifier, which was mounted on the outside of the dust mixing room. It was controlled by a humidistat mounted inside the dust mixing room in series with a flow-sensing pressure switch in the supply duct to disable the humidifier if the AHU was not circulating air.

The AHU was controlled by a standard heat pump thermostat mounted in the dust mixing room. The heater thermostat, humidistat, and AHU thermostat were used in concert to provide an acceptable on / off time for the HAC equipment.

The equipment control concept for normal operation was to keep the heaters and humidifier on continuously to generate a load for the air conditioner, which was allowed to cycle on and off under conventional thermostatic control. The heater thermostat was used as a high limit control (should the air conditioner fail.)

4.1.5 Instrument Room

4.1.5.1 Objectives and Design. The purpose of the instrument room was to allow simultaneous comparison of the IAQ evaluation aerosol instruments slated for use during the field study and to provide an indication of the magnitude of effects that might be caused by ACS cleaning. As shown in Figure 1, the room was bypassed and kept closed during the duct contamination and cleaning phases of the PACS operation to keep it clean. The bypass was removed and the low velocity return opened to achieve an air flow rate and return velocity reasonable for a residential room when the PACS was operated to compare the instruments.

4.1.5.2 Apparatus. The instrument room was the same size as the dust mixing room: approximately 2.44 m high by 2.44 m deep by 3.05 m wide (8 x 8 x 10 ft), with a volume of 18.2 m^3 (640 ft^3). The room was empty except for lights, a small mixing fan, and electrical power outlets. The room was operated in two modes: 1) normal room operation and 2) bypass during dust injection. As shown in Figure 1, when operated as a normal room the bypass duct was disconnected from the sidewall supply vent and sealed with a metal plate. A diffuser was placed over the sidewall supply vent, which then discharged into the instrument room as would normally be expected for a residential forced air ventilation system. The low velocity filtered air return between the dust mixing and instrument rooms was opened to allow ventilation air to flow between the instrument and dust mixing rooms at relatively low velocity, much as would occur in a residence in which ventilation air leaving a room returns through an open door. The low velocity return was filtered (ASHRAE 60% dust spot filters) to prevent contamination from readily backflowing due to movement or opening the door in the dust mixing room.

In the bypass mode, the sidewall diffuser grill was removed, the bypass duct connected, and the low velocity air return sealed so that the instrument room was no longer part of the ventilation system air flow. In this way, the PACS could be contaminated with high levels of dust without contaminating the instrument room with high levels of particles that might overload the instruments or be easily resuspended by people working on the instruments.

4.1.6 Dust Generation System.

4.1.6.1 Design. The primary design considerations for the dust generation system were to provide a soiled ACS that was representative of, or a realisitic surrogate for, field contaminated ACS and to contaminate the ACS within 24 hours. Duct dust has not been characterized in this sense, so no quantitative measures are available. Resuspended duct dust was chosen rather than a synthetic dust. In this context, reasonable surrogate dust was taken to mean:

1) Deposits with the same appearance as those found in the field,

2) Deposits having the same apparent interparticle adhesion as those in the field,
3) Deposits having about the same apparent duct wall adhesion as those in the field,
4) Penetration into fibrous materials apparently about the same, as is found in the field.

With respect to all characteristics, the dust was evaluated by the project team during sampling and by the NADCA representatives as they cleaned the PACS.

4.1.6.2 Apparatus. Previously collected duct dust was injected as an aerosol. The dust was dry and free flowing as received from duct cleaning companies, and was not dried further before injection. The dust was obtained from the a duct cleaning company in the Dallas/Ft. Worth, TX area, and though not identical all injected batches were similar in appearance. The dust had a high volume fraction of fibers, and these had a tendency to mat and clog the aerosol generator. The dust was not screened, but large pieces of debris (coins, toys, candy, small adhesive bandages, sticks, feathers, etc.) were not injected.

As shown in Figure 3, the primary dust dispersion device was a high volume blower that discharged directly into the dust mixing room. The dust was resuspended and fed into the blower using either an aspirator (for part of the first test) or a blade-mill aerosol generator. Both resuspension devices were workable but had shortcomings. The aspirator was simple and inexpensive, having no moving parts. Prior to aspiration, the duct dust deposit had to be cut with a utility knife to shorten fibers and prevent plugging. Even with the preparation, the aspirator plugged several times while in use. It would be more suitable for a screened and sifted dust. The blade-mill generator was able to feed the dust without cutting (that operation being done by the blades), but was still possible to plug if the dust was fed too fast. Overall, however, the dust injection process was not sensitive to the type of generator used because only finely dispersed aerosol entered the duct, while coarse aerosol settled in the mixing room. When contaminating the duct, the instrument room was bypassed and the dust mixing room fan was on. The AHU blower was on to transport the dust into the ducts, but the baseboard heaters were off and the A/C was not on so that excessive dust would not collect on the wet coil. The target dust mass deposit was 10 to 50 mg/100 cm^2 of duct surface, which is 10 to 50 times the NADCA 92 -1 Standard for an acceptably clean duct.

Following dust injection, the high speed blower was repeatedly directed at the floor to resuspend as much dust as possible. This effort was stopped after 10 to 20 minutes, by which time the blower no longer reentrained large quantities of dust from the mixing room floor. The dust was then allowed to settle for a few hours. At this point, the dust was widely distributed in the duct but was adhering only loosely to the duct material. Conditioning, which consisted of several days of exposure to a high relative humidity, made the dust adhere tightly to the duct wall in a manner qualitatively more representative of duct dust in field applications. Dust conditioning was not quantitatively investigated. The humidifier was set to maximum output with the HAC system in thermostat control, which resulted in near continuous humidification. During conditioning the mixing room and duct humidities remained between 70 and 90% (generally near 90%) while the temperature ranged from 23 to 27°C (73 to 80°F). Overnight conditioning caused a noticeable increase in dust adhesion as evaluated by touching the dust and by sampling with the various vacuum surface samplers.

Because the duct dust was not sterilized prior to injection, it contained whatever microbiological contamination was present when it was collected. Not all of the material would remain culturable during the storage period, but spores are hardy and can remain viable for extended periods. The deposited dust was a suitable source for collection of microbiological contamination deposited on the duct, but would not serve as a surrogate for actively growing microbiological contamination.

4.1.7 HVAC Instrumentation

4.1.7.1 Objectives and Design. The objectives of the HAC instrumentation were to monitor performance of the PACS during the various operational phases (duct soiling, conditioning, after cleaning, etc.) so that approximately the same conditions could be reproduced for all three duct materials. Because the temperature, relative humidity, and air flow were not directly controlled, but were parameters resulting from the on-off time of the A/C system and its interaction with the heaters, humidifier, and laboratory environment, inexpensive HAC instrumentation was used in the PACS.

4.1.7.2 Apparatus. Temperature, RH, and air flow sensors were positioned in the supply and return duct at the locations shown in Figure 2. Temperature and RH sensors were also placed in the dust mixing room and in the ambient air of the room containing the PACS. The temperature sensors were 1000Ω platinum RTDs, while the RH sensors were based the resistance change of a polymer sensor. Air flow sensors of the averaging pitot type were placed in the galvanized supply and return duct at the same approximate location. As discussed in Section 7, the duct sensors were used only with the galvanized duct.

Continuous watt meters were placed on the baseboard heaters (in total), the air handler, and the compressor/condenser unit. The energy use rates were used as on-off indicators for the equipment and compared with air flow, temperature, and RH measurements to better understand the operation of the PACS. To monitor refrigerant temperature changes, thermocouples were installed under the refrigerant line insulation between the evaporator and condenser. These thermocouples were continuously recorded.

All PACS continuous instrumentation was connected to an A/D board, digitized, and displayed on a computer screen for easy access. (Commercial HAC instrumentation requires external monitoring devices.) Following the checkout operational phase, system performance was monitored but not recorded.

Room pressure was measured during normal operation and while injecting dust to evaluate the degree of pressurization of the PACS. It was not regularly monitored.

4.2 PACS Checkout

The checkout phase of the project was intended to ensure that all the equipment was working properly and determining the proper operating values. In addition, the checkout allowed the determination of which operating parameters were important to control and which to simply monitor. The dust injection system, in particular, had not been tested and considerable modification was thought possible before acceptable duct dust was achieved. The dust conditioning procedure described above was developed at this time.

All portions of the system were fully exercised with the galvanized duct system in place. The duct integrity was evaluated, some leaks sealed, and the infiltration evaluated using a CO_2 decay measurement. The infiltration rate was found to be 0.0145 m^3/s (30.7 ft^3/min) with the AHU blower on low speed, which is about 8 percent of the total supply air flow. At the medium blower speed, the infiltration rate was 0.0187 m^3/s (39.4 ft^3/min) or 7 percent of the supply flow rate. The apparent infiltration rate with the air handler off (diffusion or sorption) was 0.002 m^3/s

(4.2 ft^3/min). Careful examination of the ACS showed that many of the largest apparent leak sites were in the air handling unit access door, and could only be prevented by modifying the unit.

Dust was initially injected in 50 g increments. The target was to deposit 10 to 50 times the amount of dust that can remain for in a cleaned ACS that passes NADCA Standard 92-1, or 1 to 5 g/m^2 (10 to 50 mg/100 cm^2) on the duct surface. The bottom horizontal surface area of the ACS, (including 1/3 of the round duct surface) was about 11 m^2 (120 ft^2), which would require about 1 g injected to deposit 1 mg / 100 cm2 assuming everything deposited on the bottom surface. Because the larger, high mass particles preferentially dropped out in the mixing room, only about 25% of the total dust injected actually deposited in the ACS. The mass of dust actually injected into each duct system was between 300 and 500 g.

The duct dust distribution was visually evaluated for uniformity (axially and radially). As described below, differences were noted between ACS types. Dust was present throughout the ACS, with the heaviest deposits on the bottom of the return duct Substantial amounts of dust penetrated to the supply side of the system. The duct sidewall and top deposits were much lighter than those on the duct bottom. Quantitative evaluation was conducted during the method evaluation, and the results are reported in Section 6.

4.3 PACS Operation

Once checkout was completed and the desired set-points were known, operation of the PACS consisted of turning everything on, ensuring that the thermostat setting was correct, and occasional inspection. The test series, as described below, required that the system be operated briefly in particular non-routine configurations (i.e., fan only for dust loading, off while sampling.) Except for those excursions, the PACS operated at all times with the heaters and humidifier on and the air conditioner cycling on about every five minutes.

5.0 EXPERIMENTAL PROCEDURES

5.1 Overview

The initial step in a test utilizing each type of duct system was to evaluate the duct system background. Duct dust was then injected into the PACS. Once the PACS was soiled, the experimental protocol consisted of conducting duct and air evaluation tests at various times in the cleaning process: before, during, immediately after, and 24 hours after cleaning. In the discussion below, all measurement procedures are presented in section 5.2 and their use in the sampling plan is presented in section 5.3. Section 5.4 presents a discussion of the duct cleaning methods as applied to the PACS.

5.2 Sampling and Measurement Procedures

The measurement parameters and sampling and analysis methods are summarized in Table 2 and described in detail in the balance of this section.

The primary sampling method being evaluated (and hence, the parameter of greatest interest) was measurement of the mass of dust on surfaces of the ACS components prior to and following ACS cleaning. The dust mass sampling had the following purposes:

- To evaluate the MVDS and NADCA dust sampling methods by collection of samples at multiple locations and by collection of replicate samples. Two different MVDS collection nozzles were evaluated during the testing.
- To collect information on dust sampling to develop the sampling protocol for the field study.
- To measure the mass of duct dust (particulate matter and fibers) on the surfaces at various locations in the ACS prior to cleaning to determine the amount and pattern of dust deposition in the ACS. This was necessary to ensure that the amount of dust on the surfaces was adequate to assess the effectiveness of the ACS cleaning.
- To measure the mass of duct dust on the surfaces after ACS cleaning to evaluate the effectiveness of the cleaning methods.

Table 2. Measurement Parameters and Methods

Parameter	Sampling Method	Instrumentation	Analysis Method	Notes
Dust loading	Manual	MVDS - brush	Gravimetric	Primary method
Dust loading	Manual	MVDS - nozzle	Gravimetric	For FDB
Dust loading	Manual	NADCA method	Gravimetric	Un-lined galvanized only
Dust loading	Manual	High volume sampler	Gravimetric	Cooling coils only
Microbial loading	Manual	Pipet tip sampler	Plate counting	Applied to all ducts
Bioaerosol concentration	Integrated	Mattson-Garvin slit to agar impactor	Plate counting	1-hr integrated samples
$PM_{2.5}$	Integrated	MS&T impactor/filter and 20 lpm pump	Gravimetric	24-hr integrated samples
PM_{10}	Integrated	MS&T impactor/filter and 20 lpm pump	Gravimetric	24-hr integrated samples
Particles > 0.5 µm (counts)	Continuous : 10-min averages	Climet CI-4100	Optical (scattered light)	Recorded with IAQDS and Climet
Particles > 5.0 µm (counts)	Continuous: 10-min averages	Climet CI-4100	Optical (scattered light)	Recorded by Climet
Particle count - 16 channel	Continuous: 60-min averages	LAS-X	Laser aerosol spectrometer	Direct download to laptop computer
Fibers	Integrated	Filter/SKC pump	Phase contrast microscopy	NIOSH 7400 method - 24-hr integrated samples
Fibers	Semi-continuous	MIE FAM-1	Optical fiber monitor	PDL-10 data logger

For the same reasons, a second important parameter measured was the number of culturable microbial organisms deposited on the duct and HVAC surfaces. As with the dust mass sampling the goals of the PACS measurement were method development and performance evaluation, with a secondary goal of evaluating the impact of ACS cleaning on microbial deposits in ducts. Because of the short time between injecting the dust and sampling during most of these tests, microbial growth on the duct was not an issue during this research. Regions with high microbial counts were potential areas for growth and amplification, particularly in the case of fungi. Only an extremely wet region would be expected to support bacterial growth.

Other parameters were measured during the three tests, also for the purpose of instrument "shake-down," method evaluation, and collection of information for refining and finalizing the sampling and monitoring protocols for the field study. Continuous optical particle monitors were set up in the instrumentation room of the PACS. Integrated air samples and bioaerosol samples were also collected in the room. Although the data, particularly that collected with the continuous optical particle counters, showed changes in particle concentrations during the test, the reader is cautioned not to draw conclusions about the impact of ACS cleaning on airborne particle concentrations based on the data presented in this report due to the limited scope of the measurements and the artificial nature of the dust deposits and physical arrangement of the room in which the measurements were made.

5.2.1 Duct Dust Surface Mass Sampling

The levels of dust in ducts (g/m^2) were determined by collection of dust samples at selected locations with the MVDS, the NADCA Standard 92-1 vacuum test method, and a high volume vacuum cleaner. Duct dust was defined as all particulate and fiber matter collected with the method. Samples were analyzed gravimetrically; the composition of the dust was not determined in this study. The methods used in these tests are described below.

5.2.1.1 NADCA Vacuum Test Method (Standard Method 1992-01). The NADCA Vacuum Test Method is described in Standard Method 1992-01, *Mechanical Cleaning of Non-Porous Air Conveyance System Components* (NADCA, 1992). The hardware for the method consists of a vacuum pump operated at 10 L/min, a filter cassette, and a template for sampling. An open-face 37-mm diameter plastic filter cassette is used as the nozzle. The purpose of the method is to document the effectiveness of cleaning of non-porous ducts. During the tests described in this report, a Thomas Model 2107CA20A dual diaphragm pump was used. An in-line valve was used to adjust the air flow rate to 10 L/min which was determined from a calibrated in-line rotameter. The NADCA Vacuum Test Method template consisting of two 25 cm by 2 cm slots was used in the study. The template, which is 0.4 mm (15 mil) thick, was supplied by NADCA, and used to define the area from which the sample was collected

Collection efficiency for the NADCA Vacuum Test Method was evaluated in previous testing. The initial evaluation showed the collection efficiency was low (47%) at low dust mass levels (3 mg/100 cm^2). At higher dust levels, the collection efficiency was better, but highly variable (70 ± 19%). All tests were conducted with unconditioned dust deposits. Sampling was performed according to the NADCA sampling protocol (Appendix A of Standard 1992-01). Measured dust levels were not corrected for collection efficiency. The NADCA Vacuum Test Method was used only for post-cleaning measurements on galvanized ducts to document cleaning effectiveness. The method was not developed for pre-cleaning sample collection or for collection of dust from porous surfaces.

Gravimetric analyses of filters to determine tare weights and final weights were performed in the EPA weighing facility at the EPA Annex in Research Triangle Park, NC. Filters were conditioned in the controlled environment weighing facility for 24 hours prior to weighing. Mass determinations were performed using the Cahn C-31 microbalance located in the facility. Gravimetric mass was determined as the difference between the final weight and the tare weight of the filter.

5.2.1.2 Medium Volume Dust Sampler (MVDS). A medium volume vacuum method was developed for use in the field study and was initially evaluated under laboratory conditions. It was further evaluated during the three ACS cleaning tests. The sampler consists of the following components:

- Thomas Model 2107CA20A dual diaphragm vacuum pump with nominal free air flow of 50 L/min,
- Gelman Model 2220 stainless steel 47 mm diameter in-line low pressure filter holder,
- Whatman EPM 2000, 47 mm, high-volume air sampling filters rated at 99.997% retention for 0.3 μm DOP,
- Brooks rotameter, 0 - 50 L/min range, in-line, calibrated with a wet test meter,
- Six inch long, 0.5 inch O.D. stainless steel tube for attachment of nozzles,
- Nozzle developed by Acurex Environmental - stainless steel, 30 mm X 3 mm inlet (0.9 cm^2 face area of nozzle), and
- Brush nozzle - nylon bristle brush, oval shaped, with an opening of approximately 18 mm by 10 mm, with 10 mm long nylon bristles (Source: Enervac Battery-Powered Vacuum Cleaner).

The sampler was operated at 40 L/min. Initial evaluation of the sampler with the stainless steel nozzle was performed in the laboratory. Dust collection efficiency with the nozzle was 98% from galvanized duct, 86% from duct liner, and 76% from fiberboard when the estimated background fiber contribution was subtracted. Tests were performed with nominal loading of 3 g/m^2 (30 $mg/100\ cm^2$).

The first tests in the PACS indicated that the nozzle was suitable for collection of newly-deposited dust, but that the brush was required for conditioned dust that adheres more strongly and realistically on the duct materials. The brush was used as the primary method during the study.

The sampler was used with templates having an area of 100 cm^2. Three different templates were tested during the study. They included the NADCA template (two slots 25 cm X 2 cm), a template with three 20 cm X 2 cm slots, and a 10 cm X 10 cm template. The NADCA template was too large and the multiple slot template did not offer any substantial advantages over the 10 cm X 10 cm template, which was used for most sampling.

Tare weights and final weights were determined by weighing on the balance in the EPA controlled environment weighing facility at the EPA Annex in Research Triangle Park, NC.

5.2.1.3 High Volume Sampler. A high volume vacuum sampler consisting of a Dirt Devil Can Vac with a reported flow rate of 20 cfm, a cyclone for particle collection, a collection jar, flow controller, magnehelic gauge, associated tubing, and nozzle was proposed for use in this study to sample dust from the cooling coils. The sampler could not be used to collect pre-cleaning samples because it had to be applied over a large area, and effectively it cleaned the cooling coils. Post-cleaning samples were collected from the cooling coils with the high volume sampler for the galvanized and FDL tests. But the post-cleaning samples collected with this method were of limited value without precleaning data. Therefore, use of the sampler was discontinued and the results are not reported.

5.2.2 PM_{10} and $PM_{2.5}$ Particle Mass Measurements

Integrated samples of PM_{10} and $PM_{2.5}$ mass were collected during selected time periods with size selective impactors developed at Harvard University, referred to as the MS&T sampler.

The sampling method is the same as that used in the EPA Office of Research and Development (ORD) Large Buildings Study and in the EPA Indoor Environment Division's Building Assessment and Survey Evaluation (BASE) program. Samples were collected over nominal 24-hr periods using Air Diagnostics and Engineering, Inc. (Naples, MA) pumps that operated at 20 L/min. Samples were collected on 37 mm, 2.0 µm pore size, Teflon filters (Gelman Sciences, Inc.). Pump air flow rates were measured at the start of the sampling period with a calibrated Sierra TopTrak mass flow meter.

Gravimetric analyses of filters to determine tare weights and final weights were performed in the EPA weighing facility at the EPA Annex in Research Triangle Park, NC. Filters were conditioned in the controlled environment weighing facility for 24 hours prior to weighing. Mass determinations were performed using the Cahn C-31 microbalance located in the facility. Gravimetric mass was determined as the difference between the final weight and the tare weight of the filter.

5.2.3 Particle Concentration Measurements - Laser Particle Counter

Airborne particle concentrations were measured during the tests with a Climet CI-4100 Laser Particle Counter. The particle sensor is a forward light scattering design. The instrument collects particle counts in two size fractions: > 0.5 µm and > 5.0 µm in diameter. The monitor has internal data storage for both channels or data can be output (4 - 20 mA proportional to concentration) for one channel. During this study the data for the > 0.5 µm channel was output to the Blue Earth data acquisition system of the EPA Indoor Air Quality Data Station. Data were saved as 10-min. averages. Data for the > 5.0 µm channel could not be output simultaneously. But the data were obtained by downloading the data directly from the Climet using a laptop computer and ProCom software. The Climet can store only 33 hours of 10-min. averages requiring daily data downloading. During some periods, the averaging time was changed to 20 minutes to extend the period between data downloading.

5.2.4 Particle Concentration Measurements - Laser Aerosol Spectrometer

Particle concentrations were also measured during the first two duct system tests with a LAS-X Laser Aerosol Spectrometer, which is a high resolution optical particle counter with an especially small lower size limit. The instrument collects particle counts in 16 channels over the range from 0.1 to 7.5 μm diameter. The spectrometer was operated in a 60-min. acquisition mode and data were output in real-time via an RS-232 connection to a dedicated computer.

5.2.5 Fiber Monitoring and Sampling Methods

Fiber concentrations were monitored continuously in the instrumentation room during tests with the galvanized steel duct system and the FDL system using an MIE FAM-1 Fibrous Aerosol Monitor. The FAM-1 uses an oscillating high-intensity electric field to both align and cause oscillatory motion in airborne fibers. Light pulses scattered by the individual fibers as they pass through the focused continuous wave laser are detected. The FAM-1 electronics accept only pulses synchronous with the oscillatory electric field, thus discriminating against particles that are not fibers. Pulse sharpness, which is proportional to length, is electronically determined. The FAM-1 returns a fiber count that has been calibrated against a fiber count by phase contrast microscopy. Data were recorded with an MIE PDL-10 data logger. An acquisition (integration) time of 100 minutes was used to obtain a detection limit of 0.1 fiber/cm^3.

Integrated samples of airborne fibers were collected according to the NIOSH Method 7400, *Asbestos and Other Fibers by PCM.* Samples were collected on 25 mm cellulose ester membrane filters (0.8 μm pore diameter) housed in a conductive cowl. A nominal sample volume of 2800 liters was collected over a 24-hour time period. Total fiber concentrations were determined by phase contrast microscopy in accordance to the NIOSH Method 7400 B counting rules.

Fiber samples were collected in duplicate in the instrumentation room. Samples were also collected outside of the room to verify that there was not a significant source of fibers in the facility in which the PACS was housed.

5.2.6 Microbial Surface Sampling

The primary microbial measurement was of the culturable microbial surface loading, expressed as colony forming units (cfu) per cm^2. Samples of deposited materials within a template defined area of 10 cm^2 were obtained by two techniques:

1) Suctioned at 10 L/min through a sterile pipet tip nozzle directly into a filter cassette, from which they were eluted, and plated onto Trypicase Soy Agar (TSA) and Sabourauds Dextrose Agar (SDA) for culture, identification, and colony counting.
2) Collected with a sterile swab that had been wetted in a saline solution. The sample was then eluted into a saline solution and plated onto TSA and SDA for culture, identification, and colony counting.

For both methods, the samples plated onto TSA were evaluated for fungal growth and the SDA plates for bacterial growth. The plates were evaluated by counting colonies and reporting the results as colony forming units (cfu) per area for surface samples or air volume for the bioaerosol sampling. The methods are described in *Air Conveyance System Cleaning Pilot System Development, Characterization, and Operation: Project Work and QA Plan* (RTI, 1995) and *Field Microbiological Investigation of Ventilation System Cleaning: Project Work/QA Plan* (RTI, 1996).

These measurements were conducted near where the dust mass loading measurements were made to permit evaluation of the correlation between dust mass and microbial populations. Co-located vacuum and swab samples were collected in most cases to allow comparison of the two methods. While the use of swabs to obtain surface samples is a traditional technique for non-porous surfaces, its use on rough-surfaced or porous materials cannot be quantitative because contact between the swab and the surface is imperfect. The vacuum technique was developed for improved efficiency on porous materials. The pilot unit afforded an opportunity for a direct comparision of the two microbial sampling methods with each other and the gravimetric tests described above. Because duct dust deposits can vary greatly over small areas in the relatively small residential ducts, differences between duplicate tests and co-located samples can reflect dust non-uniformity as much or more than measurement variability.

5.2.7 Bioaerosol Sampling

Bioaerosol samples were obtained with Mattson-Garvin slit-to-agar samplers operated over 60-minute periods with a fungal media. The Mattson-Garvin sampler draws air directly from the room at 28.3 L/min through a 0.15 mm slit allowing a broad range of airborne particles to be impacted upon the surface of a 150 mm rotating agar plate. The agar plate is then incubated and the number of colonies present counted and the organisms identified. Details of the sampling method can be found in *Field Microbiological Investigation of Ventilation System Cleaning: Project Work/QA Plan* (RTI, 1996). The sampler was disinfected with 70% ethanol before the initial sampling and between each individual sample. Two samplers were operated simultaneously to obtain duplicate fungal samples.

5.3 Test Protocol

The overall pilot unit ACS cleaning test matrix, given in Table 3, included a test series for each duct type. The duct systems all had nominally identical internal dimensions (construction details caused some differences, particularly in fittings) and were installed sequentially following the same paths. Flexible ducts were used for the supply drops in all cases. The flexible duct and the air handler were new for each test series.

Table 3. Test Matrix

Test ID	Duct System Design	Target Dust Loading	Cleaning Method
Test 1	Trunks of conventional galvanized duct, insulated outside. Supply feeders of flex duct to registers.	10 to 50 g/m^2 (100 to 500 mg / 100 cm^2)	As chosen on site by NADCA representatives
Test 2	Trunks of acrylic polymer faced, 1 in. thick, 1.5 lb/ft^3 FDL with flex duct feeders to registers.	10 to 50 g/m^2 (100 to 500 mg / 100 cm^2)	As chosen on site by NADCA representatives
Test 3	Trunks of unfaced, 1 in. thick EI-475 FDB with flex duct feeders to registers.	10 to 50 g/m^2 (100 to 500 mg / 100 cm^2)	As chosen on site by NADCA representatives

5.3.1 Dust Injection and Deposition.

To achieve the target dust loading, approximately 300 - 500 grams of collected duct dust were injected over a period of about one hour. The amount of dust injected was not considered critical, and varied depending on the frequency of dust injector plugging and the amount of dust lost when restoring operation. As expected, a large fraction of the injected dust never entered the duct system, settling instead in the dust mixing room. Distributed evenly over the approximately 11 m^2 of duct bottom surface (where most of the dust deposited), 400 grams would amount to 36g/m^2. The actual measured deposition was around 25% of the injected total.

When injecting dust, the pilot HAC was operated in "fan-only" mode. The air conditioning coil was allowed to dry before injecting the dust to allow as much dust as possible to penetrate past the coil into the supply ducts. (Krafthefer and Bonne, 1986, showed that coils "retain particulates more efficiently than common lint or dust stop filters.") The instrument room was bypassed, and the mixing fan in the dust mixing room was on at high speed. The humidifier was turned off.

Following duct soiling, the humidifier and the air conditioner were turned back on to condition the dust by exposure to several days of high humidity. The humidistat was set to maximum to give continuous humidifer output, the dust mixing room thermostat to 23.5°C (74°F), and the AHU fan to low speed. This resulted in mixing room and duct RH's of 90% or higher for most of the time and temperatures ranging from 23°C (73°F) to 27° (80°F). The air conditioner cycled on 4 or 5 times an hour for about 5 minutes, and during that time briefly reduced the mixing room humidity to about 70%. Conditioning was continued as long as allowed by the testing schedule. For the galvanized duct test, this allowed about 6 weeks of conditioning while the other two duct systems were allowed only 2 to 3 days. The conditioning process was not investigated. Subjectively, the individuals operating the surface sampling equipment were of the impression that the character of the dust was similar for each run.

The dust deposited differently in the different types of ACS. The deposit was most non-uniform in the bare galvanized sheet metal duct. This dust deposit was visibly thick in the stiffening beads, and in some places, particularly near flow obstructions, was not uniform across the width of the duct. The non-uniformity was evident on a large scale in the supply duct near the flexible duct takeoffs, where dust was deposited in swirled deposits on the order of 10 cm in size immediately next to relatively clean areas.

At a given sampling location, the FDL and FDB duct systems appeared more uniformly soiled than did the bare galvanized duct system. The galvanized duct system had by far the longest operating period between dust injection and sampling (4 months compared to a few days), so the difference may have been caused by redistribution during the extended period of operation. For FDL, the pattern of non-uniformity across the bottom of the duct was similar at all sample points, with dust trapped in the depressions associated with attachment pins and lesser amounts of dust in rough spots in the lining. Poorly fit joints also caused dust deposits. No large swirled deposits were noted.

The dust deposit was most uniform for the FDB system, with poor joints causing areas of increased deposition, as did the surface depressions. The non-uniformity was at a smaller scale than for bare galvanized metal, and there were no attachment pins.

5.3.2 Application of the Test Methods in the PACS

A complete test series for a single duct system consisted of a number of operating periods:

1) installation of the new duct system and checkout;
2) pre-soiling measurements to evaluate measurement backgrounds in ACS,
3) ACS soiling and deposited dust conditioning,
4) post-soiling, pre-cleaning evaluation of duct and AHU,
5) measurements conducted after soiling the ACS, but prior to cleaning to evaluate the dust deposit and particle loading,
6) cleaning the ACS,
7) surface mass and microbiological measurements made after cleaning the ACS and before restarting the AHU,
8) air sampling during and shortly after AHU startup,
9) integrated air sampling for total particles after cleaning, and
10) air sampling 24 hours and more after cleaning.

Table 4 shows the operating periods during which the various parmeters were measured.

Table 4. Measurement Schedule

Parameter	Pre-soiling	Pre-soiling AHU on	Soiling	Post-Soiling AHU off	Post-soiling, AHU on	Cleaning	Post-clean, before starting	Post-clean, AHU on	24 hour Post-clean
Dust loading, MVDS	X			X			X		
Dust loading, NADCA				X			X		
Microbial loading	X			X			X		
Bioaerosol concentration		60 min			60 min			60 min	60 min
$PM_{2.5}$		24 hr			24 hr			24 hr	
PM_{10}		24 hr			24 hr			24 hr	
Particles > 0.5 µm (counts)		continuous			continuous			continuous	
Particles > 5.0 µm (counts)		Continuous			Continuous			Continuous	
Particle count - 16 channel		Continuous			Continuous			Continuous	
Fibers, filter		24 hr			24 hr			24 hr	
Fibers, counter		Continuous			Continuous			Continuous	

5.4 Air Conveyance System Cleaning Operations Applied in the PACS

5.4.1 Operations Applied to All Systems

The following procedures used during the cleaning phase of PACS operation were common to all three duct systems:

- Safety Precautions. All duct cleaning operations were conducted while wearing safety glasses and safety shoes. Lock-out / tag-out procedures were applied to the air handler electrical mains. Respirators were used when working close to the duct.
- *Grill Removal and Cleaning.* The supply and return grills were removed as one of the first steps, power washed and hand-scrubbed with a commercial detergent solution when necessary, rinsed, and allowed to air dry. They were replaced as one of the final steps.

- *Air Handler and Blower.* The interior of the air handling unit (AHU) was cleaned each time by hand vacuuming with a soft brush attachment to a HEPA-filtered portable vacuum. The design of the AHU was such that the interior insulation was readily accessible. The AHU blower was removed each time the AHU was cleaned, the motor disconnected, and the blower wheel and case cleaned with the power washer (again using a commercial, biodegradeable detergent), and hand-scrubbed if needed.
- *Coil Cleaning.* The evaporator coil in the AHU was inspected and cleaned each time using a commercial coil cleaner, mixed as directed, and sprayed from a common pneumatic garden sprayer. While care was taken to minimize wetting the equipment liner, some overspray was observed. The coil was cleaned from the downstream side as much as possible.
- *Negative System Pressure* is achieved by placing large portions of the duct system under vacuum so that the dust and debris loosened and entrained by the cleaning devices is transported and removed from the system. For the PACS, negative system pressure was provided by a commercial vacuum blower capable of drawing 2000 cfm through two prefilters and discharging it back into the room through HEPA filters. The vacuum blower suction hose was temporarily fixed in the the air handler, in the side (supply or return) being cleaned, and loosely sealed in place using temporary connections. It remained running as long as NADCA continued cleaning operations.

5.4.2 Galvanized Steel Duct

With the duct system isolated and under negative pressure, the galvanized steel duct was cleaned using primarily a stiff, abrasive-coated, cylindrical rotary power brush to loosen the dust. Cleaning access was through the supply and return registers as well as the access doors shown in Figure 2. The test dust adhered well and multiple passes were required to clean corners and the stiffening beads in the duct. Following brushing, air washing was used to entrain and transport any remaining dislodged dust to the collector. Air washing is done by injecting compressed air against the duct walls through flexible hoses or nozzles mounted at the end of an air line that has been inserted some distance into the duct. The air jets blow the dust into the moving negative air, which transports the dust to the collector. The dust and debris are always kept moving towards the negative air collector.

The flexible duct used to supply individual registers was cleaned using a soft-bristle cylindrical rotary power brush and with air whips to loosen the dust and entrain it into the negative air flow. As in all cleaning, the brush was run from clean to dirty, which for these ducts meant from the supply registers toward the AHU.

5.4.3 Fibrous Glass Lined Duct

With the duct system isolated and under negative pressure, the FDL duct was cleaned using primarily a cylindrical rotary power brush of cloth strips to loosen the dust. Multiple passes were used as required to clean the duct. Following brushing, air washing (moving through the system toward the main vacuum source) was used to entrain and transport any remaining dislodged dust to the collector. The other aspects of cleaning the FDL duct were very similar to the galvanized duct.

5.4.4 Fiberglass Duct Board System

With the duct system isolated and under negative pressure, the FDB duct was cleaned using primarily a cylindrical rotary power brush of cloth strips to loosen the dust. Multiple passes were used as required to clean the duct. Following brushing, air washing (moving through the system toward the main vacuum source) was used to entrain and transport any remaining dislodged dust to the collector. Frequent inspection was used to ensure that the duct surface was not damaged. Some sections of the duct were hand-brushed to complete the cleaning process. The other aspects of cleaning the FDB duct system were very similar to the galvanized duct.

6. RESULTS AND DISCUSSION

6.1 Pilot Ventilation System Operation

PACS operation during soiling and dust conditioning was described in Section 5.3. Normal operation for the PACS was intended to mimic normal residential use as much as possible, and was used except during soiling, conditioning, and cleaning. In normal operating mode, the bypass duct was disconnected, and supply air entered the instrument room through a conventional wall diffuser, mixed within the room with the small mixing fan on, and flowed into the dust mixing room through the open low air velocity return. The instruments being compared were located on the floor or on portable stands near the center of the room. The door to the instrument room was closed.

When in normal operating mode the thermostat, located in the dust mixing room, was set to 21°C (70°F) and the humidistat to 70%. At these settings, the air conditioner was required 4 to 5 times an hour, running for about 5 minutes each time. The temperature in the dust mixing and instrument rooms was 22°C - 2/+3°C, with the temperature dropping after the air conditioner came on and rising more slowly after it shut off. Similarly, the humidity in the mixing room dropped when the air conditioner was on and then rose after it was off. Relative humidity ranged from 30 to 70% but was normally about 50% to 60%. As estimated by CO_2 injection and decay, the PACS infiltration rate from the surrounding laboratory was about 0.02 m^3/s (40 cfm), or 5% of the HAC circulation rate.

6.2 Surface Deposit Measurements

6.2.1 Gravimetric Duct Dust Measurement Results

Duct dust samples were collected prior to ACS cleaning and following ACS cleaning for tests with each of the three duct systems (galvanized steel, FDL, and FDB). Duct dust was defined as any material that could be collected with the MVDS or NADCA sampling methods. As defined, duct dust could include inorganic particulate matter, organic particulate matter, and fibers. The MVDS was the primary sampling method used in this study. Most samples were collected with the MVDS fitted with the brush. The nozzle, which was determined early in the study to have a lower collection efficiency, was used to collect a limited number of samples, as described below. The NADCA sampling method was used only for the galvanized steel duct system for collection of samples after ACS cleaning. The objectives of the duct dust sampling were to:

- Determine the dust mass that was deposited on the surfaces at various locations in the duct and on other components of the ACS system,
- Evaluate the sampling methods proposed for use in the field study, and
- Collect information to develop and refine sampling protocols for the field study.

6.2.1.1 *Galvanized Steel Duct System*

Results for duct dust measurements performed during the testing with the galvanized steel duct system are summarized in Tables 5 (pre-cleaning samples) and 6 (post-cleaning samples). Results are shown for locations in the supply, return, and flexible ducts. The locations are depicted in Figure 2 above. Samples were also collected from the cooling coil, side wall of the plenum box, and the foil liner in the air handler.

All samples were collected with the brush attachment on the MVDS during this test. Collection efficiency using the MVDS with the stainless steel nozzle was poor based on visual observation; dust remained on the galvanized steel surface after collection with the nozzle. The NADCA method was developed only for post-cleaning sample and was not used for pre-cleaning sampling. Previous evaluation of the method indicated that collection efficiency was poor at the dust mass levels present in ducts prior to cleaning.

Dust samples collected prior to cleaning demonstrated that deposition of dust in the ducts was not uniform, as was apparent after visual inspection. The deposits in the return duct were especially non-uniform in that a noticeable amount of dust had collected in the stiffening beads (1 cm wide depressions in the sheet metal extending the full width of the duct). In the supply duct, the effects of non-uniform flow were evident near the flexible duct takeoffs. To the extent possible, the samples were taken to be representative of the region near the access doors.

Table 5. Dust Levels in the Galvanized Duct System Prior to Cleaning

Duct	Location	Sampler	Nozzle	Surface Sampled	g/m^2
Supply	S-1	MVDS	Brush	Bottom	2.66
	S-2	MVDS	Brush	Bottom - Primary	7.29
		MVDS	Brush	Bottom - Duplicate	4.27
				Avg. ± SD[a]	5.78 ± 2.14
	S-3	MVDS	Brush	Bottom	6.43
	S-4	MVDS	Brush	Bottom	1.86
Return	R-1	MVDS	Brush	Bottom	5.04
	R-2	MVDS	Brush	Bottom	7.51
	R-3	MVDS	Brush	Bottom - Primary	14.73
		MVDS	Brush	Bottom - Duplicate	13.02
				Avg. ± SD[a]	13.87 ± 1.21
	R-4	MVDS	Brush	Bottom	1.40
Flexible	F-1	MVDS	Brush	Bottom - Primary	1.17
		MVDS	Brush	Bottom - Duplicate	1.38
				Avg. ± SD[a]	1.27 ± 0.12
	F-2	MVDS	Brush	Bottom	1.14
	F-3	MVDS	Brush	Bottom	1.47
	F-4	MVDS	Brush	Bottom	1.83
AH[b]	Coils	MVDS	Brush	Upstream	1.22
	Plenum	MVDS	Brush	Bottom	0.72
	Foil Liner	MVDS	Brush	Side-wall	0.64

[a] Average ± Standard Deviation for duplicate dust samples collected at adjacent locations

[b] Samples collected from the air handler

Table 6. Dust Levels in the Galvanized Duct System After Cleaning

Duct	Location	Sampler	Nozzle	Surface Sampled	g/m^2
Supply	S-1	MVDS	Brush	Bottom	0.26
		MVDS	Nozzle	Bottom	0.15
		NADCA		Bottom	< MDL[a]
	S-2	MVDS	Brush	Bottom	0.37
		MVDS	Brush	Sidewall	0.16
		MVDS	Nozzle	Bottom	0.09
		NADCA		Bottom	0.01[b]
Return	R-2	MVDS	Brush	Bottom	0.36
		MVDS	Brush	Sidewall	0.14
		MVDS	Nozzle	Bottom	0.30
		NADCA		Bottom	0.02[c]
Average Residual Dust ± SD on Galvanized Surfaces Sampled with the MVDS/Brush (N=5)					0.26 ± 0.11
Flexible	F-1	MVDS	Brush	Bottom	0.17
		MVDS	Nozzle	Bottom	0.22
	F-4	MVDS	Brush	Bottom	0.38
		MVDS	Nozzle	Bottom	0.30
Average Residual Dust ± SD on Flexible Duct Surfaces Sampled with the MVDS-Brush (N=2)					0.28 ± 0.15
AHU[d]	Coils	MVDS	Brush	Bottom	0.26
	Plenum	MVDS	Brush	Bottom	0.33
	Foil Liner	MVDS	Brush	Bottom	0.28

[a] Less than the minimum detection limit of 0.01 g/m^2 (0.1 mg/100 cm^2)

[b] Equals 0.1 mg/100 cm^2

[c] Equals 0.2 mg/100 cm^2

[d] Samples collected in air handler

As shown in Table 5, dust levels in the return duct ranged from 1.4 to 14.7 g/m^2. In the supply duct, the dust levels ranged from 1.9 to 7.3 g/m^2. The lowest dust levels in the galvanized steel ducts were at the sampling location in the supply duct farthest away from the air handler. Dust levels in the flexible ducts were lower than in the galvanized supply duct and the return duct, ranging from 1.1to 1.8 g/m^2. Dust levels were also lower on the components of the air handler. During this test, all dust samples were collected from the bottom of the ducts, where the dust deposition was highest. During the initial testing with the galvanized duct system, samples were collected from the top and side of the duct at location R-2. Dust levels were substantially lower than on the bottom, being 1.0 g/m^2 on the sidewall and 0.3 g/m^2 on the top surface. Based on visual observation, loading on the sidewalls and top of the duct appeared to be light and relatively uniform. Therefore, additional samples were not collected during the test.

Duplicate samples collected in the return duct at location R-3 showed good precision with a relative standard deviation (RSD) of 8.7%. Similar precision was observed for duplicate samples collected at one location in a flexible duct. The precision was not as good (RSD of 37%) for the duplicates collected in the supply location S-2. This was expected becausevisual inspection showed a highly variable dust deposition pattern at this location.

The post-cleaning measurement results (Table 6) showed that the cleaning methods effectively removed the dust from the system. Visual inspection indicated that all but a light "film" of dust had been removed from the galvanized steel duct surfaces. The dust mass was less than 0.4 g/m^2 (4 mg/100 cm^2) for all samples. The average dust mass on the galvanized steel duct surfaces after cleaning was 0.26 ± 0.09 g/m^2 (2.6 mg/100 cm^2) when measured with the MVDS fitted with the brush. Using the nozzle on the MVDS, the average was 0.18 ± 0.11 g/m^2. In contrast, the mass of dust measured on the galvanized steel ducts with the NADCA Vacuum Test method was 0.1, 0.2, and less than 0.01 mg/100 cm^2, meeting the requirement of NADCA Standard 1992-01 that dust weight after cleaning be less than 1 mg/100 cm^2. The higher efficiency MVDS measurement gave results that were greater than the NADCA criterion for cleanliness of 1 mg/100 cm^2, while the results with the NADCA method were below the criterion.

These tests with the galvanized duct system showed that the nozzle developed for the MVDS would probably be inadequate for pre-cleaning sampling in the field. Although the nozzle had a high collection efficiency for "newly-deposited" dust on galvanized steel surfaces during laboratory tests, visual observation indicated that it could not effectively collect dust adhering to the steel surface. It was necessary to use a brush to dislodge dust adhered to the surface. As a result of the test in the PACS, the brush was used as the primary method of sampling in the field study.

Results of the pre-cleaning sampling in the galvanized system confirmed that dust levels were in the range desired for the cleaning test. The results also showed that dust deposition was variable, as expected. The results suggested that sampling of duct dust in the field study would require sampling at multiple locations and extensive visual inspection of the ducts in the system to identify representative areas for sample collection.

6.2.1.2 Fibrous Glass Duct Liner System. Results for duct dust measurements performed during the testing with the system constructed of FDL in the supply and return trunks and flexible feeder ducts are summarized in Tables 7 (background dust samples), 8 (pre-cleaning samples) and 9 (post-cleaning samples). Background samples were collected to determine the amount of dust on the components of the system that may have resulted from manufacturing and construction activities or that may have been dislodged from the surface of the materials during sampling. This was of particular concern for the FDL because previous testing showed that the sampling method could dislodge loose material from the surface of this product. The sampling locations are those depicted previously in Figure 2. Location R-4 was not used in this test. Background and pre-cleaning samples were collected with the brush attachment on the MVDS, the most aggressive and most efficient sampling method.

Samples collected from the "clean" surfaces of the ACS components prior to loading the test dust into the system contained measurable background material (Table 7). The average mass collected from the FDL surfaces in the supply and return ducts was 0.38 ± 0.08 g/m^2. The material collected was weighed but not identified; its source is unknown. Although, the source of the background material on the FDL was not determined in this study, it is interesting to note that background material was also measured on the flexible duct and on surfaces in the air handler. The amount of background dust collected on the flexible duct surface and foil liner of the air handler was similar to that collected from the FDL surfaces, suggesting that the source of the material is the manufacturing process or deposition during construction of the system. It

Table 7. Background Dust Levels from the Surfaces in the FDL System Prior to Soiling

Duct	Location	Sampler	Nozzle	Surface Sampled	g/m^2
Supply	S-2	MVDS	Brush	Bottom	0.42
	S-3	MVDS	Brush	Bottom	0.44
Return	R-1	MVDS	Brush	Bottom	0.21
	R-1	MVDS	Brush	Top	0.43
	R-1	MVDS	Brush	Sidewall -Outside	0.43
	R-1	MVDS	Brush	Sidewall - Inside	0.40
	R-3	MVDS	Brush	Bottom	0.36
Average Background Dust ± SD for FDL Surfaces N=7)[a]					0.38 ± 0.08
Flexible	F-2	MVDS	Brush		0.35
AH[b]	Coils	MVDS	Brush		0.27
	Foil Liner	MVDS	Brush		0.24
Avg. Background Dust ± SD for all Surfaces (N=10)					0.36 ± 0.09

[a] Average ± Standard Deviation for seven samples collected on the FDL surfaces

[b] Samples collected from the air handler

should be noted that the background mass collected from the new, "clean, surfaces of the air handler components and flexible duct was nearly identical to the mass collected from similar surfaces after cleaning the galvanized steel duct system (Table 6).

Dust levels on the surfaces of the ACS components of the FDL system prior to cleaning are presented in Table 8. The mass of dust on the bottom surface of the FDL return ranged from 4.78 to 11.32 g/m^2. At location R-1, dust mass was lower on the top (1.20 g/m^2) and two sidewalls (1.47 and 1.12 g/m^2) than on the bottom surface of the duct. In the supply, the dust loading ranged from 0.65 to 1.4 g/m^2 on the bottom. The dust mass on the top and sides of the duct at location S-1 was in the same range as the mass on the bottom of the duct at the three sampling locations. The mass of dust deposited in the components of the FDL system was generally less than that in the galvanized system (Table 5).

Table 8. Dust Levels in the Fibrous Glass Duct Liner System Prior to Cleaning

Duct	Location	Sampler	Nozzle	Surface Sampled	g/m^2
Supply	S-1	MVDS	Brush	Bottom - Primary	0.73
		MVDS	Brush	Bottom - Duplicate	0.65
				Avg. ± SD[a]	0.69 ± 0.06
		MVDS	Brush	Top	1.15
		MVDS	Brush	Sidewall - Outside	0.50
		MVDS	Brush	Sidewall - Inside	0.82
	S-2	MVDS	Brush	Bottom	1.42
	S-3	MVDS	Brush	Bottom	1.23
Return	R-1	MVDS	Brush	Bottom	5.99
		MVDS	Brush	Top	1.20
		MVDS	Brush	Sidewall - Outside	1.47
		MVDS	Brush	Sidewall - Inside	1.12
	R-2	MVDS	Brush	Bottom	4.78
	R-3	MVDS	Brush	Bottom - Primary	11.32
		MVDS	Brush	Bottom - Duplicate	7.95
				Avg. ± SD[a]	9.64 ± 2.38
Flexible	F-1	MVDS	Brush	Bottom - Primary	1.31
		MVDS	Brush	Bottom - Duplicate	0.73
				Avg. ± SD[a]	1.02 ± 0.41
	F-2	MVDS	Brush	Bottom	0.83
	F-3	MVDS	Brush	Bottom	0.50
	F-4	MVDS	Brush	Bottom	0.66
AH[b]	Coils	MVDS	Brush	Bottom	0.80
	Plenum	MVDS	Brush	Side	0.54
	Foil liner	MVDS	Brush		0.53

[a] Average ± Standard Deviation for duplicate dust samples collected at adjacent locations
[b] Samples collected from the air handler

Table 9. Dust Levels in the FDL System After Cleaning

Duct	Location in System	Sampler	Nozzle	Surface Sampled	g/m^2
Supply	S-1	MVDS	Brush	Bottom	0.45
		MVDS	Nozzle	Bottom	0.25
		MVDS	Brush	Sidewall - Inside	0.29
	S-2	MVDS	Brush	Bottom - Primary	0.35
		MVDS	Brush	Bottom - Duplicate	0.49
				Avg. ± SD[a]	0.42 ± 0.10
Return	R-1	MVDS	Brush	Sidewall - Outside	0.45
	R-2	MVDS	Brush	Bottom	0.31
		MVDS	Nozzle	Bottom	0.36
Average Residual Dust ± SD on FDL Surfaces Sampled with the MVDS-Brush (N=6)					0.39 ± 0.08
Flexible	F-1	MVDS	Brush	Bottom - Primary	0.24
		MVDS	Brush	Bottom - Duplicate	0.34
				Avg. ± SD[a]	0.29 ± 0.07
	F-4	MVDS	Brush	Bottom	0.33
Average Residual Dust ± SD on Flexible Duct Surfaces Sampled with the MVDS-Brush (N=3)					0.30 ± 0.06
AH[b]	Coils	MVDS	Brush		0.26
	Plenum	MVDS	Brush	Bottom	0.25
	Foil Liner	MVDS	Brush	Bottom	0.24

[a] Average ± Standard Deviation for duplicate dust samples collected at adjacent locations

[b] Samples collected in air handler

Duplicate samples collected in the return duct at location R-3 had a relative standard deviation of 25%. Precision of the duplicates collected in the supply was better (%RSD = 8%). Visual inspection indicated that the deposition was more uniform in the supply ducts. The precision for the duplicate samples collected in the flexible duct was poor (%RSD = 40%). The poorer precision may reflect non-uniform dust deposition in the duct. It may also reflect sample loss caused by movement of the duct material to gain access or the fact that collection of samples out of the end of the flexible duct was difficult due to the small size of the opening.

The post-cleaning measurement results (Table 9) showed that the cleaning methods effectively removed the dust from the system. The dust mass was less than 0.5 g/m^2 (5 mg/100 cm^2) for all samples collected with the MVDS with the brush attachment. The average dust mass collected with the MVDS-brush sampler from the FDL surfaces in the supply and return ducts was 0.39 ± 0.07 g/m2. This compared to an average residual mass of 0.30 ± 0.06 g/m^2 on the flexible duct surface and 0.25 ± 0.1 g/m^2 on the air handler components sampled with the MVDS, indicating that the residual dust on the FDL surfaces was not substantially different from that on other types of surfaces. The amount of dust collected after cleaning of the flexible ducts and the air handler components was similar in both the galvanized steel duct and FDL system tests. Comparison of the measurement results for samples collected on "clean" surfaces prior to loading of the dust into the test system (Table 7) with the results for samples from the same surfaces after cleaning (Table 9) shows that the levels are similar. The average background on "clean" FDL surfaces was 0.38 ± 0.18 g/m^2 which was not significantly different from the post-cleaning dust mass of 0.39 ± 0.07 g/m^2.

6.2.1.3 Fiberglass Duct Board System. Results for duct dust measurements performed during the testing with the system constructed of FDB for the supply trunk and return ducts and flexible feeder ducts are summarized in Tables 10 (background samples and pre-cleaning samples) and 11 (post-cleaning samples). The measurement locations are those depicted previously in Figure 2. Background samples were collected from the FDB surface prior to installation in the system because laboratory evaluation of the MVDS showed that the sampler would collect a substantial amount of fibers from new FDB. Background sampling would determine the mass of fibers dislodged during sampling as well as the amount of dust and fiber mass on the surface of the FDB that may have resulted from manufacturing, storage of the

Table 10. Dust Levels in the FDB System Prior to Cleaning

Duct	Location	Sampler	Nozzle	Surface Sampled	g/m^2
Background Samples - New FDB					
Pre-Loading[a]		MVDS	Nozzle		0.99
		MVDS	Nozzle		1.29
		MVDS	Nozzle		1.43
		Avg. ± SD[b] for the MVDS/Nozzle			1.24 ± 0.18
		MVDS	Brush		1.26
Pre-Cleaning Samples - Dust Loaded					
Supply	S-1	MVDS	Nozzle	Bottom	1.92
	S-2	MVDS	Nozzle	Bottom - Primary	0.50
		MVDS	Nozzle	Bottom - Duplicate	0.51
				Avg. ± SD[b]	0.50 ± 0.10
	S-3	MVDS	Nozzle	Bottom	0.51
Supply	S-1	MVDS	Brush	Bottom	1.74
	S-2	MVDS	Brush	Bottom	0.44
Return	R-1	MVDS	Nozzle	Bottom	3.00
	R-3	MVDS	Nozzle	Bottom	0.67
	R-3	MVDS	Nozzle	Sidewall- Inside	2.65
Return	R-1	MVDS	Brush	Bottom	17.0
	R-2	MVDS	Brush	Bottom	7.57
	R-3	MVDS	Brush	Bottom	5.02
	R-3	MVDS	Brush	Sidewall - Inside	2.73
Flexible	F-1	MVDS	Brush	Bottom - Primary	0.18
		MVDS	Brush	Bottom - Duplicate	0.15
				Avg. ± SD[b]	0.17 ± 0.02
AH[c]	Foil liner	MVDS	Brush		0.38

[a] Samples were collected after duct fabrication but prior to assembly of the system.

[b] Average ± Standard Deviation for duplicate dust samples collected at adjacent locations

[c] Samples collected from the air handler

Table 11. Dust Levels in the FDB System After Cleaning

Duct	Location	Sampler	Nozzle	Surface Sampled	g/m^2
Supply	S-1	MVDS	Nozzle	Bottom	0.16
	S-2	MVDS	Nozzle	Bottom - Primary	0.20
		MVDS	Nozzle	Bottom - Duplicate	0.33
				Avg. ± SD[a]	0.27 ± 0.09
Return	R-1	MVDS	Nozzle	Bottom	0.17
	R-2	MVDS	Nozzle	Bottom	0.54
Average Residual Dust ± SD on FDB Surfaces Sampled with the MVDS-Nozzle (N=5)					0.28 ± 0.16
Flexible	F-1	MVDS	Brush	Bottom	0.15
AH[b]	Coils	MVDS	Brush		0.12
	Foil Liner	MVDS	Nozzle		0.02

[a] Average ± Standard Deviation and % Relative Standard Deviation for duplicate dust samples collected at adjacent locations

[b] Samples collected in air handler

material, or construction activities.

Background and pre-cleaning samples were collected with both the stainless steel nozzle and the brush attachment on the MVDS. For the FDB surfaces, the nozzle was considered the primary sampler because the brush would dislodge fibers from the surface during sampling. As shown in Table 10, the average background mass was 1.24 g/m^2 for three samples collected with the nozzle. One sample collected with the brush gave similar results (1.26 g/m^2), but only because it was not used aggressively; it was pulled across the surface very gently. Although the composition of the background material was not determined analytically, visual observation suggested that the mass collected was primarily fibers.

Results for measurements of duct debris (particles and fibers) collected after loading of the dust into the system are also shown in Table 10. The results are difficult to interpret. Using the MVDS nozzle sampler, the mass loadings ranged from 0.67 to 3.0 g/m^2 on the FDB surfaces in the return and 0.5 to 1.92 g/m^2 on the FDB in the supply. These loadings were substantially lower than measured in the tests with the galvanized steel ducts and the FDL. In the previous tests, the galvanized return ducts had mass loading that ranged from 5.0 to 14.7 g/m^2 at the corresponding locations. In the FDL system, the dust mass on the bottom of the duct (collected with the brush) ranged from 4.8 to 11.3 g/m^2. The loading of dust on the FDB was comparable to previous tests, however, if the measurements with the MVDS brush sampler were used. As shown in Table 10, the mass of dust (and fibers) in samples collected from the bottom of the return duct ranged from 5.0 to 17 g/m^2 using the MVDS brush sampler. Visual inspection of the samples, however, showed that there was a substantial amount of fiber material on the filters. Confidence in the accuracy of the measurements of dust on FDB surfaces is considered to be low. Visual inspection of surfaces sampled with the nozzle indicated that particulate matter was still present on the surface, which will result in an under-estimate of the particle mass on the surface. Inspection of the samples collected with the brush indicated that substantial amounts of fibers were collected, which will result in an over-estimate of the particle loading on these surfaces. Therefore, neither sampling method appears to give accurate measurements of the dust deposited on the surfaces.

In the supply, the pre-cleaning measurements with the MVDS-nozzle were 1.92 g/m^2 at S-1 and 0.5 g/m^2 at S-2. The collocated samples with the brush were nearly the same, being 1.74 g/m^2 at S-1 and 0.44 g/m^2 at S-2. These mass loadings are nearly the same as the background measurements. Based on visual observation, the loading in the supply duct was very low; dust was barely visible on the surface. Visual inspection of the filters indicated a large amount of fibrous material on filters used for both the nozzle and filter samplers. Therefore, the results in the supply may be more indicative of background contribution from the fibers than the amount of dust deposited on the surface.

The amount of dust collected prior to cleaning from the surface of the flexible duct used in the FDB system was 0.17 g/m^2, which was lower than on comparable surfaces in the previous tests. The mass of dust collected from the foil liner in the air handler in the test with the FDB system was also lower than in previous tests. This may have resulted from higher deposition rates on the fibrous surface of the return duct in this test.

Measurements of dust in the FDB system following cleaning are presented in Table 11. The average mass collected with the MVDS-nozzle from five locations on the cleaned FDB in the supply and return was 0.28 ± 0.16 g/m^2. This was substantially lower than either the pre-cleaning or background samples collected from FDB surfaces. The mass of dust on the one flexible duct location sampled was 0.15 g/m^2, nearly the same as the pre-cleaning sample.

6.2.1.4 Evaluation of the Duct Dust Sampling Methods - Summary. The MVDS-brush method worked well on the galvanized steel surface. Because there was no concern about dislodging surface materials it could be used aggressively to obtain the maximum collection efficiency. The method also worked well on the FDL used in this study. Although background mass was collected from surfaces of the new FDL prior to loading of the dust into the system, the amount of background mass from "clean" FDL was not substantially higher than that collected from the surface of flexible duct and foil liner in the same system. The amount of mass collected from "clean" FDL surfaces was also similar to that collected from galvanized steel duct surfaces, flexible duct surfaces, and foil liner after ACS cleaning. Visual inspection of surfaces sampled with the MVDS fitted with the nozzle for sample collection indicated that the nozzle could not effectively collect dust adhered to the surfaces of ACS components. The nozzle was not considered to be adequate for dust sampling based on this study and was not used in the field study.

The precision of the MVDS/brush sampling method was generally very good for duplicate side-by-side samples in spite of the variability of particle deposition in the ducts. The %RSD for duplicates was 9% and 37% for galvanized steel surfaces in pre-cleaning samples. On the FDL surface, the % RSD was 8 and 25 % for pre-cleaning samples. The precision of the method for samples from flexible duct surfaces was 11%, 24%, and 40%. This level of precision is probably adequate for sampling duct dust from ACS components because the dust loading at different locations in an ACS can be expected to be highly variable. During this study, the precision of the NADCA method was not evaluated. It was evaluated in the laboratory and in the field study by collecting duplicate samples.

The NADCA sampling method was used only to collect post-cleaning samples from galvanized steel duct surfaces. This is currently the only application for which the method is recommended. Previous laboratory testing indicated that it was not applicable for collection of dust samples prior to cleaning because of the low collection efficiency and because particulate matter was lost from the filter if the amount of particulate mass was high. Testing in the PACS, as shown in Table 6 indicated that results with the NADCA method were substantially lower than with the MVDS-brush method. The samples collected with the NADCA method demonstrated that the ACS cleaning was effective based on the NADCA criterion that residual dust can not exceed 0.1 g/m^2 (1 $mg/100\ cm^2$). But the criterion was not met if the MVDS-brush method was used to sample from galvanized steel duct surfaces. For collocated samples with the NADCA and MVDS-brush method, the MVDS method mass measurements results were 18, 26, and 37 times higher than the NADCA method results. Measurements with the MVDS-nozzle method were 9, 15, and 30 times higher providing additional evidence that the NADCA sampler has low collection efficiency.

Results from the three tests suggest that the NADCA criterion of 1 $mg/100\ cm^2$ (0.1 g/m^2) for verification of cleaning effectiveness is too low when samples are collected with an efficient sampler. The average mass collected on the cleaned galvanized steel duct surfaces was 0.26 ± 0.11 g/m^2 (2.6 $mg/100\ cm^2$). On flexible duct surface, the average mass was 0.27 ± 0.09 g/m^2. The mass on the cleaned foil liner of the air handler was 0.28 g/m^2 in the galvanized duct system. Similar results were observed in the FDL system where the average mass on surfaces after cleaning was 0.39 ± 0.08 g/m^2 on FDL, 0.30 ± 0.06 g/m^2 on flexible duct, and 0.24 g/m^2 for the one foil liner sample. When efficient sampling methods such as the MVDS brush method are used, a more appropriate criterion for cleaning effectiveness is probably residual dust of less than 0.5 g/m^2 (5 $mg/100\ cm^2$) based on the results of these tests.

6.2.2 Microbiological Surface Samples

6.2.2.1 Galvanized Steel Duct System. The results of the microbiological surface sampling of the galvanized duct system using the two methods - swab and vacuum - are summarized in Table 12. The test locations are the same as used in the dust mass sampling, and are shown on Figure 2. The culturable fungi for all samples were below the minimum detection level. On the other hand, culturable bacteria were found above the detection limit at all locations prior to cleaning. Comparison of the precleaning bacterial loadings with the dust loadings (Tables 6 and 12) shows that the bacterial loading is somewhat correlated with the dust loading

Table 12. Microbial Results for Galvanized Steel in cfu/cm^2

Duct	Location	Sample Type	Fungi		Bacteria	
			preclean	postclean	preclean	postclean
Supply	S1	Vacuum	< 5	< 5	5	< 5
		Swab	< 5	< 5	20	< 5
	S3	Vacuum[a]	< 5	< 5	10	< 5
		Swab	< 5	< 5	25	< 5
		Swab[a]	< 5	< 5	130	< 5
Return	R1	Vacuum	< 5	< 5	5	< 5
		Swab	< 5	< 5	40	< 5
	R2	Vacuum	5	< 5	85	5
	R3	Vacuum	5	< 5	190	< 5
		Swab	5	< 5	120	< 5

[a] Swab sample collected from same area after vacuum sample completed.

but that large variation is present. The ratio of bacterial counts to dust mass varied from 2.2×10^4 to 11.3×10^4 cfu/g. All the loadings are low and would not represent serious contamination.

Comparison of the swab and vacuum technique results shows that the ratio of swab to vacuum counts ranged from 0.63 to 8 with a mean of 5.6. The wide ranges are not surprising because the measurements include dust spatial variability, variability in the particles with which the microbiological material is associated, and measurement variability. On the whole, the swab samples of galvanized duct appear to sample a larger culturable bacterial sample than does the vacuum technique.

6.2.2.2 Fibrous Glass Duct Liner System. The results of the microbiological surface sampling of the FDL system using the two methods - swab and vacuum - are summarized in Table 13. The test locations are the same as were used in the dust mass sampling, and are located on Figure 2. Prior to cleaning, the culturable fungi for many samples were below the minimum detection level while for others, the fungal levels were measurable. Following cleaning, all fungal levels were below the detection limit of 5 cfu/cm^2. As with the galvanized system, culturable bacteria were found above the detection limit at all locations prior to cleaning.

Table 13. Microbial Results for FDL in cfu/cm^2

Duct	Location	Sample Type	Fungi		Bacteria	
			preclean	postclean	preclean	postclean
Supply	S1	Vacuum	< 5	< 5	25	5
		Swab	5	< 5	5	< 5
	S3	Vacuum	< 5	< 5	< 5	30
		Swab	< 5	< 5	50	< 5
Return	R1	Vacuum	10	< 5	200	< 5
		Swab	< 5	< 5	15	< 5
	R2	Vacuum	5	< 5	30	< 5
		Swab	5	< 5	160	< 5
	R3	Vacuum	10	< 5	100	5
		Swab	5	< 5	70	< 5

Following cleaning they were found to be at or below the detection limit.

Comparison of the pre-cleaning microbial loadings with the dust loadings (Tables 8 and 13) shows that the range of culturable bacterial counts to dust loading was 9 x 10^4 to 44 x 10^4 cfu/g. As with the galvanized steel duct, on average swab sampling collected more bacterial counts than did the vacuum technique, though the levels are again low. However, individual site ratios ranged from 0.2 to 10 with a mean of 3.3 and a very large standard deviation of 4.4.

6.2.2.3 Fiberglass Duct Board System. The results of the microbiological surface sampling of the FDB system using the two methods - swab and vacuum - are summarized in Table 14. The test locations are the same as were used in the dust mass sampling, and are located on Figure 2. Prior to cleaning, the culturable fungi ranged from the minimum detection level to 450/cm^2. The duct dust was apparently more highly loaded microbially than were the other two injected dust samples. Following cleaning, the fungal levels ranged from below the detection limit to 50 cfu/cm^2, a significant reduction in numbers, but leaving ample spores for growth to occur should conditions become favorable. As shown in the last two columns, culturable

Table 14. Microbial Results for FDB in cfu/cm^2

Duct	Location	Sample Type	Fungi		Bacteria	
			preclean	postclean	preclean	postclean
Supply	S1	Vacuum	55	10	25	< 5
		Swab	20	5	15	15
	S2	Vacuum	not obtained	10	not obtained	5
	S3	Vacuum	50	not obtained	25	not obtained
		Swab	< 5	< 5	10	< 5
Return	R1	Vacuum	450	20	200	15
		Swab	190	25	130	5
	R2	Vacuum	220	50	260	10
		Swab	220	< 5	130	25
	R3	Vacuum	180	45	65	15
		Swab	50	< 5	35	5

bacteria were found be present at about the same levels as the fungi before cleaning and to be removed with approximately the same efficiency. Comparison of the microbial loadings with the dust loadings (Tables 10 and 14) again shows that the culturable bacterial loading per gram of dust ranged from 11 x 10^4 to 75 x 10^4 cfu/g. On this more open-pored material, the ratio of swab to vacuum results was uniformly less than one, with a mean of 0.43 for fungi and 0.57 for bacteria. Relative to the other two duct systems, these fungal and bacterial values are high enough to have greater significance for comparison of the two methods. This result is consistent with the observation that the FDB visibly retained more dust below the surface than did the other duct material, where it was available to the vacuum sampling technique but not to the swab.

6.3 Aerosol Measurements

6.3.1 PM_{10} and $PM_{2.5}$ Particle Mass Measurements

Integrated samples of particulate matter were collected in the instrument room on one day prior to ACS cleaning and on the day following cleaning during each of the three tests. Samples of inhalable particles (PM_{10}) and respirable ($PM_{2.5}$) particles were collected using MS&T samplers over nominal periods of 24 hours. The objective of the sampling was to shake-down the instrumentation prior to use in the field study. In particular, the tests were performed to determine if the air flow rates would be stable for a 24 hour sampling period and to verify that the pump timers and elapsed time meters worked properly. The Climet optical particle counter was operated concurrently in order to evaluate the relationship between particle counts and mass determinations. Both methods were planned for use in the field study. The sampling was limited in scope and not intended to determine the effect of ACS cleaning on IAQ, although the data may be useful in designing future tests in pilot scale ACS facilities. Table 15 presents the results

Table 15. Comparison of PM_{10} and $PM_{2.5}$ Integrated Air Samples and Concurrent Optical Particle Measurements in the Instrument Room

Parameter - Sampling Period	Units	Galvanized Steel Duct	Fibrous Glass Liner	Fiberglas Duct Board
PM_{10} - Pre-Cleaning	µg/m^3	11.8	3.8	8.0
PM_{10} - Post-Cleaning	µg/m^3	1.7	10.3	6.5
$PM_{2.5}$ - Pre-Cleaning	µg/m^3	10.5	3.2	8.5
$PM_{2.5}$ - Post-Cleaning	µg/m^3	1.8	10.1	6.5
Particles >0.5 µm (Climet) - Pre-Cleaning[a]	particles x 10^6/m^3	1.61	2.67	5.81
Particles > 0.5 µm (Climet) - Post-Cleaning[a]	particles x 10^6/m^3	1.47	4.73	2.96
Particles >5.0 µm (Climet) - Pre-Cleaning[a]	particles x 10^6/m^3	0.0011	0.0013	0.0004
Particles > 5.0 µm (Climet) - Post-Cleaning[a]	particles x 10^6/m^3	0.0012	0.0007	0.0003

[a] Average particle concentration during the period of integrated sampling

integrated and optical sampling during concurrent periods. (All the optical data is not included.)

Qualitatively, the data collected in these tests show a relationship between airborne particle concentrations and particle counts in the > 0.5 µm size fraction. In all three tests the differences between pre- and post-cleaning PM_{10} and $PM_{2.5}$ mass reflect temporal changes in the particle concentrations measured with the Climet optical particle counter. However, there was no clear correlation between the particle mass and particle concentrations. As an example, the particle mass for $PM_{2.5}$ in the pre-cleaning sample for the galvanized system was 10.5 $\mu g/m^3$ and the corresponding average particle count was 1.61 million particles/m^3, but for the $PM_{2.5}$ sample collected following cleaning of the FDL system, the particle the mass was similar, 10.1 $\mu g/m^3$, but the average particle concentration was 4.73 million particles/m^3 during the integrated sampling period. Because of the limited number of samples, the correlation between the two parameters could not be assessed. There also did not appear to be a relationship between particle counts for the > 5.0 µm fraction and PM_{10} mass.

The reader is warned not to interpret the data in Table 15 to mean that particle mass and particle counts increased in the instrumentation room following ACS cleaning. As will be shown in the following sub-section, the results are an artifact of the time period during which the integrated samples were collected.

The primary objective of the test, shakedown of the samplers, showed that they were suitable for use in the field study to collect 24-hour samples; air flow rates were stable at the end of the 24 hour period and the pumps and timers worked properly. However, as discussed below, the data also showed that use of integrated samples may be inappropriate for evaluating the impact of air duct cleaning on airborne particle concentrations if the particle concentrations are highly variable.

6.3.2 Particle Concentrations - Optical Particle Counter

The Climet CI-4100 was used during each test to monitor particle concentrations in the instrumentation room. Measurements were made in both channels; concentrations of particles in the greater than 0.5 µm size fraction and in the greater than 5.0 µm size fraction were measured. The primary purpose of the measurements was to evaluate the instrument and the monitoring protocols proposed for use in the field study. Concentrations measured in the instrument room were not intended to assess the impact of ACS cleaning on IAQ, but may be useful in designing future testing in pilot scale ACS systems.

The time variation of particle concentrations in the two size fractions during the three tests are depicted in Figures 4 through 9. Overall average particle concentrations during pre-cleaning and post-cleaning time periods are presented in Table 16 (which includes data not in the Table 15 concurrent period averages.)

The particle concentrations measured in the > 0.5 µm size fraction with the Climet were generally below 4 million particles/m^3 during the test with the galvanized duct system. As shown in Figure 4, particle concentrations in the instrumentation room dropped on the day prior to cleaning (pre-2) when the air bypass was disconnected and the air flow was restored to the instrumentation room. This air was filtered as it moved from the instrument room to the mixing room, causing the number of particles circulating in the system to drop. The average particle concentrations for the period prior to ACS cleaning were 1.62 and 0.0011 million particles/m^3 for the > 0.5 µm and > 5.0 µm size fractions, respectively (Table 16).

Following the pulse of particles observed on system start-up, the particle concentrations after ACS cleaning were similar to the period immediately before cleaning for both size fractions (Figures 4 and 5). Particle concentrations did not vary substantially during either period, as shown by the relatively flat concentration profiles. It should be noted that smoother curves following cleaning of the galvanized and FDL systems are an artifact of the sampling protocol. In the post-cleaning periods, data were saved as 20-min averages rather than as the 10-min average used in the pre-cleaning period. This was necessary in order to save all data over the weekend; the Climet has limited data storage capacity. This, however, had no impact on the interpretation of the data except that information on very short-term variability was lost, as indicated by the smoother concentration profile in the post-cleaning period.

Particle concentration profiles during the test with the FDL are depicted in Figures 6 (> 0.5 µm fraction) and 7 (> 5.0 µm size fraction). During this test, the concentrations of particles in the > 0.5 µm fraction were higher and more variable than in either of the other two tests. For an unexplained reason, particle concentrations increased dramatically on the day prior to cleaning. But after cleaning the concentrations were lower and generally continued to decrease.

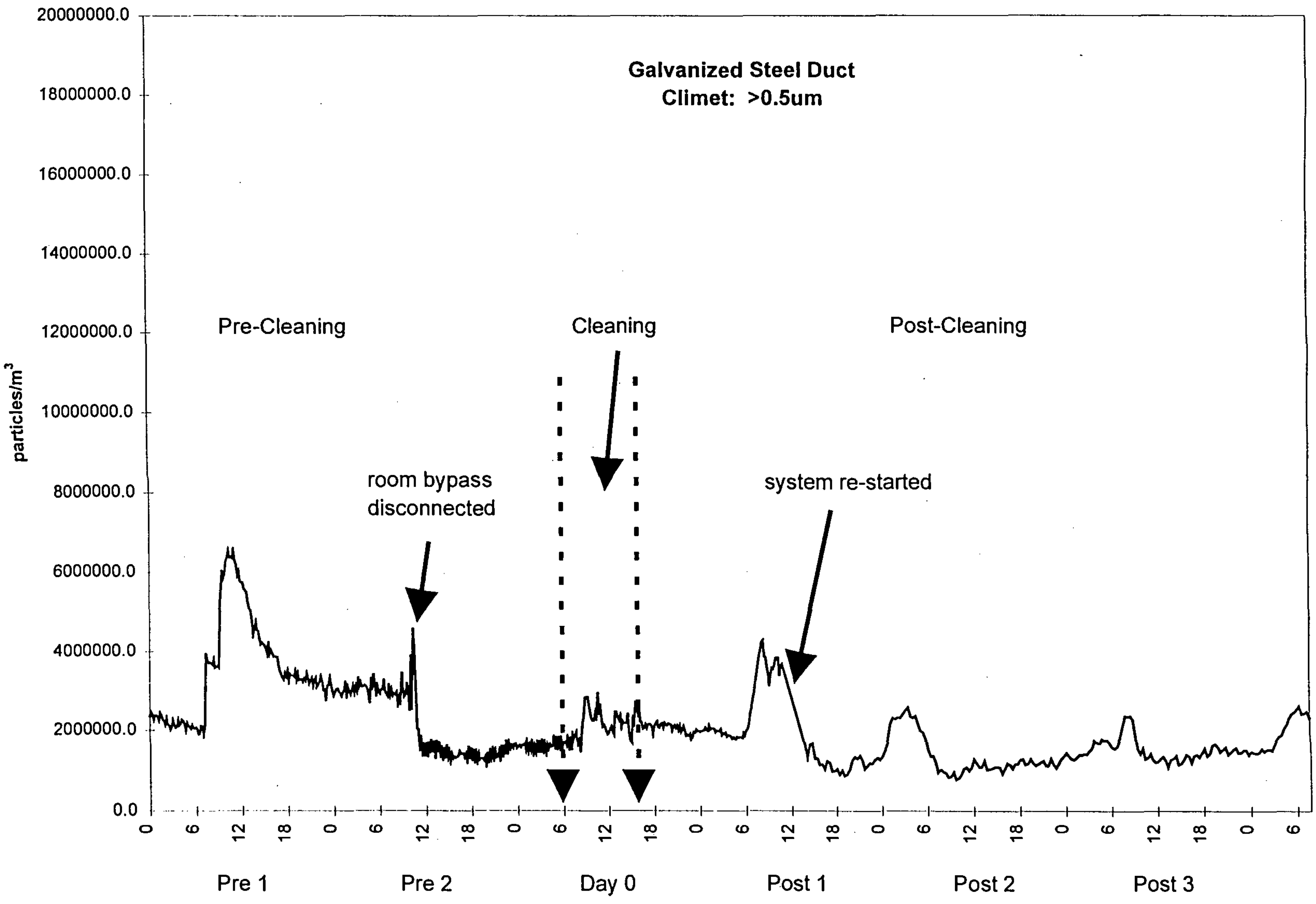


Figure 4. Airborne particle concentrations in the > 0.5 μm size fraction during the test with the galvanized steel duct system

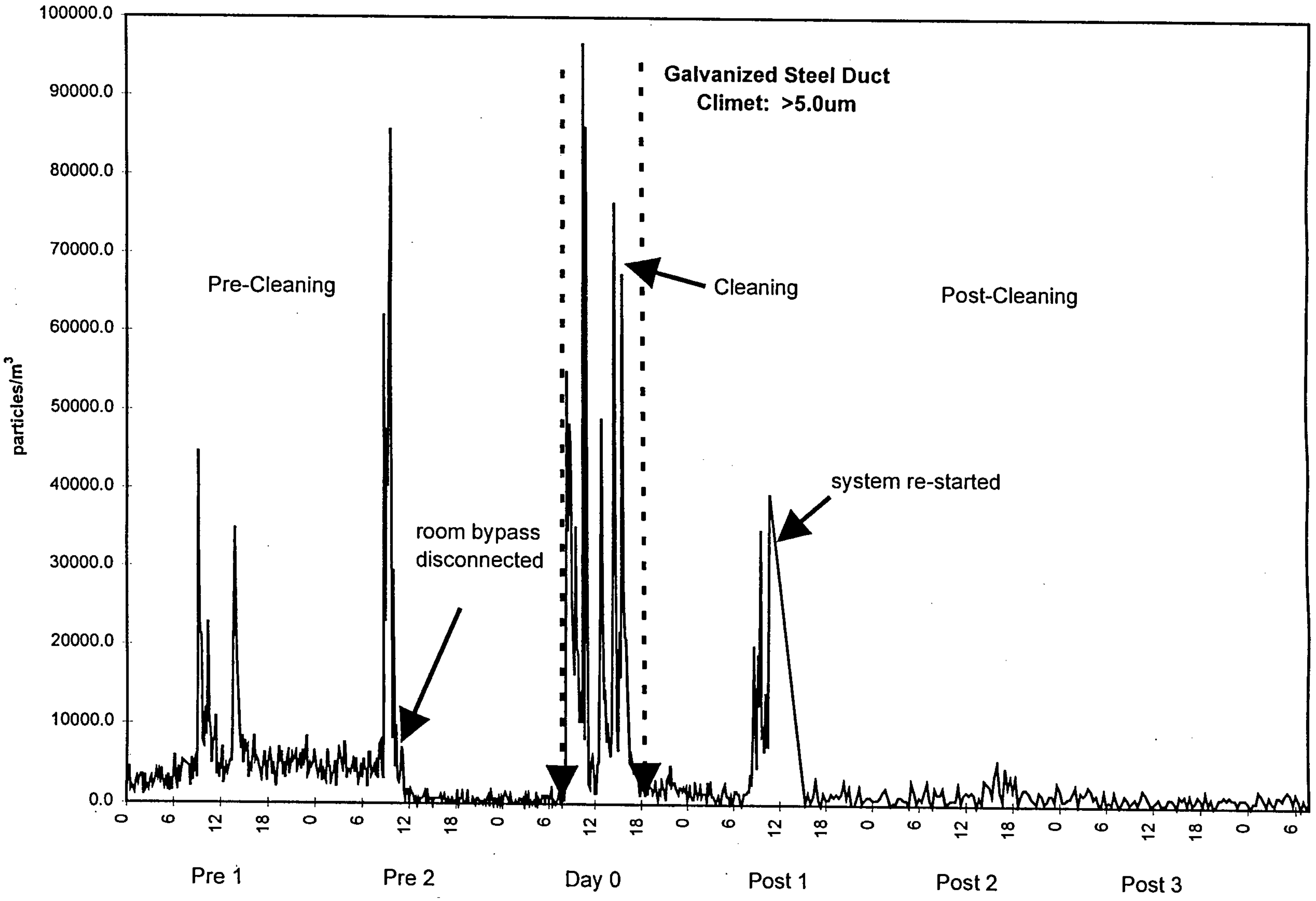


Figure 5. Airborne particle concentrations in the >5.0 µm size fraction during the test with the galvanized duct system

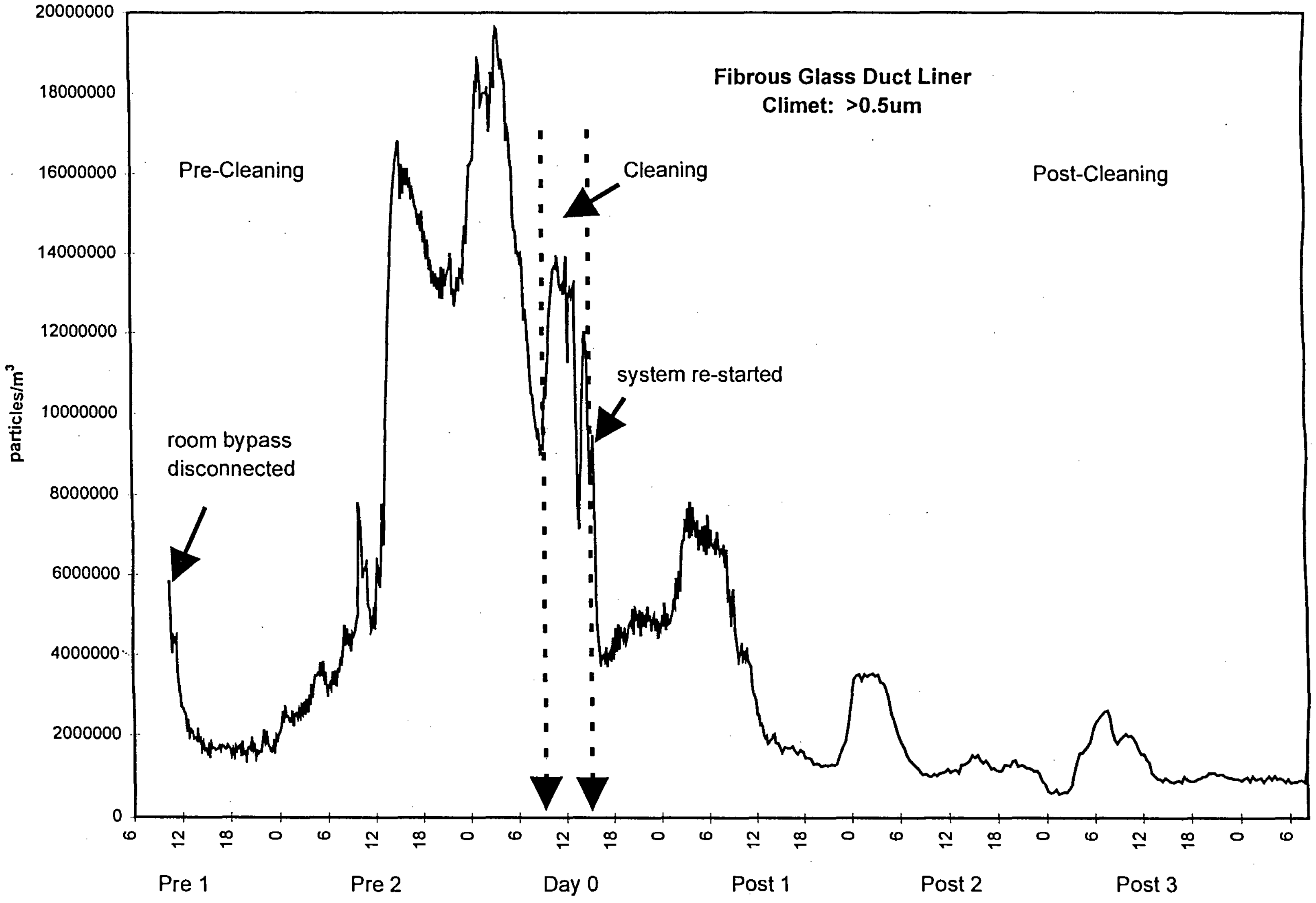


Figure 6. Airborne particle concentrations in the > 0.5 μm size fraction during the test with the fibrous duct liner system

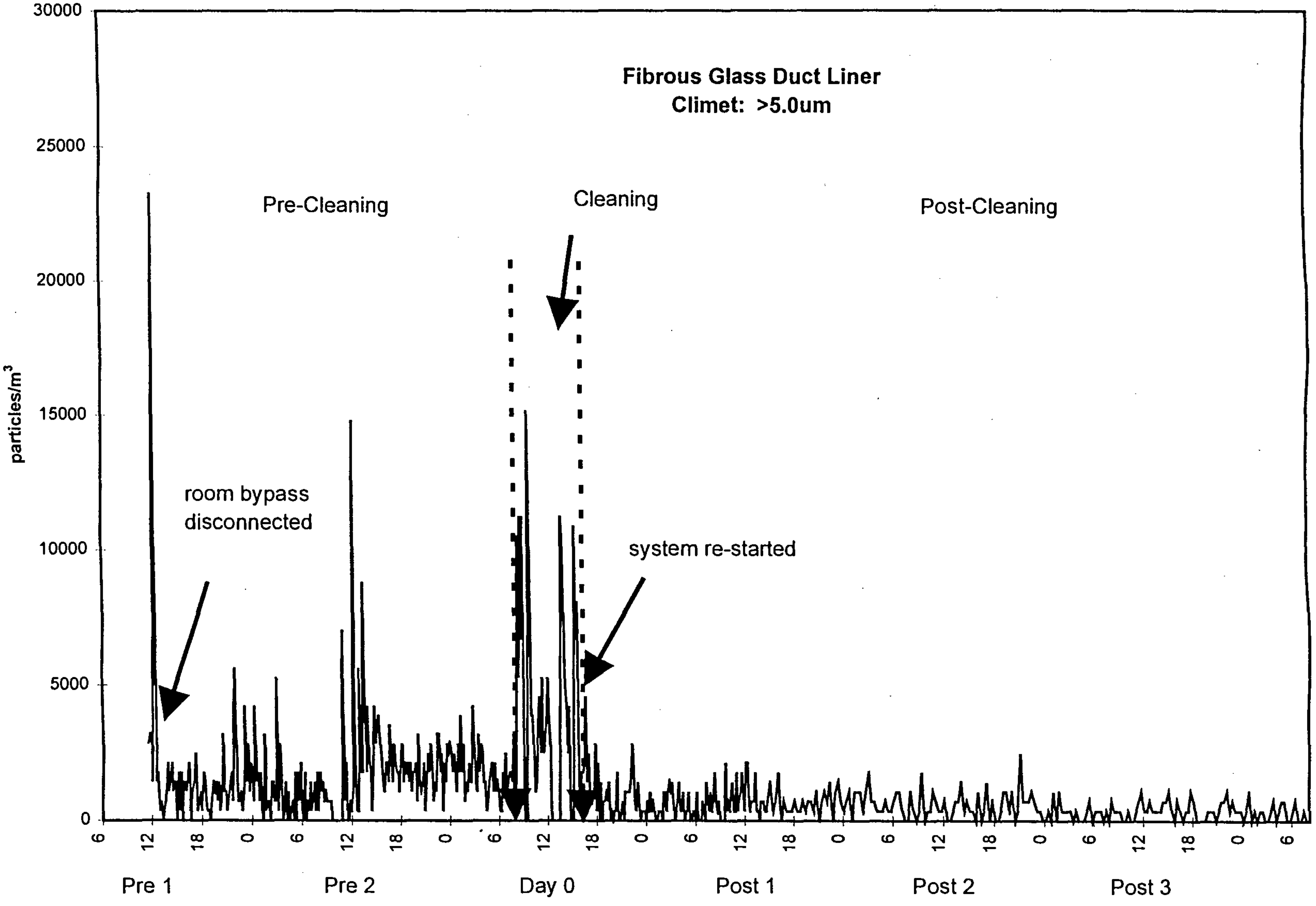


Figure 7. Airborne particle concentrations in the > 5.0 µm size fraction during the test with the fibrous duct liner system

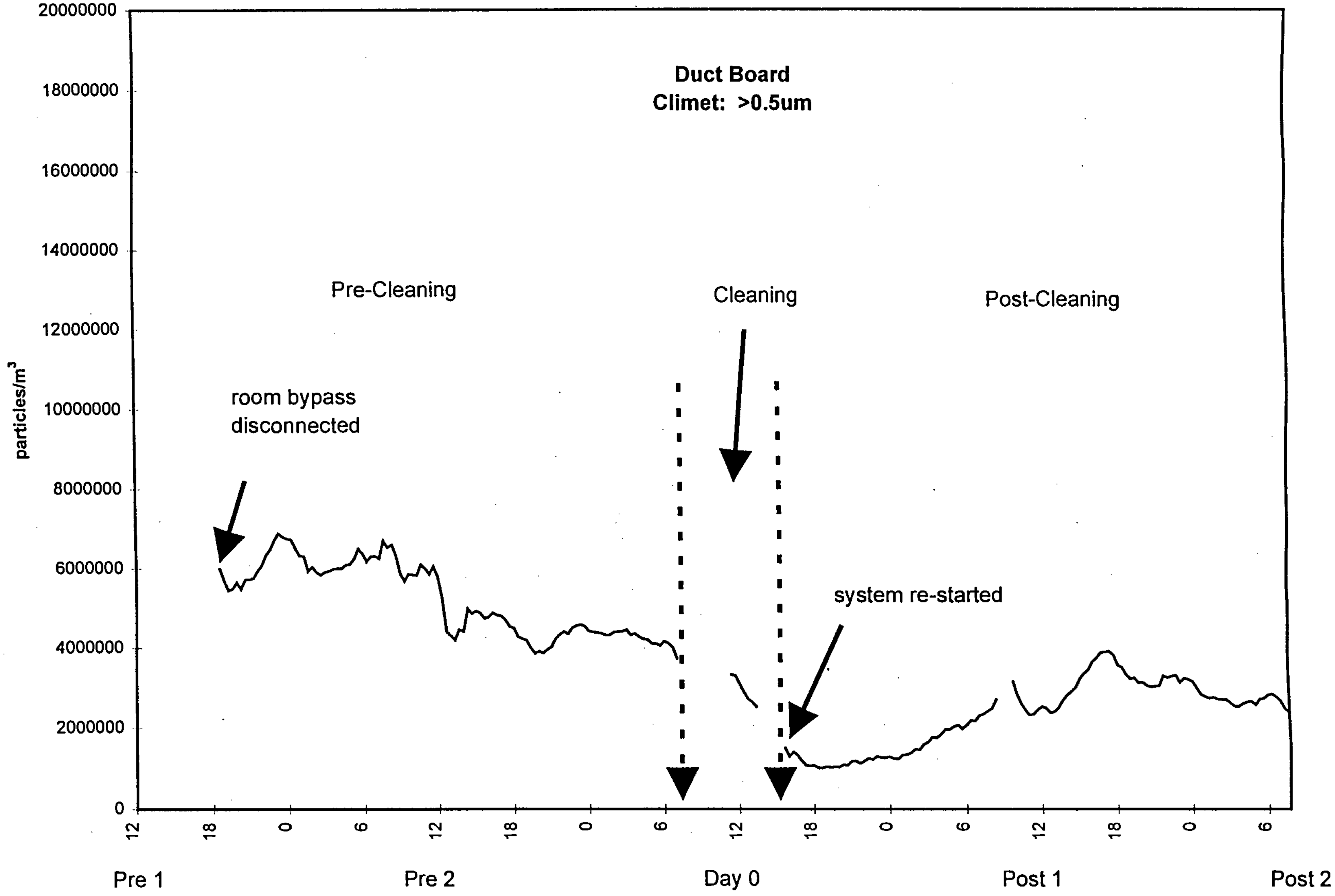


Figure 8. Airborne particle concentrations in the > 0.5 μm size fraction during the test with the FDB system

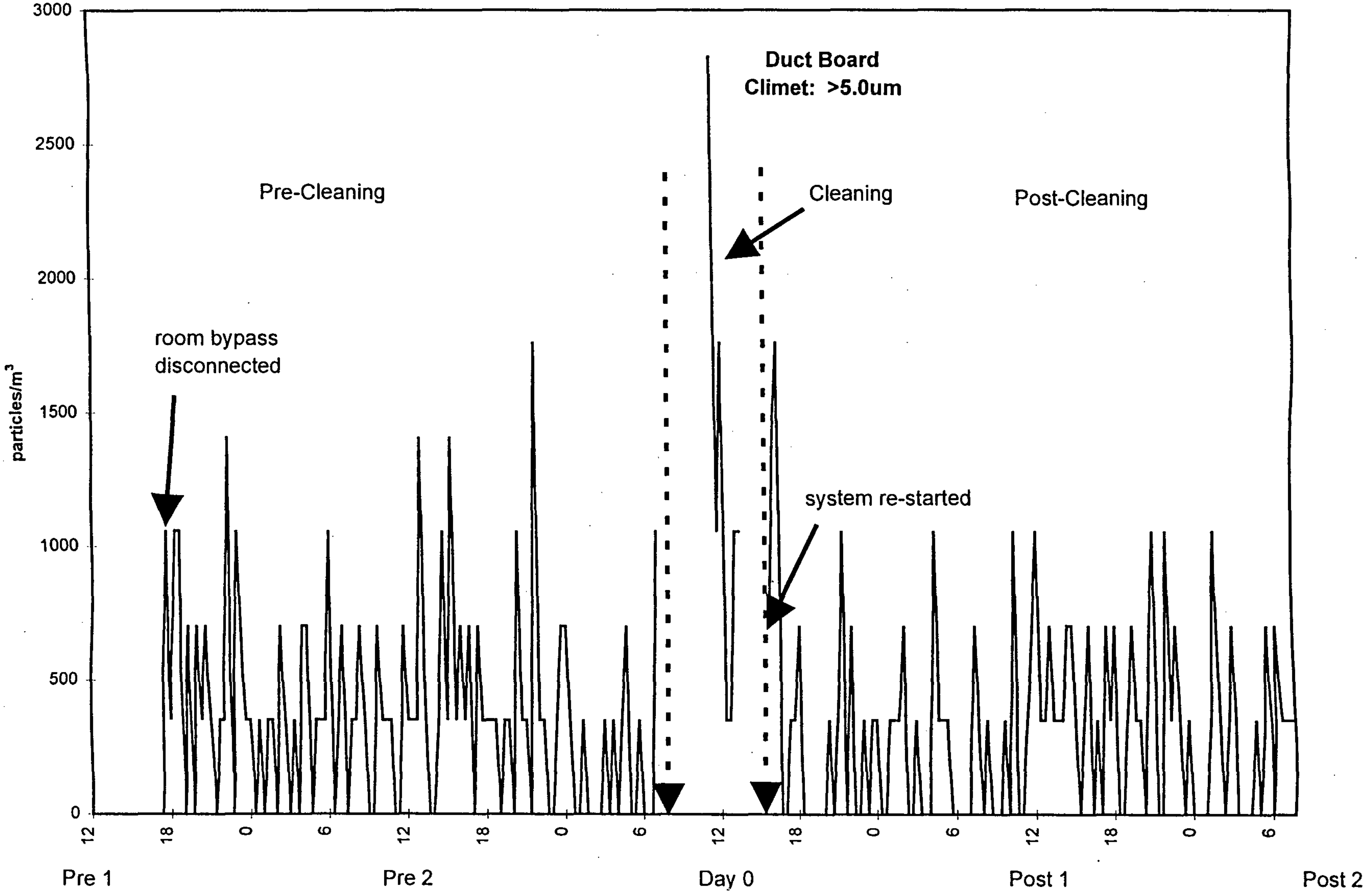


Figure 9. Airborne particle concentrations in the > 5.0 μm size fraction during the test with the FDB system

Table 16. Average Particle Concentrations (particles X $10^6/m^3$) Measured with Climet During Pre- and Post-Cleaning Periods in the Three Tests

Parameter/Test	Period	Galvanized Steel Duct	Fibrous Glass Liner	FDB
Particles >0.5 μm Pre-Cleaning	particlesX$10^6/m^3$	1.62	7.97	5.22
Particles > 0.5 μm Post-Cleaning	particlesX$10^6/m^3$	1.47	2.86	2.35
Particles >5.0 μm Pre-Cleaning	particlesX$10^6/m^3$	0.0011	0.0017	0.0003
Particles > 5.0 μm Post-Cleaning	particlesX$10^6/m^3$	0.0011	0.0006	0.0003

The pulse of particles observed on system re-start with the galvanized duct system was not clearly evident with the FDL system. Particle concentrations in the > 5.0 um fraction showed a similar, although less dramatic, trend. As shown in Table 16, the average particle concentrations in both fractions were substantially lower after cleaning.

Figures 8 and 9 show particle concentrations during the FDB test. The changes in concentrations for both size fractions show a trend similar to that observed in the FDL test. Concentrations were substantially higher in the pre-cleaning period. The average concentration after cleaning was about half that of the pre-cleaning period (Table 16) for the > 0.5 μm fraction. Average concentrations of the > 5.0 μm fraction were similar in the pre- and post-cleaning periods.

Measurements with the Climet optical particle counter in the instrument room during the three cleaning tests showed lower average airborne particles concentrations during the post-cleaning periods in all three tests. It is likely that the lower concentrations resulted from cleaning of the ACS components. But it is difficult to draw definitive conclusions from this limited data set. The instrumentation room door was kept closed except for entry to download data and to change filter media. Therefore, intrusion of particles into the room from the outside was likely to be low. However, we do not know whether higher particle concentrations in the pre-cleaning periods may have been a function of the dust in the ACS components or if it was related to a higher level of activities in the building housing the PACS which might result in higher concentrations in the instrument room.

As discussed in the previous sub-section, integrated samples were collected concurrently with the optical particle measurements during a single period in the pre-cleaning period and again in the post-cleaning period. The data collected with the Climets clearly show the limitations of these integrated samples for evaluating the impact of ACS cleaning on airborne particle concentrations. As reported in Table 15, both the $PM_{2.5}$ and the PM_{10} mass levels were higher in post-cleaning than in pre-cleaning samples during the test with the FDL. However, the continuous particle concentration data suggests that this was an artifact of the sampling protocol. Pre-cleaning samples were collected on pre-cleaning day 1 which had lower particle concentrations than pre-cleaning day 2. Had the integrated sample been collected on pre-cleaning day 2, the data would probably have shown a substantially higher particle mass concentration and changed the interpretation of the data as it related to ACS cleaning effectiveness. The effect (i.e., artifact of sampling) observed in this test would likely be important in occupied residences where particle concentrations may vary dramatically due to occupant activity. This observation confirmed the need to collect multiple integrated samples during the field study.

The testing of the Climets in the instrument room showed that they were suitable for use in the field study. The primary limitation of the Climet CI-4100 was that only a single channel of data could be output to the IAQDS data logger. During these tests, the > 0.5 μm channel was recorded with the IAQDS. Data for the > 5.0 μm fraction was saved internally in the Climet data storage system, but could not be output simultaneously. Therefore, it was necessary to also download the Climet with a laptop computer to obtain both the > 0.5 μm and the > 5.0 μm data. With a 10-min averaging time, it was necessary to download the data once every 33 hours. This was done during the tests in the PACS.

6.3.3 Particle Concentrations - Multi-Channel Spectrometer

The LAS-X spectrometer was used in the tests with the galvanized steel duct system and the FDL system. There were problems with the computer used for data logging during both tests.

Only two of the four data sets were retrieved. Due to concurrent ACS cleaning tests at the EPA test house, the LAS-X was not available for use in the tests with the FDB system.

The average particle concentrations in the 16 size fractions are presented in Table 17 to show the distribution of particles by size fraction. Although data were not collected that were useful in evaluating the impact of ACS cleaning in the PACS, the objectives of the testing of the LAS-X were met in that problems with the hardware and method were identified and resolved prior to use of the instrument in the field.

Table 17. Average Particle Concentrations Measured With the LAS-X in the Instrumentation Room (Particles X $10^6/m^3$)

Particle Size Fraction (μm)	Galvanized - Post-Cleaning	FDL - Pre-Cleaning
0.10 - 0.12	10.383	51.272
0.12 - 0.15	10.912	52.414
0.15 - 0.20	11.103	70.405
0.20 - 0.25	4.484	47.587
0.25 - 0.35	3.854	52.126
0.35 - 0.45	1.268	20.020
0.45 - 0.60	0.379	4.965
0.60 - 0.75	0.038	0.562
0.75 - 1.0	0.037	0.376
1.0 - 1.5	0.029	0.160
1.5 - 2.0	0.009	0.033
2.0 - 3.0	0.006	0.014
3.0 - 4.5	0.003	0.005
4.5 - 6.0	0.001	0.002
6.0 - 7.5	0.0006	0.0007
> 7.5	0.003	0.004

6.3.4 Fiber Concentrations

Concentrations of airborne fibers were measured with the integrated sampling method prior to, and following, ACS cleaning in the three tests. The fiber samples were collected in duplicate in the instrument room. A sample was also collected outside of the PACS in the large bay where the test facility was housed. The sampler was placed within 5 meters of the instrumentation room and samples were collected concurrently. The minimum detection limit of the sampling method was 0.001 fibers/cm^3. Fibers were detected in only one of the 15 samples collected during the study. In the pre-cleaning sample collected during the test with the galvanized system, the concentration was 0.001 fibers/cm^3 in one sample, but below the detection limit in the duplicate sample. Fibers were not detected in any samples collected during tests with the FDL system or the FDB system.

The MIE FAM-1 Fibrous Aerosol Monitor was also used during selected periods during the tests with the galvanized duct and the FDL. Fiber concentrations were below the limits of detection of the instrument throughout the tests.

The method selected for fiber sampling was a standard method used for collection of asbestos and non-asbestos man-made fibers. The detection limit was considered to be adequate for the purposes of this testing. Although fibers could not be detected in air samples collected during these tests, the method was still considered adequate for the field study.

6.3.5 Bioaerosols

The test dust was not sterilized prior to injection, and thus contained whatever microbiological contaminants were present when it was collected. These particles had the potential to become airborne during PACS operation. The concentrations of culturable fungi were measured in the instrument room at four times through a duct system cleaning cycle. (Bacteria are not a common indoor bioaerosol.) A background measurement was made prior to soiling the duct, with the bypass in place. A dirty duct sample was collected following soiling and conditioning, removal of the bypass, and with the system running. For the galvanized duct, a duct cleaning sample was taken just as the system was restarted following cleaning. The post clean sample was taken 24 hours following cleaning. The results for the galvanized duct are given in Table 18.

The fungal concentrations reported in Table 18 are relatively low, and below what are frequently encountered outdoors. However, they are well above the detection limit for the Mattson-Garvin and the replication is good. Except for the post cleaning sample, all the samples,

Table 18. Airborne Fungal Concentrations for Galvanized Steel Duct in cfu/m^3

Time	Galvanized Steel Duct	
	replicate	mean
background	23	18
	12	
dirty duct	23	26
	28	
duct clean	31	19
	7	
post clean	119	104
	88	

including the background taken prior to dust injection, are about the same. The results of the galvanized duct post clean sample taken beginning just as the PACS was started up following cleaning was interesting in that detailed examination of the Mattson-Garvin plates showed that most microorganisms were collected in the first 15 min (83%), with 11% collected in the second 15 min, 4% in the third, and 2% in the balance of the sample period.

The airborne concentrations for the FDL and FDB systems are given in Table 19. While higher levels were detected for the galvanized duct, that may be related to the extended conditioning period rather than any characteristic of the duct. The results for the FDL and FDB

Table 19. Airborne Fungal Data for FDL and FDB Systems, cfu/m^3

Time	FDL		FDB	
	replicate	mean	replicate	mean
background	nd	nd	nd	nd
	nd		nd	
dirty duct	8	9	nd	nd
	10		nd	
duct clean	nd	nd	nd	nd
	nd		nd	
post clean	5	7	10	10
	8		na	

duct systems indicate that few fungal spores became airborne from the freshly deposited and conditioned dust, and the levels are so low that the samples do not provide any information about performance of the systems. The post clean samples for the FDL and FDB systems were taken after 24 hours rather than at startup because the presence of an initial particle pulse had been previously reported and confirmed with the galvanized duct results. The effects 24 hours later were thought to be more important.

7.0 QUALITY ASSURANCE/QUALITY CONTROL

Quality control and quality assurance for this project were described in *Air Conveyance System Cleaning Pilot System Development, Characterization, and Operation: Project Work and QA Plan* (RTI, 1995). The project included method development and environmental parameter measurement, as well as application of duct cleaning methods. The QA plan included environmental measurement instrument calibration and adjustment during the equipment checkout period and field blanks and duplicates for the sampling activities. The sampling methods were largely developmental and followed written procedures that were modified as required. The data quality indicators for the project are given in Table 20.

7.1 Quality Control

7.1.1 Environmental Instrumentation

The PACS thermocouples (as read through the data acquisition system) were compared to a reference thermocouple at the time of installation. The PACS thermocouples were read with a precision of 0.06°C (0.1°F) and had a claimed bias of ± 0.06°C (0.1°F). Using the reference thermocouple, they were found to be calibrated to within ± 2°C for the in-room sensors and to be identical for the in-duct sensors. Relative humidity was measured using a sensor with 0.1% RH precision and a claimed ± 3% bias. The sensors were compared to a sling psychrometer in fan-only operation of the PACS. Relative to a sling psychrometer, the in-room sensors (low flow) had a -7 to -9% RH bias. The in-duct RH sensors had a -10 to -11% RH bias. The values reported in this report are uncorrected.

While the QA plan contemplated flow rate measurement using a velocity traverse, the velocity pressure was marginally low for a standard pitot tube. An averaging pitot device with a hydraulically amplified pressure differential was used instead. The measurement precision was 1 ft/min at 500 cfm and the bias was stated to be ± 1% at 500 ft/min. The supply and return velocity probes were found to give the same velocity results, and the velocity was in agreement with the air handler performance. No change in instrument reading was noted on dust injection,

Table 20. Data Quality Indicator Goals.

Measurement Parameter	Precision	Bias	Completeness
PACS Temperature	1°C	1°C	90%
PACS Relative Humidity	2% RH	5%RH	90%
PACS Air Flow Rate	1%	5%	90%
MVDS Sampler	20%	>75%[a]	90%
NADCA Method 1992-01	20%	>75%[a]	90%
High Volume Surface Sampler	20%	>75%[a]	90%
Microbial Surface Measurement	20%	>75%[a]	90%

[a] Percent recovery from surface being sampled.

though the instruments became noticeably soiled.

As the experiment developed, the environmental parameter measurements were found not to be critical measurements and the in-duct sensors were used only with the galvanized duct. Primarily, these measurements were intended to characterize the air handling units and assist in understanding dust transport. Initial dust loading experiments showed that no special effort was required to disperse the dust, and that the mixing room temperature and RH measurements were adequate to characterize the system. Thus the duct environmental measurements became of secondary interest. In addition, physical access constraints made the instruments very difficult to remove, clean, and reinstall. Time constraints on the dust loading, conditioning, and cleaning phases of the research were also severe and prevented redesign of the instrumentation.

7.1.2 Dust Mass Sample QC

Duplicate samples were identified in the data tables presented in Section 6.2.1. The precision of the MVDS/brush sampling method was generally very good for duplicate side-by-side samples in spite of the variability of particle deposition in the ducts, except for the FDB. The %RSD for duplicates was 9% and 37% for galvanized steel surfaces in pre-cleaning samples. On the FDL surface, the % RSD was 8 and 25 % for pre-cleaning samples. The precision of the method for samples from flexible duct surfaces was 11%, 24%, and 40%. This level of precision is probably adequate for sampling duct dust from galvanized and FDL ACS components because the dust loading at different locations in an ACS can be expected to be highly variable.

Also discussed in Section 6.2.1 was the unsuitability of the tested methods when used with FDB systems. The loading of dust on the FDB was comparable to previous tests, however, if the measurements with the MVDS brush sampler were used, ranging from 5.0 to 17 g/m^2 using the MVDS brush sampler. Visual inspection of the samples, however, showed that there was a substantial amount of fiber material on the filters. Confidence in the accuracy of the measurements of dust on FDB surfaces is considered to be low. Visual inspection of surfaces sampled with the nozzle indicated that particulate matter was still present on the surface, which will result in an under-estimate of the particle mass on the surface. Inspection of the samples collected with the brush indicated that substantial amounts of fibers were collected, which will result in an over-estimate of the particle loading on these surfaces. Therefore, neither sampling method appears to give accurate measurements of the dust deposited on the FDB surfaces.

During this study, the precision of the NADCA method was not evaluated. It was evaluated in the laboratory and in the field study by collecting duplicate samples.

7.1.3 Microbiological Duct Sample QC

The microbiological duplicates were comparisons of swab and vacuum samples as described in Section 6.2.2. The loadings were generally low and therefore of limited comparative value. Treating the supply samples and the return samples as replicates for each duct material, and considering the precleaning bacterial loadings, the vacuum method gave %RSDs of 0 to 99% over the three materials. In the same way, the swab sample method results gave %RSDs between 28 and 116%. Over all samples, the ratio of bacterial counts to dust mass ranged from 2.2 to 75 cfu/g. Based on these measurements, the vacuum and swab sample methods are estimated to be capable of measurement precision in the range of 20 to 50%, which is greater than expected. Bias cannot be estimated.

7.1.4 Microbial Aerosol QC

Microbial aerosol measurements were made only for fungi because these organisms are the likely indoor microbial hazard. Only the galvanized steel duct gave moderate airborne fungal levels, perhaps because some active growth occurred during the extended conditioning period. Duplicates were run each time, and the mean %RSD for the galvanized steel test series was 42%.

7.1.5 Aerosol Measurement QC

Pump air flow rates were measured at the start of the sampling period and required to be within ± 5% of the target flow rate of 20 L/min. Gravimetric mass determinations were performed in the EPA controlled environment weighing facility in the Annex at EPA-RTP in accordance with the SOP cited on page 20, Section 5.2.2. The SOP specifies that prior to analysis of filters, the balance span is set with a calibrated S class weight. The balance is also zeroed prior to weighing. A daily check filter is then weighed. At the completion of each 10 filter weighings, the zero and span settings are rechecked.

The Climets, LAS-X, and aerosol fiber monitor were not calibrated prior to the tests in the PACS. The objective was to shake-down the sampling and monitoring methods prior to use in the field study, not to collect quantitative data on air contaminants in the PACS. The instruments were calibrated prior to Phase II, the field study.

7.2 Method Performance

As discussed at length in Section 6.2.1.4, the MVDS-brush method was found to work well for surface dust collection on the galvanized steel surface and on the FDL surface. The MVDS-nozzle method was not satisfactory and its use is not recommended. No method worked well for FDB. Similarly, no sampling method worked for air conditioner coils.

The NADCA method was found to greatly understate the dust mass remaining on the surface when compared to the MVDS brush method.

For microbiological surface measurements, the vacuum method was found to be more reliable on a variety of surfaces than the swab method, though either could be used for qualitative measurements. The methods used were satisfactory.

The various particle and aerosol measurements were well developed and functioned as expected. Comparison of particle mass samplers and various optical particle counters is problematical in most applications and was so in this research. However, the instruments appeared to function properly.

7.3 Data Completeness

The data completeness goal for all sample types was 90%. This goal was met for all sampling measurements, except the dirty duct bioaerosol sampling in the FDB system, which were not collected.

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