**RESIDENTIAL INDOOR AIR FORMALDEHYDE
TESTING PROGRAM: PILOT STUDY**

IE-2814

Final Report

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1.0 INTRODUCTION

1.1 BACKGROUND

The U.S. Environmental Protection Agency (EPA) is investigating residential exposure to formaldehyde emitted from urea-formaldehyde (UF) resins contained in wood building materials and products (USEPA 1993a). UF-bonded wood products may be incorporated into the structure of conventional and manufactured houses (e.g., underlayment and floor decking) and also may appear in the form of cabinets and wall paneling.

The current project is the first stage of a program to evaluate formaldehyde levels in new houses. Instead of monitoring formaldehyde levels in a large sample of American houses, the Indoor Air Residential Formaldehyde Testing Program (USEPA 1993b) involves measurements in a relatively small number of new-house configurations under controlled conditions, along with laboratory chamber testing of UF-bonded wood products. The primary objective of the testing program is to characterize the contribution of UF-bonded wood products to initial indoor formaldehyde concentrations. The overall program also involves evaluation of current EPA formaldehyde exposure models and examination of chamber testing techniques to simulate the dynamics of real-world scenarios in the laboratory.

This pilot study has been undertaken to evaluate logistical restraints, to determine practical limits for precision and accuracy of measurement systems, and to examine underlying issues of repeatability and variability across the range of experimental conditions. All sampling and analytical techniques have been drawn from recognized standard methods, and a comprehensive quality assurance project plan (GEOMET 1994) has been developed to provide operational guidelines. Pilot study testing originally was planned in one conventional house and in four manufactured houses. The testing involves setting experimental conditions for controlled loading of UF-bonded wood products, air exchange, and temperature. Large- and small-volume chamber tests also were planned to quantify product-specific formaldehyde emissions under controlled laboratory conditions. Additional small-volume chamber tests were intended to estimate formaldehyde sink parameters and to assess possible barrier effects of carpet and padding over underlayment.

The pilot study was funded by the National Particleboard Association (NPA) through a Cooperative Research and Development Agreement (CRDA) with EPA. Additional contributions in the form of building materials and other items for the project were made by NPA and other industry participants.

1.2 OBJECTIVES

The Indoor Air Residential Formaldehyde Testing Program involves measurements in a relatively small number of new houses under controlled conditions along with chamber testing in the laboratory to meet the following objectives:

- Evaluate the ability of current EPA indoor air models to estimate reliably the concentration of formaldehyde in newly constructed single-family houses, where the principal sources of formaldehyde emissions are composite wood building products containing urea-formaldehyde (UF) adhesive resins.

- Characterize the contribution of formaldehyde emissions from UF-bonded wood products to initial indoor formaldehyde concentrations in newly-constructed single-family houses.

- Quantify the decay characteristic of formaldehyde concentrations in newly-constructed

single-family houses over time.

- Evaluate the advantages of chamber techniques that simulate the multi-source decay environment in newly-constructed single-family houses for use in assessing the decay characteristics of UF-bonded wood products.

The pilot study was undertaken to obtain information necessary to develop the protocol for the full study, and to initially assess the precision of the measurement procedure for repeats of specific experimental conditions. Consequently, the objectives of the pilot study were to:

1. Test the logistical considerations relevant to carrying out the experimental procedures of the testing program in a single conventionally-built single-family house and in multiple manufactured houses.

2. Demonstrate that the experimental variables or conditions likely to affect formaldehyde concentrations in new houses (namely, UF-bonded wood product emission characteristics, UF-bonded wood product loading rates, temperature and indoor air exchange rates) can be controlled, individually and jointly varied, and held sufficiently constant, and that the response can be measured to a specified precision.

3. Demonstrate that test results can be obtained across a range of different experimental conditions similar to that which can be present in new houses and that the response can be measured with specified precision.

4. Estimate the extent of variability of the experimental results and the variation with changes in experimental conditions.

5. Determine how to account for, or to eliminate or minimize, residual formaldehyde carryover between test runs in the conventional house due to the effects of inherent sinks.

6. Evaluate the ability to control and vary the air exchange rate of houses using an adjustable mechanical air handling system.

1.3 THIS REPORT

Section 2.0 of the report outlines the experimental design and general monitoring strategy for the pilot study together with project planning and management activities. As noted in that section, the planned pilot tests involving manufactured houses were deferred due to certain difficulties that were encountered in carrying out pilot tests at the conventional house. At the same time, greater emphasis was given to certain aspects of the chamber tests.

Test procedures at the conventional house, and affiliated activities such as house characterization, configuration of monitoring equipment, and selection and storage of UF-bonded wood products to be loaded into the house, are described in Section 3.0. Test procedures for laboratory chamber tests are summarized in Section 4.0; these include emission tests by NPA and the Hardwood Plywood and Veneer Association (HPVA) as well as sink and barrier tests by GEOMET. Section 5.0 provides a description of quality assurance and control activities such as system and performance audits, laboratory/field sample spikes and blanks, and problems encountered during the testing and their resolution.

The major monitoring results from the study, concerning conventional house tests,

chamber emission tests and chamber sink/barrier tests, are presented in Section 6.0. Ancillary results, such as those relating to alternative monitoring technologies or adjustment of as-monitored formaldehyde levels, are presented in various appendices to the report. Conclusions stemming from the pilot study are provided in Section 7.0.

2.0 EXPERIMENTAL DESIGN AND PROJECT PLANNING

2.1 EXPERIMENTAL DESIGN

        The first objective of the pilot study, concerning logistical considerations, was to be addressed by demonstrating whether or not the study could be carried out through cooperation among builders, suppliers of UF-bonded wood products and independent product testing facilities, and by utilizing available techniques for conducting environmental measurements. The next three objectives, concerning control of experimental variables and repeatability/variability of results, were to be addressed by conducting a series of replicated tests in newly-constructed, unoccupied, conventional and manufactured single-family houses over a small number of differing experimental conditions. In one conventionally-built single-family house, different loading conditions were to be achieved through temporary installation of prescribed amounts of UF-bonded wood products having prescribed formaldehyde emission characteristics. Upon completion of all testing for a given loading condition, the installed UF-bonded wood products would be removed and the house would be prepared for temporary installation and testing of another loading of UF-bonded wood products. In the manufactured houses, different loading conditions were to be evaluated using multiple houses built with prescribed amounts of UF-bonded wood products that have prescribed formaldehyde emission characteristics. Examining the effects of residual formaldehyde from previous loadings of the conventional house (the fifth objective) requires monitoring between successive runs. The final objective of the pilot study (control of air exchange) was to be addressed in both housing types utilizing an adjustable mechanical air handling system installed in each house.

        The response of primary interest was the measured concentration of formaldehyde in a particular room of a particular house at a specified age ("age" refers to the time from installation of formaldehyde-emitting wood products in the house until the time when house testing is performed). Collection of time-integrated formaldehyde samples for a given loading was to begin at two points in time: (1) one week after loading the house with formaldehyde-bearing materials; and (2) four weeks after loading the house. The measurement point one week after loading provides compatibility with large-chamber test procedures for UF-bonded wood products (ASTM Standard E 1333-90), which require a one-week conditioning period prior to testing. The measurement point four weeks after loading allows an assessment of how the formaldehyde concentrations in the house have responded relative to the one-week measurement point.

        The full study is to include four primary experimental variables: loading rate for UF-bonded wood products, emission rate of UF-bonded wood products, indoor-outdoor air exchange rate, and indoor temperature. For each of these four variables, three levels (called "low," "medium" and "high") have been defined so as to provide a reasonable range of testing conditions for the full study. For the pilot study product loading was limited to medium and high levels, and all other experimental variables were held at fixed levels. Formaldehyde-bearing materials were selected by the National Particleboard Association (NPA) and other industry participants from mills so as to provide a medium overall emission rate. The air exchange rate was set at a medium value of 0.5 air changes per hour (ACH) (other values for the full study are 0.15 and 1.2 ACH). A medium thermostat setting of 75° F also was used (other values for the full study are 65° F and 85° F). Relative humidity, which is not one of the primary experimental variables but can confound the results if highly variable, was to be maintained near 50 percent indoors.

        One conventional house was to be tested in the pilot study. As shown in Table 2-1, a total of four loading configurations (high and medium, each to be repeated) was planned. The planned order of the loading configurations was medium first, followed by high, high, and medium. Within each loading configuration, four sets (or "runs") of time-integrated formaldehyde

samples were to be collected, each 24 hours in duration. The four sets were to be collected over time as follows: 7 days, 12 days, 28 days, and 33 days after loading. The measurement sets at 12 days and 33 days were to be viewed statistically as replicates of those at 7 days and 28 days, respectively.

Table 2-1. Design Matrix for Conventional House in the Pilot Study

| Loading | Run[a] | Loading Configuration | Emission Rate[b] | Air Exchange Rate[c] | Temperature[d] | Indoor Formaldehyde Measurements[e] | | |
						Kitchen	Living Room	Bedroom
Baseline Measurements				M	M	X	X	X
1	1	M	M	M	M	XX	X	X
1	2	M	M	M	M	X	XX	X
1	3	M	M	M	M	X	X	XX
1	4	M	M	M	M	XX	X	X
Baseline Measurements				M	M	X	X	X
2	5	H	M	M	M	X	XX	X
2	6	H	M	M	M	X	X	XX
2	7	H	M	M	M	XX	X	X
2	8	H	M	M	M	X	XX	X
Baseline Measurements				M	M	X	X	X
3	9	H	M	M	M	X	X	XX
3	10	H	M	M	M	XX	X	X
3	11	H	M	M	M	X	XX	X
3	12	H	M	M	M	X	X	XX
Baseline Measurements				M	M	X	X	X
4	13	M	M	M	M	XX	X	X
4	14	M	M	M	M	X	XX	X
4	15	M	M	M	M	X	X	XX
4	16	M	M	M	M	XX	X	X
Evaluate need to continue the pilot								

[a] "Run" refers to a set of time-integrated formaldehyde measurements; runs 1 and 2, starting one week after loading, are to be separated in time by 3 to 5 days, as are runs 3 and 4, starting four weeks after loading.
[b] "M" or medium corresponds to a range of 0.12-0.14 ppm (based on large-chamber tests) for particleboard underlayment, for example; the range refers to a chamber concentration from which the emission rate can be derived.
[c] Target setting of 0.5 ACH.
[d] Target setting of 75 °F.
[e] "X" refers to a time-integrated formaldehyde measurement; "XX" refers to duplicate measurements.

Time-integrated formaldehyde measurements were to be collected in four locations-- kitchen, living room, bedroom and outdoors. One duplicate formaldehyde measurement, for assessment of combined sampling and analytical precision, was to be collected during each run; the location for the duplicate sample was to be varied systematically. The baseline measurement period for each loading configuration was to include monitoring of formaldehyde, temperature, humidity and air exchange.

Loading configurations for the conventional house are summarized in Table 2-2 (see Section 3.5 for further details). Although only high and medium scenarios were to be used for the pilot study, the table presents all three scenarios that would be required for the main study. The high and medium scenarios are distinguished by different loadings for flooring and paneling materials, and the medium and low scenarios differ in loadings for flooring and door materials. A full loading of cabinets and counter tops would be common to all three loading scenarios, as would the package of finishing/trim materials (not shown in the table); the specific loading of these materials would be dictated by the house design.

Table 2-2. Loading Configurations for the Conventional House

TYPE OF MATERIAL	LOADING[a]		
	High	Medium	Low
Flooring	Full (0.10)[b]	Half	None
Cabinets	Full	Full	Full
Counter top	Full	Full	Full
Doors	UF (0.02)	UF (0.02)	Non-UF
HDP[c] Paneling	Full (0.02 - 0.036)	None	None

[a] For the pilot study, only high and medium loadings were to be used.
[b] Figures in parentheses represent approximate loading rates in ft^2/ft^3.
[c] HDP = hardwood plywood.

The design matrix for testing in manufactured houses is presented in Table 2-3. Because it is not practical to install multiple loadings of wood products in a single manufactured house, separate manufactured houses were to be used for each loading, identical in all respects except for the loading of UF-bonded wood products. The manufactured houses were to be tested at a site agreed upon by the investigators and the manufactured house builders. Loading configurations are summarized in Table 2-4. The high and medium scenarios to be used for the pilot study differ in terms of flooring materials, doors and paneling.

Table 2-3. Design Matrix for Manufactured Houses in the Pilot Study

House[a]	Run[b]	Loading Configuration	Emission Rate[c]	Air Exchange Rate[d]	Temperature[e]	Indoor Formaldehyde Measurements[f]		
						Kitchen	Living Room	Bedroom
Baseline Measurements				M	M	X	X	X
1	1	H	M	M	M	XX	X	X
1	2	H	M	M	M	X	XX	X
1	3	H	M	M	M	X	X	XX
1	4	H	M	M	M	XX	X	X
Baseline Measurements				M	M	X	X	X
2	5	M	M	M	M	X	XX	X
2	6	M	M	M	M	X	X	XX
2	7	M	M	M	M	XX	X	X
2	8	M	M	M	M	X	XX	X
Baseline Measurements				M	M	X	X	X
3	9	M	M	M	M	X	X	XX
3	10	M	M	M	M	XX	X	X
3	11	M	M	M	M	X	XX	X
3	12	M	M	M	M	X	X	XX
Baseline Measurements				M	M	X	X	X
4	13	H	M	M	M	XX	X	X
4	14	H	M	M	M	X	XX	X
4	15	H	M	M	M	X	X	XX
4	16	H	M	M	M	XX	X	X
Evaluate need to continue the pilot								

[a] Houses 1 and 2 are to be built by one manufacturer, and houses 3 and 4 by a second manufacturer.
[b] "Run" refers to a set of time-integrated formaldehyde measurements; runs 1 and 2, starting one week after loading, are to be separated in time by 3 to 5 days, as are runs 3 and 4, starting four weeks after loading.
[c] "M" or medium corresponds to a range of 0.12-0.14 ppm (based on large-chamber tests) for particleboard underlayment, for example; the range refers to a chamber concentration from which the emission rate can be derived.
[d] Target setting of 0.5 ACH.
[e] Target setting of 75 °F.
[f] "X" refers to a time-integrated formaldehyde measurement; "XX" refers to duplicate measurements.

Table 2-4. Loading Configurations for Manufactured Houses

Type of Material	LOADING[a]		
	High	Medium	Low
Flooring	Full	Full	None
Cabinets	Full	Full	Full
Counter top	Full	Full	Full
Doors	UF	Non-UF	Non-UF
HDP Paneling	0.02-0.036 ft^2/ft^3	None	None

[a] For the pilot study, only high and medium loadings are to be used.

Laboratory chamber tests were to be conducted by industry to estimate emissions for each type of UF-bonded wood product used in each test run for each type of house. Specimens tested were to be from the same lot, and of the same age (within ±2 weeks) as the products used in each house at the time of the formaldehyde measurements. ASTM large-chamber procedure E 1333- 90 was to be used for determining formaldehyde emissions from UF-bonded wood products. Each product was to be tested at three air exchange rates to estimate the dependence of the formaldehyde emission rate on the room-air concentration.

Chamber tests were to be conducted by industry for the five types of material listed in Tables 2-2 and 2-4--flooring, cabinets, finished counter top, doors and hardwood plywood paneling. Cabinets and doors were to be tested in large-chamber facilities. Each product was to be tested at three air exchange rates: 0.15, 0.5 and 1.2 ACH. Other products were to be tested using a dynamic micro-chamber. Trim materials (e.g., crown molding), carpeting and padding used in the study house were to be tested in EPA chamber facilities to confirm the anticipated low level of formaldehyde emissions.

Low, medium and high emission rates were defined for this study so as to achieve narrow ranges that do not overlap. For example, historical test results (equilibrium concentrations under ASTM E 1333-90) for all certified particleboard vary from 0.04 to 0.20 ppm. Material in the 0.04-0.06 ppm range was to be selected to obtain a low-emitting product, a 0.12 to 0.14 ppm range was to be selected to obtain a medium-emitting product and a 0.18 to 0.20 ppm range for a high-emitting product. Only medium-emitting materials were to be selected for the pilot study. Industry was to perform tests to confirm that materials selected for the study were in the desired range of emissions, and EPA was to perform verification testing of a sample of these materials.

For conventional house cabinetry, the high/medium/low emission distinctions were defined based on the expected emissions of the various component materials that go into cabinet construction (Table 2-5). Test cabinets were to be built by the customary manufacturers using their own inventory of cabinet materials. Cabinets for manufactured houses were to be taken from standard cabinet lines offered by home manufacturers. These lines were to be subjectively evaluated by the study team in choosing one that is consistent with the criteria for medium cabinet emissions for the conventional house. Samples of the individual cabinet materials were to be taken and tested by industry to verify their separate emissions characteristics; however, only the full cabinet emission test data were to be used for modeling purposes. Particleboard for countertops was to be supplied by industry in the medium emission range as previously described.

Table 2-5. Components Associated with Low, Medium and High Emission Rates
for Conventional House Cabinets

Cabinet Components	Low	Medium	High
Cabinet Sides	Vinyl Wrapped Particleboard	Melamine Wrapped Particleboard	UV Roll Coated Particleboard
Shelves	Vinyl Wrapped Particleboard	Melamine Wrapped Particleboard	UV Roll Coated Particleboard
Frame	Solid Wood- Nitrocellulose Coating	Solid Wood- Nitrocellulose Coating	Solid Wood- Alkyd Urea Coating
Drawer Sides/Bottom	Vinyl Wrapped Particleboard	Melamine Wrapped Particleboard	Printed Particleboard
Toe Kick	Painted Particleboard	Painted Particleboard	Painted Particleboard
Doors/Drawer Fronts	Melamine Wrapped Particleboard on All Sides	Wood/Veneer- Nitrocellulose Coating	Wood/Veneer- Alkyd Urea Coating
Backs	Hard Board	Particleboard	Medium Density Fiberboard (MDF)

The air exchange rate was to be controlled by a mechanical ventilation unit (heat recovery ventilator, or HRV) installed by the project team. The heating and air conditioning (HAC) fan was to be run constantly to minimize "noise" due to weather-dependent demand for space conditioning. It was recognized that this approach would tend to homogenize the concentrations across locations within a house. For the pilot study the air exchange rate was set at a medium level (0.5 ACH) during each experimental run. Tracer-gas measurements were to be taken to verify that the installed ventilation unit could control the air exchange rate. During the first baseline measurement period, sulfur hexafluoride (SF_6) and perfluorocarbon tracer (PFT) measurements were to be taken to verify the ability of the mechanical ventilation unit to achieve target air exchange rates for low (0.15 ACH, unit off), medium (0.5 ACH), and high (1.2 ACH). The three target air exchange rates correspond approximately to the 10th, 50th, and 90th percentiles of the estimated national distribution of residential air exchange rates (Koontz and Rector 1995). The measurements at the low and high settings were to be replicated to assess the variability of the actual air exchange rate about the target setting. SF_6 and PFT measurements were to be taken in different areas of the house to assess the uniformity of air

exchange throughout the house.

Three target temperatures were planned for the full study, 65, 75, and 85 °F. During the pilot study runs the thermostat temperature was to be set at 75 °F and then "fine-tuned" to achieve an average daily temperature that meets the target. The ability of the HAC system to maintain this temperature was to be assessed by comparing the target temperature with temperatures recorded by thermistors. Relative humidity is a covariate throughout the pilot study, and was to be measured during each experimental run both indoors and outdoors. Outdoor measurements, such as ambient formaldehyde, temperature, solar radiation, and wind speed and direction (using data from the nearest airport) also were to be recorded during each experimental run.

2.2 GENERAL MONITORING STRATEGY

The measurement plan is largely built around the following standard methods to measure airborne concentrations of formaldehyde:

- EPA Method IP-6A (Solid Adsorbent Cartridge), which involves collection of formaldehyde onto a sorbent bed coated with 2,4-dinitrophenylhydrazine (DNPH) reagent followed by high performance liquid chromatography (HPLC) in the laboratory (USEPA 1990).

- NIOSH Method 3500 (Chromotropic Acid), which involves collection of formaldehyde in liquid-filled impingers (sodium bisulfite solution) followed by spectrophotometric analysis in the laboratory (NIOSH 1994).

EPA Method IP-4A, Perfluorocarbon Tracer, was invoked for one type of air exchange measurement. The method, based on technology developed by researchers at Brookhaven National Laboratory (Dietz et al. 1986), involves constant release of perfluorocarbon tracers (PFTs) using permeation cartridges allied to diffusion-limited sample collection, followed by analysis in the laboratory using gas chromatography equipped for electron-capture detection (GC/ECD). Guidance and specification for air exchange measurements using SF_6 are offered in EPA Method IP-4B (USEPA 1990) and ASTM E-641 (generalized guidance for measuring air exchange using tracer gas dilution). The PFT method would be preferred for the main study to restrain costs and simplify logistics, particularly in the event that measurements are carried out simultaneously in multiple geographic areas. The SF_6 methodology has been included to provide the means to confirm the acceptability of PFT results through independent testing.

The experimental design placed strong reliance on controlling circumstances that define source/receptor relationships for a given experimental setting. Generally accepted criteria for representative placement of samplers and analyzers were taken from EPA's Indoor Air Compendium (USEPA 1990). Guidance for operational details (sampling interval and frequency) and for indoor-outdoor environmental monitoring at the conventional house enrolled in the pilot study were derived from earlier work in unoccupied research houses (GEOMET 1991).

Operational aspects of formaldehyde emissions testing for full-sized items were derived from ASTM E 1333 - 90, *Standard Test Method for Determining Formaldehyde Levels from Wood Products Under Defined Test Conditions Using a Large Chamber*. The pilot study also involved small-volume chamber testing to estimate formaldehyde sink parameters for selected materials using smaller test specimens. Operational aspects of these tests were derived from ASTM D 5116 - 90, *Standard Guide for Small-Scale Environmental Chamber Determinations of Organic Emissions from Indoor Materials/Products.*

Analytical responsibilities for the project are summarized in Table 2-6. GEOMET was to

be responsible for all data collection activities related to experiments in the conventional and manufactured houses as well as the small-chamber sink and barrier tests. Industry was to be responsible for conducting formaldehyde emission tests in their large-chamber facility. Formaldehyde samples collected using the DNPH cartridge method were to be analyzed by Acurex Environmental Corporation; formaldehyde samples collected using the chromotropic acid procedure were to be analyzed by the organization conducting the test, as were the continuous monitors for formaldehyde. All PFT samples collected in the conventional and manufactured houses were to be analyzed by Brookhaven National Laboratory; SF_6 samples were to be analyzed by GEOMET.

Table 2-6. Analytical Responsibilities for the Project

Measurement Parameter	Method	Conventional House Experiments (GEOMET)	Manufactured House Experiments (GEOMET)	Small Chamber Experiments (GEOMET)	Large Chamber Tests (NPA)
Time-Integrated Formaldehyde	DNPH Cartridge	Acurex	Acurex	Acurex	---
Time-Integrated Formaldehyde	Chromotropic Acid	GEOMET	GEOMET	GEOMET	NPA
Continuous Formaldehyde	Electrochemical Transducer	GEOMET	GEOMET	GEOMET	NPA
Perfluorocarbon Tracer	GC/ECD	Brookhaven	Brookhaven	---	---
SF_6 Tracer	GC/ECD	GEOMET	GEOMET	---	---
Air Temperature	Thermistor	GEOMET	GEOMET	GEOMET	NPA
Relative Humidity	Thin Film Capacitance	GEOMET	GEOMET	GEOMET	NPA
Solar Radiation	Pyranometer	GEOMET	GEOMET	---	---

Generally accepted practice (USEPA 1983a, Taylor 1987, USEPA 1993c) considers quality assurance objectives in terms of accuracy (the degree of agreement with accepted reference or "true" values) and precision (the degree of mutual agreement among individual measurements taken under the same prescribed conditions). Additional considerations include completeness (compared with expectations, the amount of valid data recovered) as well as representativeness (an expression of the degree to which measurement results relate to key characteristics or conditions) and comparability (an expression of the degree to which one data set can be related to another). Data quality objectives (DQOs) for the main measurement parameters in the pilot study are listed in Table 2-7. These performance targets were derived from documented research and development studies.

Table 2-7. Data Quality Objectives For Accuracy and Precision

Measurement Parameter	Method	Accuracy	Precision	Detection Limit	Complete-ness	References
Time-Integrated Formaldehyde	DNPH Cartridge	± 20%	± 20%	0.5 ppb	95%	EPA 1990, 1994

Time-Integrated Formaldehyde	Chromotropic Acid	± 20%	± 20%	0.02 ppm	95%	NIOSH 1994 EPA 1990, 1994
Continuous Formaldehyde	Electrochemical Transducer	± 20%	± 20%	3 ppb	95%	EPA 1990 NCASI 1989
Perfluorocarbon Tracer	GC/ECD	± 10%	± 10%	5 ppb	95%	Dietz et al. 1986 EPA 1990
SF_6 Tracer	GC/ECD	± 10%	± 10%	5 ppb	95%	EPA 1990 ASTM 1981
Air Temperature	Thermistor	± 5%	± 5%	0.3 °C (resolution)	95%	GEOMET 1991
Relative Humidity	Thin Film Capacitance	± 10%	± 10%	5% RH (resolution)	95%	GEOMET 1991
Solar Radiation	Pyranometer	± 10%	± 10%	1 gcal/cm^2 /min	95%	EPA 1983b

2.3 PROJECT PLANNING AND MANAGEMENT

The Quality Assurance Project Plan (QAPP) serves as the primary reference document for project planning and management. Following the initial draft of the QAPP by GEOMET, an interim revision was completed and circulated for external review during late summer 1994. Following the signing of the Cooperative Research and Development Agreement (CRDA) between EPA and NPA during September 1994, the third revision of the QAPP was issued on October 14.

Planning and management of the pilot study has been a cooperative effort involving representatives from GEOMET, Versar, EPA and industry. These representatives formed a Technical Panel that included experts in the fields of manufactured wood products and manufactured housing, assembled by NPA for this purpose (the NPA Home Study Technical Team). The Technical Panel met on various occasions throughout the pilot study to discuss important technical and logistical issues.

Prior to development of the QAPP, the focus of these meetings was on planning efforts such as the preceding subsection on experimental design (most of the subsection was carried forward from the QAPP). Since the issuance of the third revision of the QAPP in October 1994, meetings of the Technical Panel have been convened on six occasions to discuss project-related issues:

- November 4, 1994--to discuss the composition/loading of cabinets and countertops for manufactured houses.

- January 11, 1995--to plan site visits to plants for manufactured houses and to discuss manufactured house funding issues.

- February 3, 1995--to discuss issues related to conventional house loading and testing, conditioning for product emission tests, the continuous formaldehyde analyzer, quality assurance and control, and recruitment of manufactured house builders.

- April 17, 1995--to discuss installation procedures for underlayment and cabinets immediately before the first loading of the conventional house.

- July 27, 1995--to discuss project resources and priorities.

- November 29, 1995--to plan and discuss the scope, contents and schedule for the final report.

Following the February 3 meeting, tentative QAPP revisions reflecting discussions among Technical Panel members were submitted to EPA. It was subsequently determined that the revisions would not be formally added to the QAPP until such time as outstanding issues relating to the manufactured houses were fully resolved.

During the early stages of the project, many of the Technical Panel members visited the conventional house on several occasions. The first of these visits occurred on November 22, 1994 as construction of the house (see Section 3.2) neared completion to the point where interior finishings could be completed under project control. The second visit was on February 2, 1995 as preparations for initial house loading and monitoring were nearing completion. Several factors delayed the first loading of the conventional house until mid-April 1995. The third visit to the house occurred on April 20, 1995 as this loading was being completed.

Technical Panel members also made several visits to plants of prospective manufactured house builders in Pennsylvania, for purposes of builder/house selection and identification of technical and logistical issues. Two manufacturers in Pennsylvania were initially considered, and their manufacturing plants were visited by Technical Panel members on October 11, 1994. Consideration was given to assigning the high-loading houses to one builder and the medium-loading houses to the other, in accordance with the experimental design. However, due to difficulties in determining the responsible party for assumption of financial risk for the houses following their use under the project, Versar/GEOMET withdrew consideration of one manufacturer. In early April 1995, the Versar project manager and the GEOMET field test manager visited the remaining manufacturer with EPA and NPA representatives to inspect the proposed location for the manufactured house tests and to obtain site details.

At the meeting of the Technical Panel convened on July 27, 1995, it was determined that remaining project resources were insufficient to accommodate the portion of the study involving manufactured houses. Further, it was decided to scale down the testing in the conventional house by dropping one of the loading configurations--the medium loading was to be used only once, followed by two consecutive iterations of the high loading. Formaldehyde measurements with the chromotropic acid method were also dropped because of problems with data quality (see Section 5.4).

Several delays and complexities encountered early in the project, which required unanticipated expenditure of limited project resources, were partly responsible for the ultimate decision to drop the manufactured houses from the study. For example, it was planned that during characterization of the conventional houses (see Section 3.2) sealing procedures would be applied to reduce the air leakage of the house. One of the unanticipated challenges in sealing the house arose from the builder's use of wall cavities as part of the air return for the heating and air conditioning (HAC) system. This feature of the conventional house required careful examination and experimentation, prolonging the sealing process.

Initial study plans also did not include measurement of formaldehyde concentrations in the basement, because it was thought that the combination of house-sealing procedures and an interior door at the top of the stairwell to the basement would minimize air communication with

the remainder of the house. However, during tracer-gas studies to characterize the air exchange rate for the house it became obvious that tracer injected into the living area was being transferred to the basement (see Section 6.1). Consequently, it was decided to include formaldehyde measurements in the basement. In addition, PFT sources and samplers were configured so that the average airflow rate between the basement and living area could be quantitated during each sampling event.

The conventional house was essentially ready for monitoring at the end of February 1995. However, due to problems encountered in preparing performance evaluation samples for DNPH (see Section 5.2) as part of project QA activities, baseline monitoring could not begin until the end of March 1995. As shown in Table 2-8, the conventional house testing began three to four months later than originally anticipated in the QAPP, and this delay was carried through to the end of the conventional house testing.

Table 2-8. Comparison of Planned Versus Actual Dates for Key Project Activities

Activity	Planned Date[a]	Actual Date
QA System Audit and Pre-monitoring Interlaboratory Comparison	11-12-94	2-28-95
Baseline Monitoring at the Conventional House	12-12-94	3-30-95
First Interim Report	2-17-95	6-6-95
Second Interim Report	5-19-95	9-22-95
Completion of Pilot Study Field Measurements	6-30-95	11-1-95
Final Interlaboratory Comparison	6-30-95	Not Conducted

[a] Per QAPP (Revision 3) dated October 14, 1994

3.0 CONVENTIONAL HOUSE TESTING

The monitoring program was conducted at the conventional house during the March-November 1995 time period. Field measurements were preceded by builder recruitment, equipment installation, and establishing the materials storage facility.

3.1 BUILDER RECRUITMENT

Builder recruitment was initiated in the summer of 1994, before formal execution of the CRDA, in order to avoid operational delays once funding was in place. Recruitment was staged to identify multiple candidates for a competitive procurement process. In early June 1994, GEOMET identified 29 area home builders through the Yellow Pages. A presentation package was developed to summarize technical requirements of the study and to outline anticipated lease terms. Telephone and facsimile contacts resulted in delivering 20 project invitations to potential builder participants with no positive response.

In mid-June 1994, an advertisement designed to attract individuals contracting to have a home built was placed in the *Frederick* (Maryland) *Post*. One response was received from a Virginia Realtor who expressed interest in enrolling a model home into the project. This interest evaporated, however, when it was made clear that the home could not remain open for viewing during the lease period. A second response initially showed more promise. In this case, a married couple already had scheduled construction of a new home in Boonsboro, MD during the summer of 1994. In the end, however, the couple decided that their priorities lay in occupying their new home as soon after construction as possible.

In July 1994, the next level of expansion involved placing focused advertisements in smaller newspapers whose service areas covered the next tier of Maryland counties in terms of travel from GEOMET headquarters (Prince Georges, Carroll, Charles, Washington Counties). Positive response was received from a homeowner in Centreville, MD, who had scheduled replacement construction of a rental residence destroyed by fire. Because the home was being built for rental, the owner was more willing to cooperate as the project would be the first tenant. The home was completed in September 1994 and the lease was signed on November 15, 1994.

Accepting this house into the study represented compromises to the original design while illuminating practical limitations. First, the Centreville house is built over a basement (as opposed to a crawl-space configuration originally called for in the experimental design). In canvassing construction patterns in the Maryland, Virginia and Washington, DC area, however, it became clear that crawl-space houses are rare in this part of the country. Nonetheless, closing off the basement during the tests provided the means to isolate source effects with more realism than installing an unrepresentative floor in slab-on-grade construction. Second, travel distance to the site on the Eastern Shore of Maryland magnified time pressures on field technicians. This increased the labor allocation (because a partial day on site is impractical and made for longer days). Third, the somewhat unique circumstances of the only homeowner who proved willing to become involved in the study underscored the practical limitations of enrolling homes in studies such as this, because houses generally are constructed with owner occupancy in mind.

3.2 HOUSE CHARACTERIZATION

A pro-forma construction schedule for the conventional house is illustrated in Figure 3-1. The first 8 weeks of construction, which take the house through installation of interior walls, involve the resources of the home builder. The final stage of construction, under control of the project, includes installation of formaldehyde-bearing materials (e.g., underlayment, cabinets, doors) of known origin and age (see Section 3.5). Construction for the conventional house was

completed in September 1994. By the end of November, necessary modifications and repairs were completed, approved and inspected. Needed supplies for the study were then moved into the basement and an "equipment shelter" was constructed to thermally isolate the data acquisition system from the house. Telephone service for the project was also connected at that time.

An exterior view and general floorplan for the conventional house are presented in Figure 3-2. Volumes of each floor are listed in Table 3-1. The Centreville house is a two-story Cape Cod style home with a full-sized basement. The house has a master bedroom suite on the first floor along with living area, dining room, kitchen, and utility room. The second story has two dormer windows on the front and a raised roof section at the rear which provides for two eight-foot-ceiling bedrooms and a full bath. The house is a custom "stick-built" construction employing a concrete block foundation, wood framing, with gypsum wallboard for interior surfaces. The exterior is covered with vinyl siding.

Table 3-1. Conventional House Volume by Floor

Floor	Volume, ft^3 (m^3)
Basement	5941 (168)
First Floor	5931 (168)
Second Floor	4815 (136)
Total, all Floors	16,687 (472)

Heating and air conditioning (HAC) is provided by a forced-air high efficiency heat pump. In addition to the normal complement of supply registers the HAC system includes six return air registers. Unlike the all-metal supply ducting, return air ducts are connected to the air handler by a combination of metal ducting and enclosed wall cavities. This construction method, although less expensive, can result in greater air leakage to outdoors. The HAC system was retrofitted with an air-to-air heat exchanger (heat recovery ventilator, or HRV) in order to increase the air exchange rate to meet study objectives.

CONSTRUCTION STEPS	WEEKS OF CONSTRUCTION PROJECT												
	1	2	3	4	5	6	7	8	9	10	11	12	13
FOUNDATION	■	■	■										
Excavation and Footers	■												
Concrete Walls	■	■											
Utility Rough-in		■											
Pest Control			■										
Damp Proofing			■										
Slab Pour			■										
FRAMING				■									
Columns and Steel			■										
Walls, Sheathing & Decking				■									
Trusswork				■									
Windows and Doors					■								
MECHANICAL & ELECTRIC						■	■						
HVAC Rough-in					■								
Plumbing Rough-in						■							
Roof Shingles						■							
Electric Rough-in						■							
Insulation							■						
DRY WALL								■					
FINISHES									■	■	■		
Bath									■				
Interior Trim & Paint									■				
Resilient Flooring										■			
Cabinetry										■			
HVAC, Plumbing & Electric											■		
Touch-up												■	
Carpet													■

Project Intervention and Baseline Monitoring Begin

Figure 3-1. Pro-forma Construction Schedule for Conventional House (after NAHB 1993).

3-3
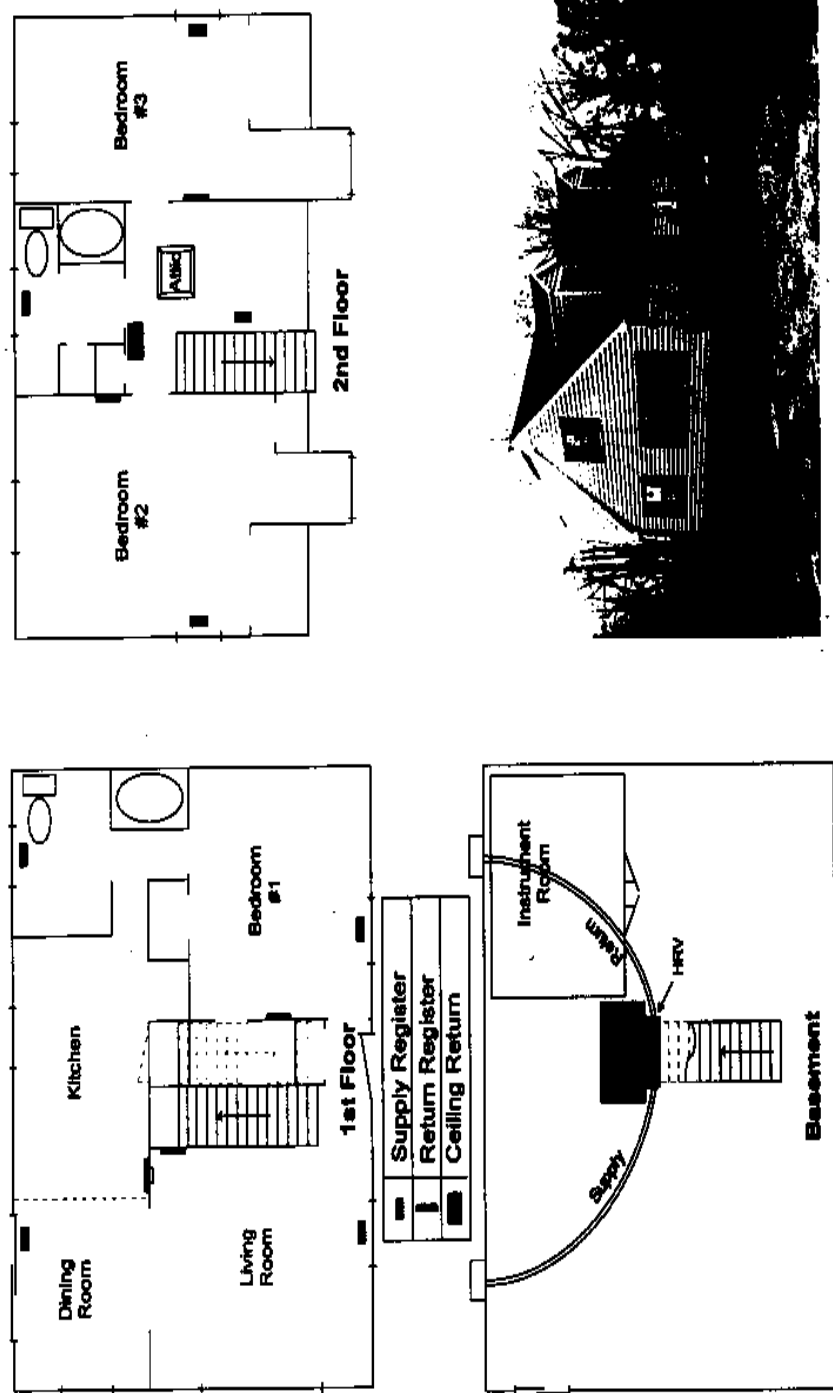
Figure 3-2. Exterior View and Floorplan of Conventional House.

| Supply Register |
| Return Register |
| Ceiling Return |

In December 1994, GEOMET staff performed a series of blower-door tests (in accordance with ASTM E 779) on the conventional house to characterize air leakage for the building shell. These tests indicated that the building was moderately leaky (10 ACH at 50 Pa, or approximately 0.5 ACH under moderate environmental conditions). Air leakage sites requiring sealing with foam or latex caulk were identified at service penetrations between the basement and the first floor as well as at the base of the drywall and along the baseplate. After sealing was completed, blower-door tests showed 4.0 ACH at 50 pascals (approximately 0.2 ACH under moderate environmental conditions). Special tests were conducted to isolate leakage in the forced-air distribution system. In the supply ducts, as-built leakage area was found to be 194 cm^2 (aerodynamic equivalent); sealing reduced this to 116 cm^2. For the return ducts, as-built leakage of 387 cm^2 was reduced to 206 cm^2. Room dimensions were physically measured and the volume of the upper floors was calculated to be 304 m^3 (10,746 ft^3). A detailed sketch was made of the ductwork system, both supply and return.

In January 1995, the heat recovery ventilator was received and installed. Detailed flow measurements were made with and without the HAC fan operating to verify that the HRV would maintain air exchange rates at design levels. Tracer-gas measurements indicated that the natural air exchange rate (i.e., with all windows closed and the HRV off) for the house ranged from 0.15 to 0.21 over a two-day period. The HRV was then set to ventilate the house at 0.50 ACH (protocol conditions). Tracer-gas measurements with SF_6 over the ensuing five-day period ranged from 0.45 to 0.55 ACH, establishing the efficacy of the HRV in maintaining the target air exchange rate for the pilot study.

The HRV was initially set at 55 cfm with the intent of ventilating the house at 0.5 ACH (protocol conditions) due to the combined effects of air infiltration and mechanical ventilation. Proximity to the target air exchange rate was assessed through tracer-dilution measurements. As milder weather conditions were encountered during the wait for the first house loading, the infiltration component decreased and the mechanical ventilation rate was correspondingly increased. The HRV setting ultimately used for the first loading was 105 cfm.

During this period, carpeting and padding were selected, detailed plans to guide loading of formaldehyde-bearing materials were completed, and arrangements were made with the building contractor for cutting of underlayment and installation of all materials. Major vacuuming and damp mop of the house were completed to remove residuals of drywall finishing. All interior doors slated for the first loading were painted at the storage area in Gaithersburg, MD.

In February, 1995, problems were noted with the operation of the heat pump in the conventional home. The installation contractor eventually determined that the outdoor unit had a defective expansion valve and performed warranty repairs. A replacement part was installed, and the unit operated properly for the remainder of the study. Discovery, investigation and resolution of this problem resulted in a two-week delay. Preparation and installation of sampling equipment was completed in March.

During the pilot study, airflows also were measured at each supply and return register (one supply register was inadvertently omitted from the measurements). These data, summarized in Figure 3-3, confirm expectations for similar supply airflows to each measurement zone of the house. The sum of the supply airflows exceeds that for the return airflows, indicating that the house may have been positively pressurized. However, measurement of differential pressures was outside the scope and mission of the study.

3.3 MONITORING CONFIGURATION

Monitoring locations for each measurement parameter are identified in Figure 3-4. Moisture-control sites (humidifiers and dehumidifiers) are also shown in this figure. One of the sampling locations for formaldehyde (including the real-time analyzer) is shown in Figure 3-5.

Two sampling methods were employed for time-integrated formaldehyde measurements; the NIOSH 3500 method, Chromotropic Acid (CA), and EPA Method IP-6A, dinitrophenylhydrazine (DNPH). Six samplers for each method were set up at the conventional house: living room, kitchen, bedroom 3 (upstairs), basement, a relocatable duplicate, plus outdoors. Both methods involve passing a known volume of air through sample media to capture formaldehyde. Flow systems consisted of a network of sample lines extending to each location from a centrally located flowmeter panel containing five calibrated rotameters. Flow for each sampler was held constant by an orifice restrictor (capillary tube) served by a common vacuum pump. All rotameters were individually calibrated against a NIST-traceable mass flow meter.

House conditions were monitored with a computer-based data acquisition system (DAS) that provides a continuous record of temperature, humidity, and solar radiation as well as command and control of sulfur hexafluoride (SF_6) ventilation measurements and the Interscan real-time analyzer for formaldehyde. Temperature and humidity sensors were calibrated with NIST-traceable standards and further verified against an EPA performance audit.

The Interscan instrument for real-time formaldehyde measurements is an electro-chemically based analyzer which provides a continuous record of the formaldehyde concentration. This unit was co-located with the integrated air samplers located in the living room and was automatically zeroed by the DAS every three hours. The instrument was fully calibrated and serviced on a weekly basis. Calibration was performed with a CEA Instruments SC-100 permeation tube calibrator. Service encompassed replenishing detector cell water and verifying proper sample flow rate.

Ventilation measurements (in air changes per hour) were obtained by the exponential dilution of SF_6 tracer gas as measured by a gas chromatograph. The measurement cycle began with an injection of tracer gas into the return air duct every eight hours; the forced-air system then mixed the SF_6 throughout the house. Following injection, samples were automatically taken at each of five locations: living room, kitchen, bedroom (second floor), basement, and outdoors. This automated system sequenced through all locations every fifteen minutes, providing four samples per hour for each location.
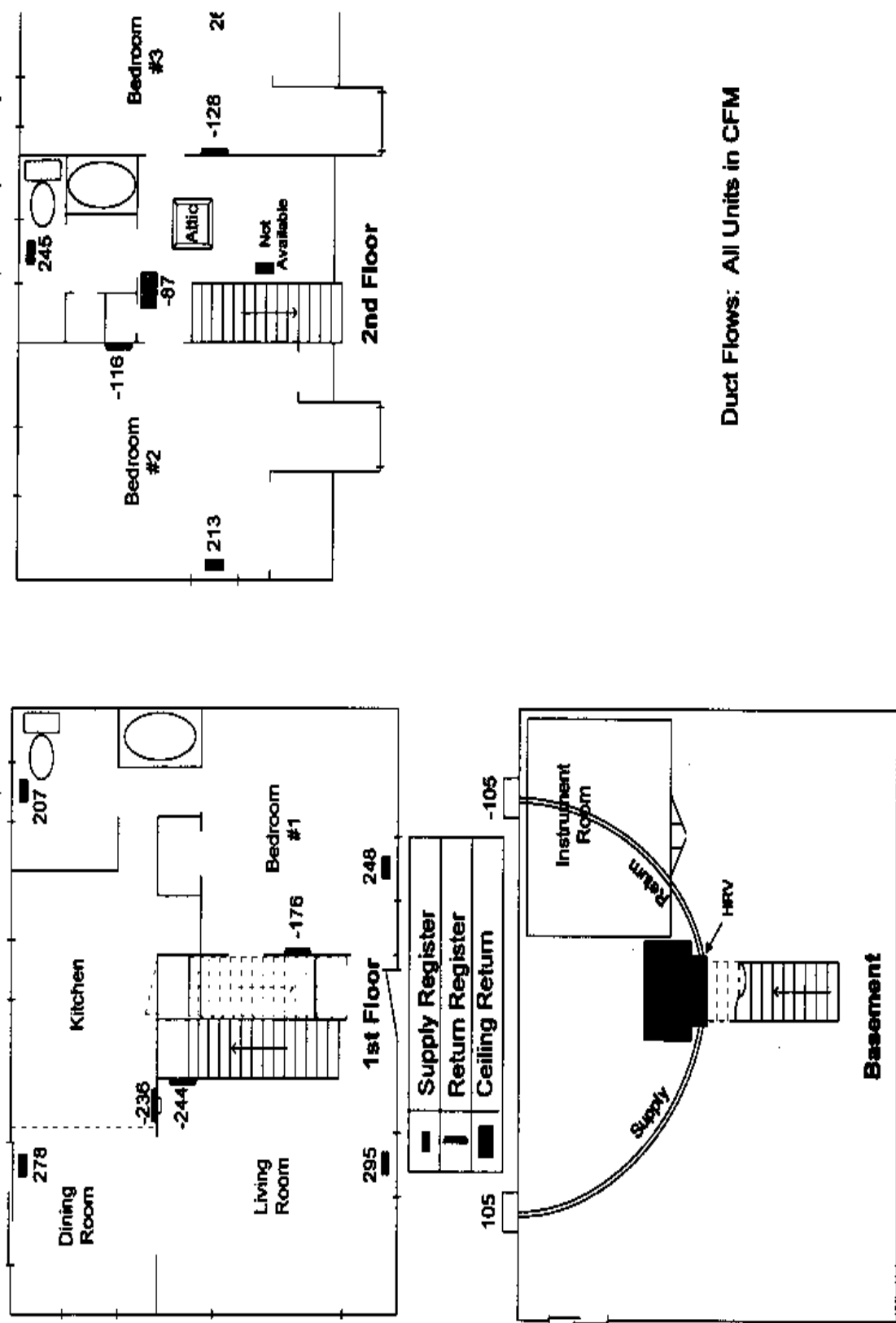
Figure 3-3. Measured Airflows in Supply and Return Registers of the Conventional House.

Duct Flows: All Units in CFM
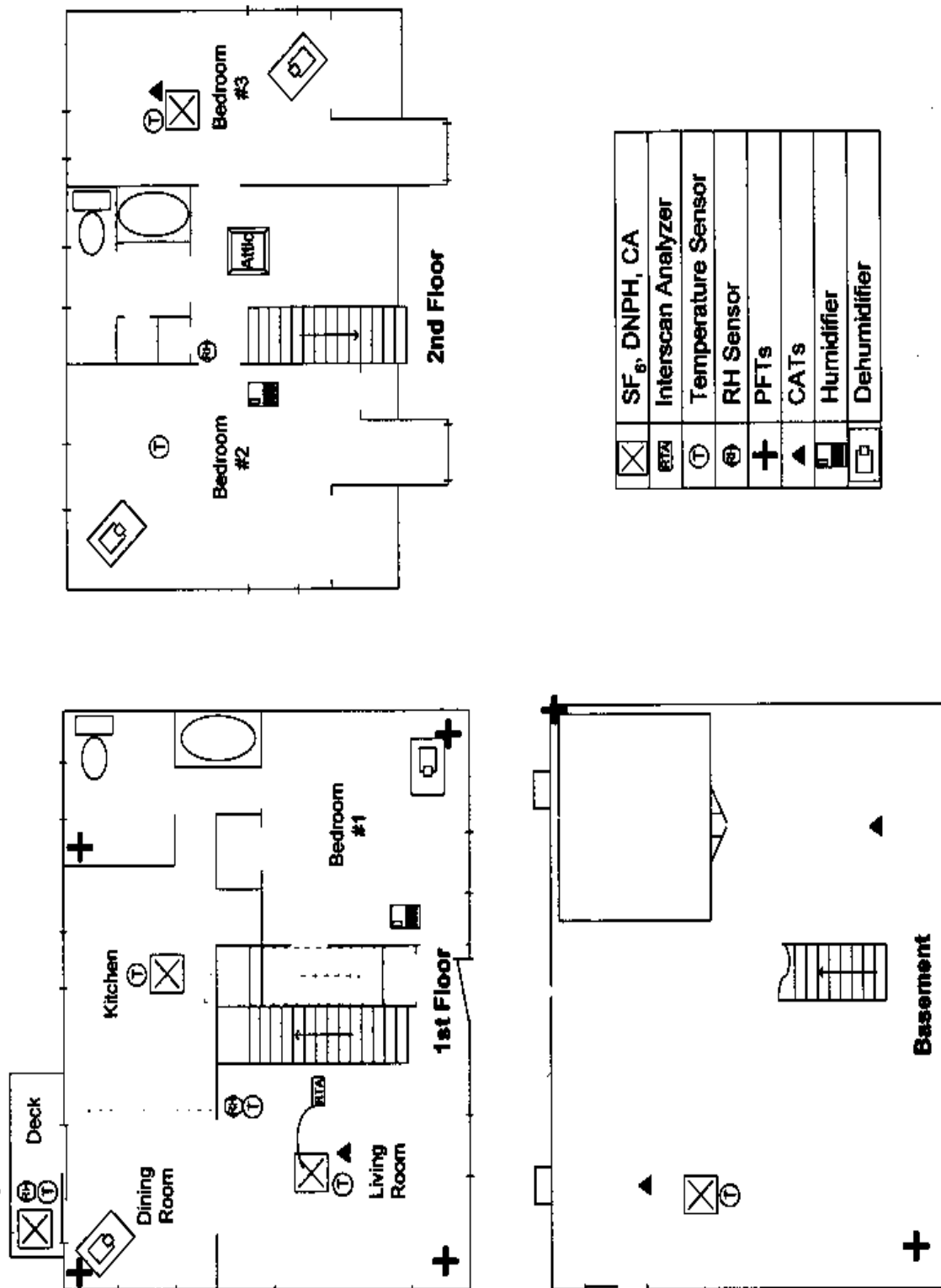
Figure 3-4. Monitoring and Moisture-Control Locations for Conventional House Testing.

⊠	SF$_6$, DNPH, CA
RTA	Interscan Analyzer
⊤	Temperature Sensor
RH	RH Sensor
+	PFTs
▲	CATs
▣	Humidifier
▢	Dehumidifier
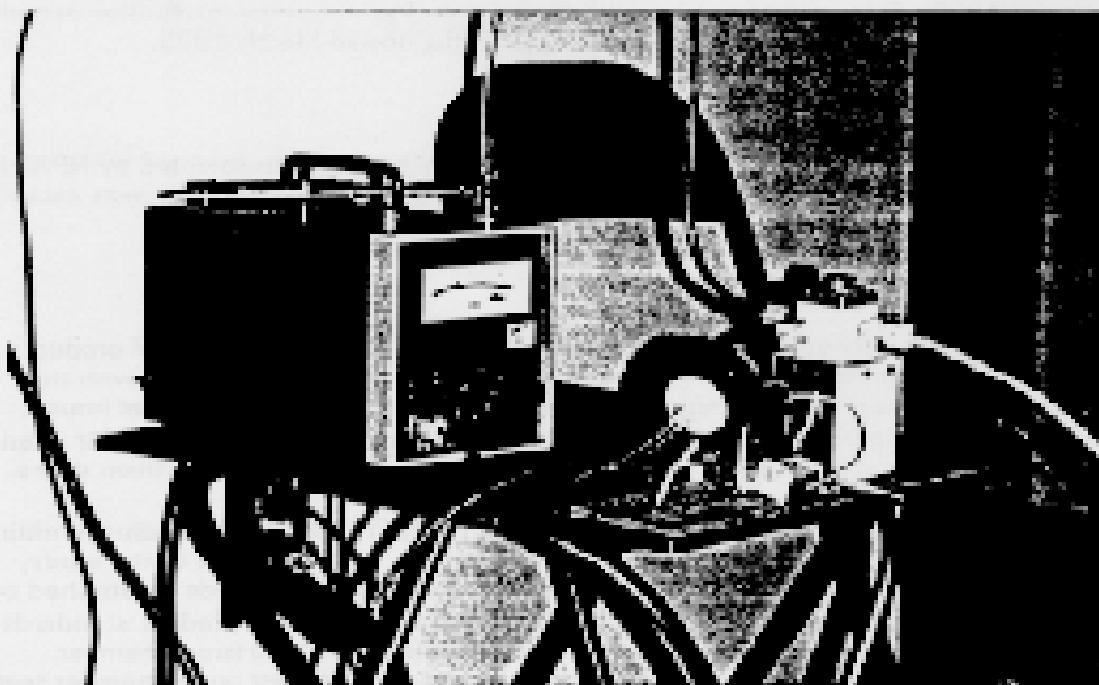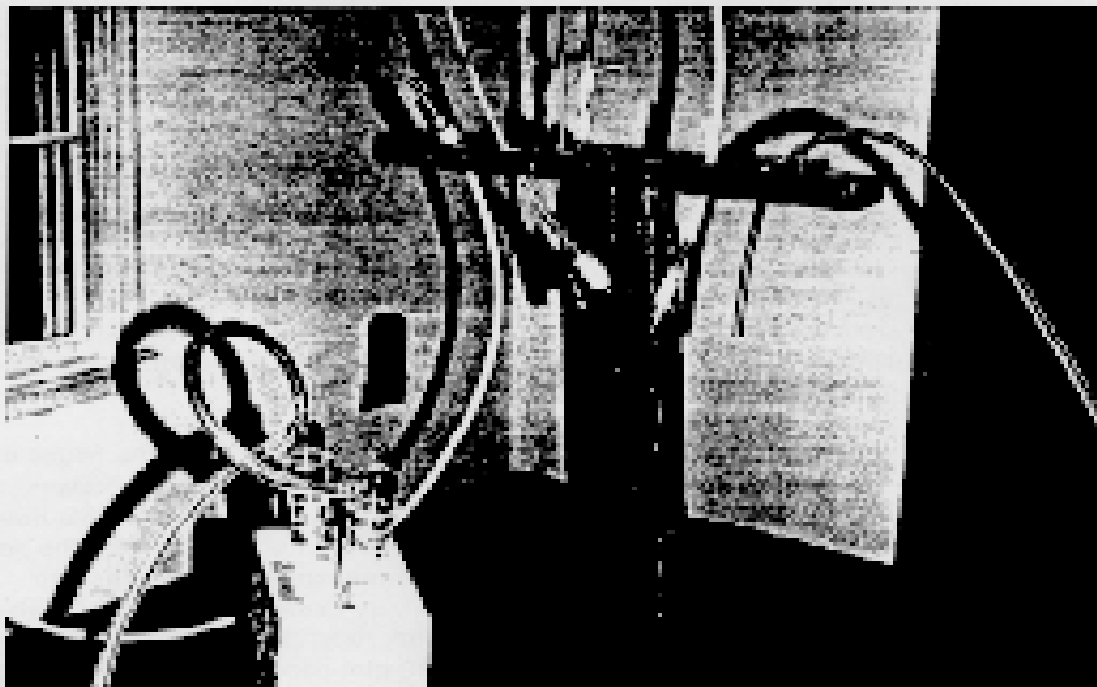
Figure 3-6. Living Room Site for Formaldehyde Monitoring.

Locations of PFT sources and samplers (capillary absorption tubes, or CATs) are also shown in Figure 3-4. Because the HAC fan was run constantly but the basement was isolated from the upper floors, the house was conceptualized as two zones: (1) the first and second floor combined; and (2) the basement. This approach allowed us to estimate the whole-house air exchange rate during each sampling event (24 hours) while also quantitating airflow rates between the basement and upper floors. Based on discussions with Brookhaven National Laboratory (the vendor for supply and analysis of PFTs), PFT sources for the upper zone were placed on all four corners of the first floor with samplers toward the center of the first and second floors. In the basement, sources were placed in two diagonally-opposite corners and samplers were placed toward the other corners but closer to the center of this floor.

To help maintain the design condition of 50% relative humidity in the house during the heating season, additional moisture was provided by four ultrasonic humidifiers, two on each floor. Ultrasonic humidifiers were chosen in lieu of a duct-mounted "whole-house" humidifier because the flow-through design of a whole-house humidifier offers the potential for scrubbing of formaldehyde from the return air. The ultrasonic humidifiers were controlled by a return-mounted humidistat and collectively capable of adding 10 gallons of water per day to the house. During the cooling season, removal of excess moisture was accomplished using portable console dehumidifiers (40-pint-per-day removal capacity) with the controls set to prevent relative humidity from exceeding 60 percent.

The conventional house was essentially ready for baseline monitoring at the end of February 1995. Delays in completing the first round of performance evaluation samples for DNPH, however, postponed initial monitoring until the end of March 1995.

3.4 MATERIALS SELECTION AND STORAGE

UF-bonded wood products for the conventional house were selected by NPA/HPVA to meet medium-emission criteria. A secure storage area for the materials was established in a leased facility.

3.4.1 Materials Selection

Urea-formaldehyde adhesives are used in making various wood panel products intended for use in the interior of homes. Four wood-based panel products with the potential for emitting formaldehyde were used in the pilot study conventional house: particleboard for flooring underlayment and counter tops, hardwood plywood for interior decorative wall paneling, cabinets for kitchens and baths, and interior partition doors.

The QA Project Plan for the study (GEOMET 1994) designated "medium emitting" wood panel products for use in the conventional house. In the context of the study, "medium emitting" refers to materials designed to conform to standards established by the U.S. Department of Housing and Urban Development and voluntary product standards for particleboard and hardwood plywood with target ASTM E 1333-90 large chamber concentration-in-air values in a 0.12 to 0.14 ppm range. Sufficient large chamber test data were in hand for particleboard and hardwood plywood from the National Particleboard

Association and the Hardwood Plywood & Veneer Association to identify products qualifying as "medium-emitters." There were limited large chamber test data available for kitchen cabinets and interior partition doors. The selection of kitchen cabinets and interior partition doors as medium emitters, therefore, was based on the quantity and type of wood panel products used as components under the expectation that finishing, painting, or decorative surface laminates would influence the diffusion of formaldehyde gas from the underlining wood-based substrate. The type and color of products desired by the home owner from which the conventional house for the pilot study was leased was also considered in the selection of kitchen cabinets and doors. The selection process for each of the wood building materials or products is described below.

Particleboard: Particleboard used in the pilot study conventional home for all house loadings was unfinished 5/8" underlayment with a limited quantity of 3/4" industrial particleboard for counter tops for base kitchen cabinets. The National Particleboard Association large chamber average survey test data for particleboard underlayment designed to meet current industry standards was 0.135 ppm for 78 tests conducted during the 1993/1994 period. The large chamber test value of 0.144 ppm for the screening test used to identify an appropriate particleboard underlayment product for the pilot study, and the 0.125 ppm test value obtained in the testing of underlayment selected for the first loading (medium) at a nominal air exchange rate of 0.5 ACH in the large chamber, places the particleboard within the range of the targeted value as a medium emitter. Three 48" wide particleboard panels with a small section cut off each end were used in achieving the 0.13 sq. ft./cu. ft. large chamber test loading ratio for this product.

Hardwood Plywood Wall Paneling: The hardwood plywood used in the second and third house loadings (high) was 3-ply 1/4" birch face, tropical hardwood back and core with 7 cut grooves along the length of each 4' x 8' panel to simulate random width lumber planking. HPVA large chamber survey data of plywood wall paneling products designed to meet current industry standards demonstrate an average of 0.133 ppm for 174 hardwood plywood wall paneling tests conducted during the 1993/1994 period. The large chamber screening value for identifying an appropriate wall paneling product for the pilot study project was 0.114 ppm and the test value for plywood selected for the second house loading (the first loading where plywood paneling was used) was 0.112 ppm as tested at a nominal 0.5 ACH in the large chamber. This value is very near but slightly less than the QAPP-designated range for a medium emitter (i.e., 0.12 to 0.14 ppm). Six 48" x 78 1/4" panels were used in achieving the 0.29 sq. ft./cu. ft. test loading ratio in the large chamber.

Kitchen Cabinets: Because only limited large chamber data were available for kitchen cabinets, the selection of cabinets was based on the composition and finish of seven cabinet components associated with three formaldehyde emission categories as detailed in the QAPP. Table 3-2 lists the components of the selected cabinets and the associated assumed emission potential. For the wood panel products used in the construction of the selected cabinets, approximately 83 percent of the cabinet surface area was particleboard of which 10 percent was unfinished. The remaining composition of cabinet surfaces was 8 percent hardboard and 9 percent solid wood. Although five of the seven kitchen cabinet component categories were "high" and two were "low," the kitchen cabinets, when tested

in a large chamber were not "high" emitting as defined in the QAPP. The initial large chamber value for cabinets used in the first loading was 0.053 ppm tested in the large chamber at an air exchange rate of 0.5 ACH and a loading ratio of 0.133 sq. ft./cu. ft. Kitchen cabinet testing consisted of testing a base and wall cabinet in combination. The base cabinet was 35" high x 30" wide x 24" deep with the top covered by a 32" x 25" counter top with high-pressure laminate on the top surface, the front edge and on two sides of a 3/4" particleboard substrate. The back edge and underside of the particleboard used for the counter top were unfinished. The wall cabinet was 30" high x 30" wide x 12" deep. Testing was performed with the doors of the two cabinets closed. The large chamber test loading ratio of 0.133 sq. ft./cu. ft. was derived by computing the surface area (back and front) of all surfaces, inside and outside the two cabinets, including the inside shelves.

Table 3-2. Emission Characteristics for Kitchen Cabinetry

Cabinet Components	Components of Cabinets in Conventional Homes	Emission Rate Category in QAPP
Cabinet Sides	UV Roll Coated Particleboard	High
Shelves	UV Roll Coated Particleboard	High
Frame	Solid Wood-Alkyd Urea Coating	High
Drawer Sides/Bottom	Printed Particleboard	High
Toe Kick	Painted Particleboard	High
Doors/Drawer Fronts	Melamine Wrapped Particleboard on All Sides	Low
Backs	Hardboard	Low

Inside Partition Doors: The selection of the inside partition doors was based on the nature of wood panel product components and finish associated with what was perceived to be a "medium emitter."   Door framing consisted of two medium density fiberboard (MDF) outside rails (horizontal edge pieces) and two solid wood stiles (vertical edge pieces). The primary exposed surfaces, the door skins, were formed MDF to simulate a 1 3/8" thick panel door (simulated lumber horizontal and vertical members with panel inserts). The doors were hollow core with honeycomb corrugated paperboard providing internal support for the door skins. The doors contained a particleboard lock block. The door skins had an embossed decorative wood grain pattern and the doors were painted with one coat of Sherwin Williams Classic 99 Enamel Pure White (BASEX). The top and bottom rail were left unpainted. Each large chamber test consisted of five 1 3/8" thick doors:

- 1 door - 29 3/4" wide by 80 " high

- 2 doors - 27 3/4" wide by 80" high

- 2 doors - 17 7/8" wide by 80" high.

The computed large chamber loading ratio was 0.125 sq. ft./cu. ft., derived by adding the overall surface areas of the ten skin surfaces of the five doors. The chamber value of the doors tested from doors selected for the first loading of the conventional house was 0.052 ppm tested at a nominal 0.5 ACH.

3.4.2 Materials Storage

Arrangements to lease the storage facility for the conventional house test materials were completed in November 1994. The facility was modified, with an added wall and lockable door for security. Materials received into storage include particleboard underlayment, doors, cabinets, industrial grade particleboard (for countertops), and paneling. As summarized in Table 3-3, all materials other than paneling were received during late November or December 1994. Underlayment was received as ten 25-sheet bundles, vinyl wrapped with an outer covering of particleboard dunnage. The doors and cabinets were vinyl-wrapped by GEOMET upon receipt. The industrial grade particleboard (countertop) material was received as two 20-sheet bundles wrapped in the same fashion as the underlayment. One of these pallets had shifted during transport, tearing the protective plastic wrap, and was subsequently rewrapped. Several sheets of the industrial grade particleboard were later delivered to a local countertop manufacturer for finishing. The completed countertop was then returned to storage and wrapped with 6-mil vinyl. The paneling was received as one 100-sheet bundle wrapped in thin (~2-mil) plastic sheeting. This shipment had also shifted in transport, tearing the protective wrap. The paneling was inspected to ensure that there was no damage, divided into manageable stacks, and rewrapped. All materials in storage were wrapped in vinyl, inventoried, separated into four groups corresponding to the four house loadings, and so labeled. Underlayment samples were sent to Battelle for large-chamber quality control testing in April 1995.

Table 3-3. Material Inventory (Wood Products) for Conventional House Testing

Category	Quantity	Date Received into Storage
Underlayment	250 - 4' x 8' sheets	November 24, 1994
Cabinets	68 - assorted types	December 13, 1994
Countertop	40 - 4' x 8' sheets	December 19, 1994[a]
Doors	53 - 3 sizes	December 15, 1994
Paneling	100 - 4' x 8' sheets	March 17, 1994

[a] Date raw material received; sent out for finishing December 22, 1994, final product
received back into storage December 30, 1994

Storage conditions were maintained by the HAC system as controlled by a thermostat located in the office portion of the warehouse. Temperature was monitored with a maximum/minimum thermometer. Observations of the minimum temperature during the heating season (Table 3-4) indicated that the HAC system would not maintain proper conditions. Consequently, a portable electric space heater was purchased and installed in the warehouse. Observations of the temperature during the cooling season indicated that temperatures would regularly exceed 80 °F. Further investigation indicated that this condition could not be remedied within resources that were available at the time.

Table 3-4. Recorded Temperatures from Max/Min Thermometer
During Periodic Visits to the Storage Facility

Date	Minimum Temperature Recorded, °F	Maximum Temperature Recorded, °F
1-12-95	44	66
2-13-95	52	58
3-17-95	52	72
4-17-95	51	64
5-8-95	58	80
6-6-95	62	78
7-19-95	62	85
8-8-95	74	86
8-16-95	70	84
10-2-95	64	83
10-13-95	67	75
10-24-95	62	73

3.5 LOADING AND MONITORING

The conventional house was loaded with UF-bonded wood products at two rates, "medium" and "high" as defined in the Quality Assurance Project Plan (QAPP).   Total surface area for each type of material is summarized in Table 3-5, and kitchen cabinets are further

broken down as shown in Table 3-6. Figure 3-6 shows the specific locations for each material in the conventional house. The medium loading consisted of 5/8" thick particleboard underlayment (PBU) on the first floor, twelve kitchen cabinets and two vanity cabinets, five 3/4" laminated particleboard countertops, and twelve painted interior partition doors. The high loading included all the materials from the medium loading in addition to PBU on the second floor and twelve 4" x 8' sheets of hardwood plywood paneling. In addition to the interior wallboard, other (potential) source/sink/barrier materials common to both loadings included carpeting and padding on both floors. The carpeting used was a 16 oz. (per sq. yd.), 100% polyolefin pile over a 3/8" thick polyurethane open-cell foam padding. Kraft-faced yellow fiberglass was used to insulate the building envelope, at locations between the floor joists in the basement (6"-R19), exterior walls (3-1/2"-R11), and attic (10"-R30 and 6"-R19).

Table 3-5. Loading Areas for Underlayment, Paneling, Doors and Countertop
at the Conventional House

Component	Loading Area - ft^2			
	1st Floor		2nd Floor	
	Medium Loading	High Loading	Medium Loading	High Loading
Underlayment	496.2	496.2	0	519.3
Paneling	0	256.0	0	128.0
Doors	203.6		169.6	
Countertop	37.9		5.65	

Table 3-6. Loading Areas for Cabinets at the Conventional House

Material	Surface Finish	Area (ft^2)	
		Exposed	Unexposed
Particleboard	None	12	51
	White - Melamine Paper	110	0
	Black - Roll Coated	4	0
	Simulated Oak Grain - Roll Coated UV Cure	91	0
	Simulated Maple Grain - Roll Coated UV Cure	252	4
	PVC Edgebanding	12	0
	TOTAL	**481**	**55**
Solid Wood	None	6	4
	Catalyzed Topcoat	55	1
	TOTAL	**61**	**5**
Hardboard	None	10	67
	Maple Grain - Roll Coated	79	0
	TOTAL	**89**	**67**
TOTAL- All Materials		**631**	**127**
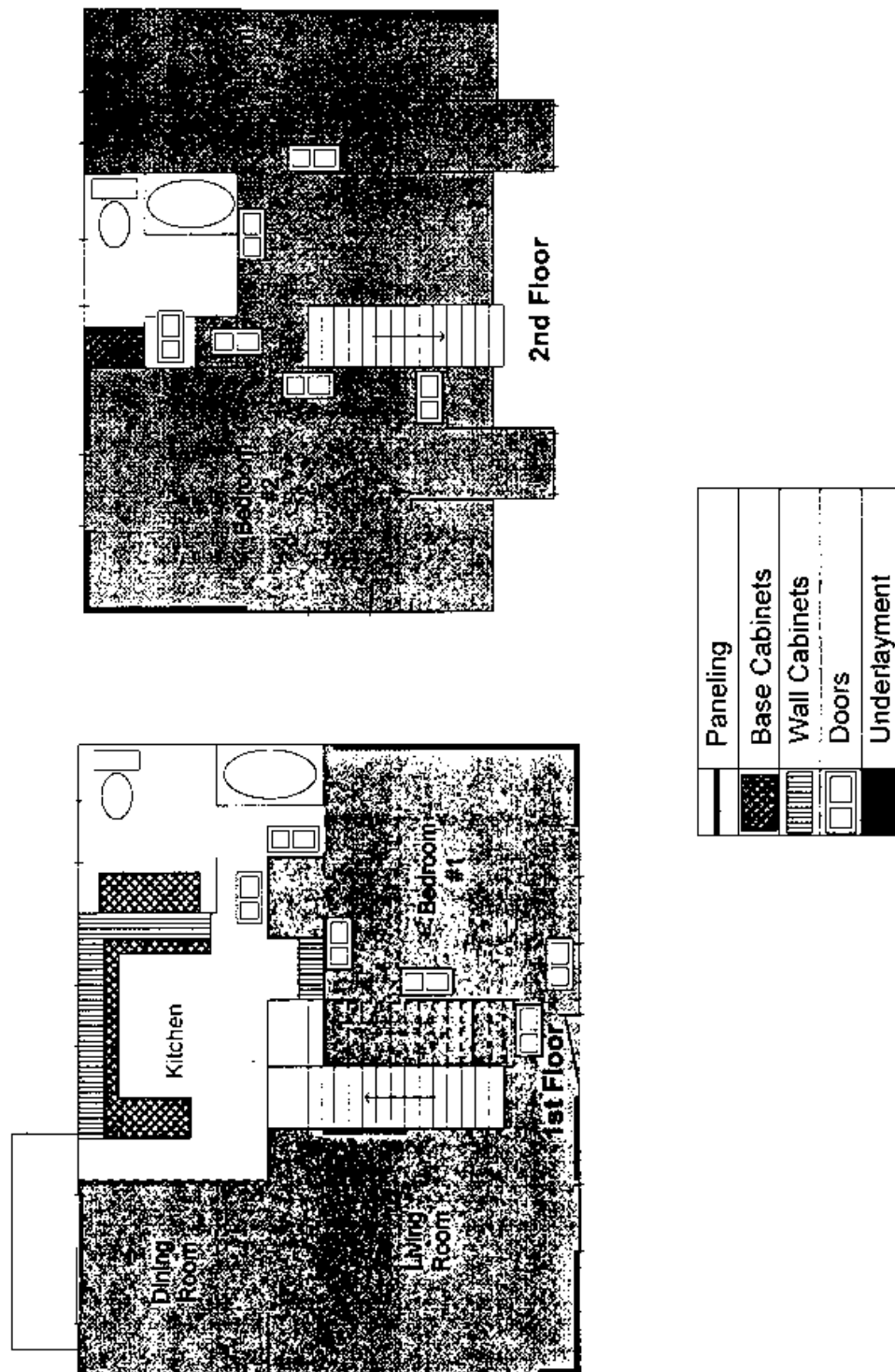
Figure 3-6. Loading Sites for UF-Bonded Wood Products (High Loading).

Paneling	
Base Cabinets	
Wall Cabinets	
Doors	
Underlayment	

3-17

Calculations of cabinet surface area (Table 3-5) were made using the engineering drawings provided by the manufacturer. Ten different combinations of base material and finish coat were found. The solid wood with catalyzed topcoat made up the front frame of the cabinets. The side panels were particleboard with a simulated oak grain on the exterior and a simulated maple grain on the interior. The shelves and drawers of the cabinet were also roll-coated with the maple grain. Door and drawer fronts had white melamine paper with maple-grain-colored PVC edgebanding on all four edges. The toekick of the cabinets was also particleboard, but with a black painted coating. The backs of all cabinets were hardboard with a maple grain coating on the interior and no coating on the exterior. The only locations of unfinished particleboard were the bottom of drawers, three of the four unexposed edges of shelves, bottoms of base cabinets, and back edges of all cabinets. Unfinished solid wood was used as back supports on all base cabinets.

Exposed areas are distinguished by any surface that is not in direct contact with another. This includes areas between cabinets where a 1/4" gap is present and interiors of cabinets. Areas that are not included as exposed (dead air spaces) are the bottoms of base cabinets and the backs of any cabinet that is up against a wall.

3.5.1 Baseline Monitoring

Baseline monitoring was completed in the final week of March 1995. Consecutive 24-hour formaldehyde sample sets were collected using the chromotropic acid method on the 29th and 30th; one 24-hour sample set was collected using the DNPH method on the 29th. Each baseline sample set measured formaldehyde levels in the living room, kitchen, upstairs bedroom, basement, and outdoors. Results are summarized in Section 6.1.

3.5.2 First Loading

The conventional house was loaded over a three day period (April 18-20). Formaldehyde sampling runs were initiated on April 26, May 1, 9, 17, and 22. Each sample set monitored concentrations in the living room, kitchen, upstairs bedroom, and outdoors using both the chromotropic acid and the DNPH methods. The duplicate sampler was repositioned among indoor zones from run to run. The automated monitoring system also collected data for temperature, relative humidity, and air exchange. Results are summarized in Section 6.1.

The underlayment cut pattern was first laid out for minimum cut and installation time, to fit against door frames and around floor vents with maximum crack area of 1/4" at the wall. Based on discussions with industry and the EPA Work Assignment Manager, this was adjusted to an exact fit pattern and then re-adjusted to avoid alignment with the subfloor seams. Underlayment cuts were made at the contractor's shop to minimize sawdust in the home. Final adjustment cuts were marked and made outdoors.

3.5.3 Second Baseline Monitoring

Materials affiliated with the first loading were removed on July 26, 1995. Monitoring for the second baseline period was conducted during the first week of August 1995. One set of 24-hour formaldehyde samples was collected using the DNPH method on August 3. Formaldehyde concentrations were measured in the living room, kitchen, upstairs bedroom, basement and outdoors. Results are summarized in Section 6.1.

3.5.4 Second Loading

The conventional house was loaded at a "high" level over a three-day period (August 7-9, 1995). The "high" loading included new materials identical to those involved with the "medium" level of the first loading--underlayment on the first floor (less the kitchen and bathroom areas) plus kitchen and bathroom cabinets and interior doors--
in addition to underlayment for the second floor and twelve sheets of paneling divided between the first and second floors. NPA also provided twelve small (20 x 40 cm) wallboard samples for exposure in the house to estimate loss rates to this potential sink. Monitoring for the second loading was completed by mid-September 1995. Separate sets of 24-hour formaldehyde samples were collected using the DNPH method on August 16 and 21, and on September 6 and 11. Formaldehyde concentrations were measured in the living room, kitchen, upstairs bedroom, basement and outdoors. Results are summarized in Section 6.1.

3.5.5 Third Baseline

Materials affiliated with the second loading were removed during September 15 and 16, 1995. Monitoring for the third baseline period was conducted during the third week of September 1995. One set of 24-hour formaldehyde samples was collected using the DNPH method on September 22. Formaldehyde concentrations were measured in the living room, kitchen, upstairs bedroom, basement and outdoors. Results are summarized in Section 6.1.

3.5.6 Third Loading

Material installation for the third loading at the conventional house took place over a four-day period (September 25-28, 1995). Materials used for this loading were of the same types and quantities as used for the second loading. Monitoring for the third loading was completed in early November 1995. Formaldehyde concentrations were measured in the living room, kitchen, upstairs bedroom, basement and outdoors. Results are summarized in Section 6.1.

3.5.7 Decommissioning

All equipment was removed upon completion of monitoring at the conventional house, and use of the dwelling reverted to the landlord on November 15, 1995. All materials remaining in the storage facility were transferred to NPA.

4.0 LABORATORY TESTING

Laboratory testing efforts by industry and by GEOMET under this project included large-chamber emissions testing of full-scale specimens, small-chamber evaluations of sink parameters, and barrier effects.

4.1 LARGE CHAMBER EMISSION TESTING

Product characterization tests were conducted at the HPVA Laboratory for underlayment, cabinetry and doors affiliated with the conventional house. Screening tests for underlayment were conducted in the NPA laboratory. All large chamber tests were conducted in general conformance with ASTM E-1333. Chamber conditions were specified at 77 $^{\circ}$F and 50% RH for each test. Nominal loading ratios specified for each product are summarized in Table 4-1.

Table 4-1. Chamber Loading

Product	Loading (ft^2/ft^3)
Particleboard Underlayment	0.13
Hardwood Plywood Wall Paneling	0.29
Kitchen Cabinets	0.13
Doors	0.13

Screening tests for the particleboard underlayment were completed in November 1994. In addition to tests conducted at 0.5 ACH to match the target air exchange rate for the conventional house, tests were conducted at or near 0.25 and 1.0 ACH to help establish the dependence of formaldehyde emissions on the room-air concentration. Chamber tests associated with the first loading were completed in May 1995, tests for the second loading were completed in August 1995, and tests for the third loading were completed in November 1995. Hardwood plywood paneling was not tested under the first loading because this product was not part of that loading in the conventional house. To conserve resources, interior partition doors were not included in the chamber testing associated with the second loading. Results are summarized in Section 6.2.

4.2 SMALL-CHAMBER TESTING

4.2.1 Sink Effects

Theoretical analysis indicates that indoor sinks would have no effect on indoor formaldehyde concentrations at equilibrium; by definition, the mass entering the sink would be equal to the mass leaving the sink when the sink is at equilibrium. Interpretation and modeling of real-world data, however, requires information on the time required to achieve equilibrium and the degree of equilibrium that prevails at any point in the house monitoring schedule. Tests at the GEOMET small-chamber facility were conducted in general conformance with ASTM D 5116 (*Standard Guide for Small-Scale Environmental Chamber Determinations of Organic Emissions from Indoor Materials/Products*) to evaluate the formaldehyde sorption and desorption properties of selected materials. The resultant data provided the means to estimate to- and from-sink rate parameters that could then be applied to indoor air quality models. Separate tests were conducted for carpet and wallboard.

For each test, a constant formaldehyde source was simulated by a calibrated feed stream, and the chamber contained a sample of the material being evaluated. Formaldehyde concentration profiles were measured using the Interscan continuous formaldehyde monitor. Chamber environmental conditions (temperature, relative humidity, airflow) also were monitored. Objectives for these tests included:

- Determine the practical impacts of formaldehyde sorption for carpet and wallboard on the reduction in indoor formaldehyde levels and the time necessary to approach equilibrium.

- Determine the practical impacts on indoor formaldehyde concentration profiles of desorption from a fully-loaded sink condition for wallboard (this assessment was not needed for carpeting because it was replaced with each new loading).

For a given test, chamber conditions were to be maintained at target values of 23 °C, 50% RH, and 1.5 ACH (1.3 L min^{-1}). Initial tests, conducted with the chamber empty, were to establish basic characteristics of the chamber system. First, controlled injection of stable tracer gas verified the completeness of air mixing in each chamber. This was followed by tests involving controlled releases of formaldehyde to establish sink effects (if any) attributable to the chamber lining. The wallboard sample was then evaluated for sorption and desorption. The carpet sample was evaluated only for sorption characteristics because carpet was replaced at the end of each loading in the conventional house testing program.

Initial tests were completed during August 1995 utilizing CO_2 as a tracer to verify the degree of mixing in the GEOMET chamber. Sink tests began during September 1995. The tank gas (certified at 13 ppm formaldehyde) was fed to the chamber through a dilution system to provide a constant feed of approximately 0.2 ppm for sink tests involving carpet and wallboard. A second round of sink tests was conducted in January 1996, this time with a constant feed stream close to 0.1 ppm. Results of these tests are summarized in Section 6.3.

4.2.2 Barrier Effects

The foam padding interposed between the floor (particleboard underlayment or decking) and the carpet could act as a permeable barrier, delaying and/or suppressing formaldehyde emissions in the indoor airspace while changing the overall emission profile. In order to integrate such effects into the model framework, the time constant for the diffusion of formaldehyde through carpet padding should be measured.

Standard methods already in use for determining the penetration and breakthrough of chemical agents in sheetstock materials were to be adopted with minimum modification. For each test, the material specimen would be mounted in a split-cell apparatus. A calibrated formaldehyde source in the lower cell was to supply a constant formaldehyde concentration to one face of the material sample. Formaldehyde concentrations were to be measured periodically in the second cell to determine the breakthrough time and the material-specific formaldehyde diffusion parameter. The primary objective of these tests was to determine the practical impacts of permeation breakthrough for carpet padding on long-term formaldehyde concentration profiles.

Further thinking led to the conclusion that the above strategy would provide only qualitative information on breakthrough time, and might be hindered by insufficient resolution or frequency of sampling to properly pinpoint the time of breakthrough. Instead, a decision was made to address the issue through two related small-chamber tests, the first with only underlayment in the chamber and the second with underlayment covered by carpet and padding.

Overlaying the resultant concentration profiles would provide visual indication of the barrier effect, which could be quantitated by modeling the chamber.

5.0 QUALITY ASSURANCE AND CONTROL

5.1 SYSTEMS AUDITS

The EPA systems audit for GEOMET and NPA laboratory facilities was conducted in December 1994 by the Quality Assurance and Technical Support Division of USEPA/ORD. Summary findings of the GEOMET audit addressed minor revisions to field forms for DNPH, requirements to complete the standard operating procedure (SOP) for chromotropic acid (CA), and a recommendation that analysis of performance evaluation samples be carried out by personnel responsible for routine sample analysis. Other minor corrections to the QA Plan were noted. A few points of NPA procedure were found to require revision. Items included increasing the frequency of calibration for the spectrophotometer and maintenance of control charts. Necessary revisions to affected elements of the QA Plan were handled through appropriate technical memoranda and addenda. There were also reminders to document the preparation of standard solutions and to maintain control charts. A copy of GEOMET's Energy and Environment Division QA Program Plan was provided to the auditor. The EPA systems audit for the HPVA facility was conducted in February 1995. Because HPVA procedures for large-chamber testing are essentially identical to those of NPA, audit findings and recommendations were similar.

5.2 PERFORMANCE AUDITS

Formaldehyde

Performance evaluation samples for both formaldehyde procedures (DNPH and CA) were prepared by the EPA audit laboratory (Mantech Environmental) and shipped to the appropriate project laboratories (GEOMET, NPA, and HPVA for CA, Acurex for DNPH) as well as the project reference laboratory (Battelle). The performance evaluation trials were run in two waves. The initial formaldehyde trial, conducted in late January 1995, involved spiking levels for the chromotropic acid method that proved too high for the analytical range. For the DNPH method, consistently low recovery levels observed in all participating laboratories indicated a need to reappraise the spiking procedure. Both trials were subsequently repeated in February under revised procedures. Agreement among the participating laboratories was within the expectations of data quality objectives. Results are summarized in Tables 5-1 and 5-2.

Table 5-1. Interlaboratory Comparison for Chromotropic Acid.

Spiking Level, $\mu g\ mL^{-1}$	GEOMET Result, $\mu g\ mL^{-1}$ (% recovery)	NPA Result, $\mu g\ mL^{-1}$ (% recovery)	HPVA Result, $\mu g\ mL^{-1}$ (% recovery)	Battelle Result, $\mu g\ mL^{-1}$ (% recovery)
0.01	<0.05	0.01	0.01	<0.13
0.01	<0.05	0.01	0.01	<0.13
0.55	0.59 (107)	0.61 (111)	0.58 (105)	0.60 (109)
0.55	0.59 (107)	0.61 (111)	0.58 (105)	0.60 (109)
1.15	1.20 (104)	1.20 (104)	1.09 (95)	1.24 (108)
1.15	1.20 (104)	1.22 (106)	1.12 (97)	1.23 (107)

Table 5-2. Interlaboratory Comparison for DNPH.

Spiking Level, μg	Acurex Results, μg (% recovery)	Battelle Results, μg (% recovery)

0	<PQL*	0.004
0	<PQL	0.004
20	22.6 (113)	25.9 (130)
20	22.2 (111)	27.1 (136)
40	45.2 (113)	48.6 (122)
40	42.2 (106)	53.4 (134)

* Below Practical Quantitation Limit

As noted in Section 5.3, recovery problems were encountered for the CA measurements at the conventional house, leading to a decision to discontinue these measurements while retaining the DNPH method that was demonstrated to be consistently in control throughout the house-measurement phase of the project. Resource conservation was also a factor in choosing to use only one method, DNPH, for the remainder of the house measurements. Performance audits were also planned for DNPH at the end of field monitoring. However, because of scheduling difficulties with the EPA audit laboratory and the consistent "in control" performance of the DNPH method throughout the field study, a decision was made in consultation with the EPA QA officer to forego the final audit.

SF_6 Tracer Gas

Performance evaluation tests for SF_6, originally scheduled to occur in March 1995, were delayed to repair a faulty valve in the instrument assigned to routine tracer gas monitoring for the project. Instrument repairs were completed during the first half of April. A set of performance evaluation samples, prepared by Battelle, was analyzed on April 27, 1995. Results are summarized in Table 5-3.

Table 5-3. Performance Audit Results for SF_6.

Sample ID	Battelle ppb	GEOMET ppb
Blank	0	0
AA	149	180
BB	641	615

The data quality objectives for SF_6 in the QA plan are specified at ± 10% for both precision and accuracy. The absolute difference between GEOMET and Battelle results is about the same for the low- and high-concentration samples (approximately 30 ppb). The percentage difference is concentration-dependent -- approximately 20 percent for the low-level sample versus 4 percent for the high-level sample.

Continuous Measurements

The EPA performance audit for equipment located at the conventional house was conducted in March 1995. Good agreement was observed between the EPA reference devices and GEOMET instrumentation for temperature, relative humidity, and air velocity. The reference device provided for verification of sampling flow rate was not in the appropriate range to audit this parameter.

Large-Chamber Testing

Battelle staff conducted a large chamber test for formaldehyde emissions from particleboard underlayment, to confirm levels reported from industry tests. Initial poor agreement was ultimately traced to an error in flow calibration for Battelle's continuous formaldehyde monitor. A repeat test indicated good correspondence with industry results.

5.3 QA SPIKES AND BLANKS

Field sample sets for chromotropic acid and DNPH include QA spikes prepared by the reference laboratory (Battelle). As shown in Table 5-4, the level of agreement between Acurex and Battelle for the DNPH spikes was quite good (>90% recovery). For chromotropic acid, however, the GEOMET results were in reasonable agreement for Run 1 of the first loading (110% recovery) but showed a rising trend for subsequent samples. This trend was also mirrored in the relative disagreement between the chromotropic acid and DNPH measurements at the conventional house. Possible causes and strategies for identifying remedies are discussed in Section 5.4.

Table 5-4. Results for Quality Assurance Spikes.

Sample Type	Spiking Level, μg	GEOMET Results, μg (% Recovery)		Acurex Results, μg (% Recovery)	
Chromotropic Acid					
Loading 1 Run 1	15.5	17.0	(110)		
Loading 1 Run 2	15.5	19.7	(127)		
Loading 1 Run 3	8.3	12.7	(153)		
Loading 1 Run 4	8.3	14.3	(172)		
DNPH					
Loading 1 Runs 1&2	22.2			20.0	(90)
Loading 1 Run 3	11.1			10.9	(98)
Loading 1 Run 4	11.1			10.8	(97)
Loading 2 Runs 1&2	22.0			19.9	(90)
Loading 2 Runs 3&4	22.0			20.9	(95)
Loading 3 Runs 1&2	11.1			11.7	(105)
Loading 3 Runs 3&4	11.1			12.8	(115)

5.4 PROBLEMS AND THEIR RESOLUTION

Once a problem is identified, resolution ideally pursues: (1) underlying causes, (2) remedies, and (3) means of correcting affected data. Problems encountered in the course of the pilot study are discussed below in terms of measurement systems and field operations.

5.4.1 Measurement Systems

TRACER GAS ANALYZER

Problem: In March 1995, the sample valve in the SF_6 tracer gas analyzer failed.

Causes: The valve had been in continuous use for a number of years and was considered to be near the end of normal service life.

Remedies: The unit was returned to the manufacturer for repair.

Data Corrections: No data corrections were necessary. The repair cycle did not delay baseline tests since the ventilation rates had already been measured and the heat recovery ventilator (HRV) setting calibrated. Analysis of the performance evaluation samples was, however, delayed until the unit was returned to service, requiring that EPA's auditor send a second set of performance evaluation samples for SF_6.

INTERSCAN CONTINUOUS ANALYZER

Problem: Significant drift in the resolution of the Interscan continuous analyzer was observed over the course of several months of operation (see Figure 5-1). Resolution declined to unacceptable levels after about 6 weeks of use.

Causes: Conversations with the manufacturer indicated that the life of the electrochemical cell should be on the order of three months. Following replacement of the electrochemical cell on July 25, 1995, acceptable resolution was observed. By August 29, 1995 (35 days later), however, adjustments were required to increase resolution. Although this adjustment improved resolution, the instrument response soon degraded.

Remedies: Maintenance schedules were amended to require replacement of the electrochemical cell after about one month of service.

Data Corrections: The data management system accounts for trends in calibration factors directly; data collected during periods of unacceptable response were flagged.

DNPH METHOD

Problem: As noted earlier, initial performance evaluation samples prepared by the EPA audit laboratory resulted in apparently low recoveries for all laboratories participating in the interlaboratory comparison.
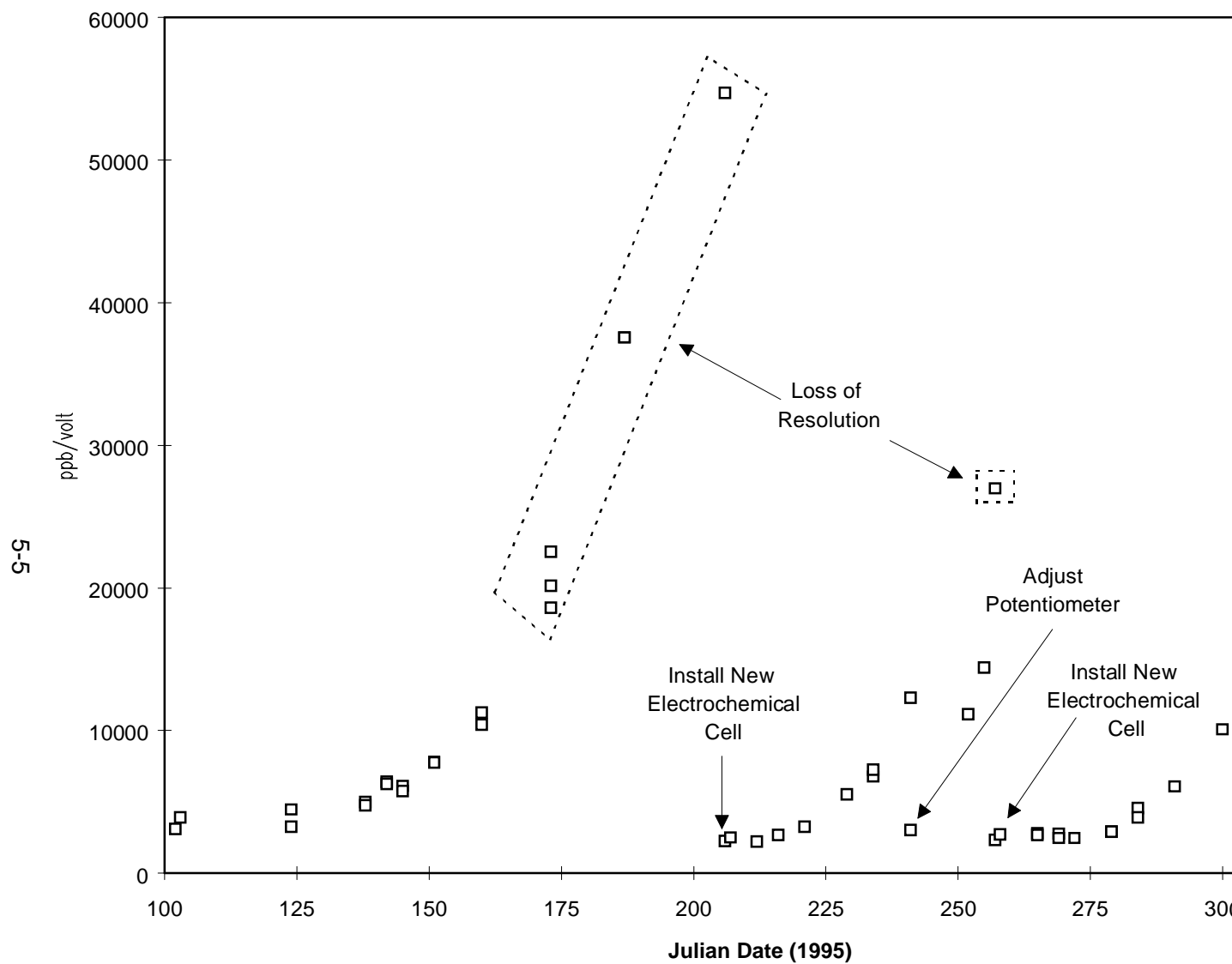
Figure 5-1. Calibration Trends for Interscan Analyzer.

Causes: The low recoveries were found to be traceable to the relatively small volume of spiking solution utilized in the procedure.

Remedies: Based on conversations with the manufacturer of the DNPH cartridges and verification studies by the EPA audit laboratory, the spiking volume was increased and anticipated recoveries were achieved.

Data Corrections: No data corrections were required. This problem delayed the baseline monitoring at the conventional house by about one month.

CHROMOTROPIC ACID METHOD

Problem: As noted earlier (Section 5.3), the chromotropic acid data indicated apparent increasing recoveries from analyses of spiked samples.

Causes: No anomalous factors were uncovered during initial review of the laboratory data. All calibration curves met statistical specifications of linearity, and reagents had been properly stored and handled. The absorbances for all blank samples were acceptably low, ruling out laboratory contamination. The monitoring scene was not considered to be a "dusty environment," so sample lines do not contain a filter at the inlet. If formaldehyde-bearing sawdust were present, particles could have affected the chromotropic acid results without affecting DNPH measurements (this would explain the lack of correspondence between the two methods, but would not explain differences between GEOMET and the reference laboratory). Colocated samples with and without inlet filters agreed to within a few percent, ruling out this prospect.

In adjusting the original NIOSH procedure to meet the analytical range for the project, the strength of the chromotropic acid reagent was reduced from 1% to ½% to accommodate smaller sample aliquots in use. Further review indicated that incomplete reaction between the reagent and the formaldehyde is the cause of the data trend. The calibration standards form a relatively small group that is analyzed first. The field samples (including the QA spikes) form a larger group. Because the procedure queues the samples for analysis based on qualitative intensity of the chromophore, higher concentration samples are analyzed at the end of the queue, giving more time for color development if the lower abundance of the chromotropic acid reagent is critical. For a large sample batch, the time extension can approach one hour.

Remedies: All reagents were replaced, and the procedure was revised to adjust the chromotropic acid strength to 1%. The procedure also was revised to require insertion of samples derived from the solution set prepared for the calibration curve into the analytical queue so that age effects, if they occur again, could be recognized directly. These revisions were appended to the SOP as a memorandum, and incorporation of formal changes within the body of text were scheduled for the next review cycle for the SOP. It was decided that acceptable recovery for at least one QA spiking test should be achieved before declaring a return to control conditions. As discussed in Section 5.2, a decision was ultimately made to drop the chromotropic method while retaining the DNPH procedure.

Data Corrections: Cost-effective solutions focused on recalculating the calibration curves for the affected data in light of the QA spikes and colocated DNPH data, and applying appropriate quality flags to the corrected data values.

5.4.2 Field Operations

CONVENTIONAL HOUSE

Problem: Beginning in late December 1994, the operation of the outdoor compressor unit for the heat pump at the conventional home was found to occasionally stick in a "lock-out" mode.

Causes: According to the installation contractor, the problem was traced to failure of the auto change-over thermostat installed for the project. This type of thermostat was selected to automatically switch between heating and cooling modes to maintain indoor temperature at the setpoint regardless of season.

Remedies: Because the system was under warranty, repairs were accomplished through the installation contractor. The original (manual change-over) thermostat was installed to control the HAC system until a replacement was obtained. Subsequent observations indicated that the HAC system was then working properly. Prior to receiving the replacement auto change-over thermostat, however, the heat pump again failed and would not restart. Investigation by on-site technicians revealed a more serious problem of burned insulation on the refrigerant lines. The installation contractor eventually determined that the problem was a defective expansion valve, ordered the replacement part and completed the warranty repair. The HAC system was returned to full service in January 1995.

Data Corrections: No data corrections were required.

Problem: The moisture-generation system deployed in the house enabled us to maintain the house near design conditions (50% relative humidity) when the indoor humidity would otherwise be too low, as often occurs during the heating season. As monitoring associated with the first loading of the house progressed into late spring, it became obvious that further controls would be needed to prevent high humidity levels indoors during the summer.

Causes: Cooling season operation of the HAC system would remove a large portion of the excess water vapor. Additional dehumidification would be needed, however, when the system was idle because high-humidity air would continue to enter the house through air exchange.

Remedies: In late May 1995, a portable console dehumidifier with a 40-pint-per-day removal capacity was added to the conventional house. The humidistat control was set to prevent relative humidity from exceeding 60 percent, and water removed from the air was diverted to the sanitary sewer.

Data Corrections: Monitored formaldehyde concentrations were adjusted for monitored humidity levels during each sampling period. Adjustment procedures and results for DNPH measurements are given in Appendix B.

Miscellaneous Problems at the Conventional House: The solar pyranometer at the conventional house site was vandalized in May 1995; a replacement was installed in June. Industry representatives periodically visited the conventional house to collect air samples in conjunction with scheduled sampling for independent formaldehyde analysis (shadow testing). Rather than augment field staff on these occasions, it was decided that the EPA WAM would be in attendance to establish security of the site.

STORAGE FACILITY

Problem: Observations of the temperature during the cooling season (by a max/min thermometer) indicated that temperatures would regularly exceed 85 °F.

Causes: Environmental conditions in the storage facility were maintained by a HAC system serving more than one tenant. The thermostat controlling the storage facility was located in the office portion of the warehouse.

Remedies: Two options were identified. Under option 1, the HAC system could be reconfigured to serve the storage facility independently. Under option 2, the entire facility (warehouse and office of the prime tenant plus the project storage facility) could be maintained at design conditions. Neither remedy was considered cost-effective in the light of the short-term lease (option 1) or increased operating costs (option 2).

Data Corrections: No data corrections were practical. It is believed that the combination of wrapping and stacking the products to be tested minimized the effect of temperature on emissions of the stored materials.

6.0 MONITORING RESULTS

This section summarizes data collected for conventional house testing (Section 6.1), large-chamber emission testing (Section 6.2), and small-chamber sink testing (Section 6.3).

6.1 CONVENTIONAL HOUSE TESTING

Results are shown below for each monitoring episode (including baselines for each loading) at the conventional house. The monitoring results include 24-hour averages for formaldehyde (DNPH method), temperature, relative humidity and air exchange. Results for the chromotropic acid method used for the first loading are given in Appendix A. The DNPH results for formaldehyde are as-monitored values, that is, not adjusted for recovery because recoveries were in the relatively narrow range from 90 to 100 percent. Adjustment of the DNPH-measured concentrations to a common temperature and relative humidity are presented in Appendix B. Parallel testing procedures used by NPA during selected sampling events (CA method) are described in Appendix C. Results for passive samplers deployed over 5-day periods are presented and evaluated, in relation to DNPH results, in Appendix D.

Following the presentation of results below for each monitoring episode associated with each loading of the conventional house, results are presented separately for continuously monitored parameters (formaldehyde, temperature and humidity) in Section 6.1.7, after which the conventional house testing results are summarized and discussed in Section 6.1.8.

6.1.1 First Baseline

Monitoring results for the baseline period (March 30-31, 1995), prior to the first loading of the conventional house, are summarized in Table 6-1. Formaldehyde levels in the house were relatively low, close to 10 ppb as measured with the DNPH method. Indoor temperatures were maintained within ±1 °F of the target (75 °F) on the first and second floors. The indoor humidity level was relatively low (below 25 percent) because the moisture-generation system was just coming on line at that time. The air exchange rate (0.5 ACH) was measured using PFTs alone because a faulty sample valve in the SF_6 analyzer had been sent out for repair.

Table 6-1. Monitoring Results for First Baseline

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	9.1	75.7	22.8
Kitchen	9.8	75.8	
Bedroom	9.5	74.0	24.4
Basement	9.1	63.4	
Ambient	1.3	49.0	55.2

Air Exchange Rate: 0.50 ACH (PFT Method)
Start: 03/30/95 @ 1453
End: 03/31/95 @ 1453

6.1.2 First Loading

The conventional house was loaded with UF-bonded wood products on April 18-19, 1995. Results for the first run, starting seven days after completion of loading (April 26), are given in Table 6-2. The DNPH results indicated indoor formaldehyde levels approaching 30 ppb on the first floor (kitchen and living room) and 20 ppb on the second floor (bedroom). The precision, based on duplicates in the kitchen, was close to ±5 percent (ratio of the standard deviation to the mean for the duplicate set). Temperature was maintained between 73 and 74 °F with indoor relative humidity between 40 and 45 percent. The whole-house air exchange rate, as measured by the tracer-dilution method using SF_6, was 0.44 ACH as compared to 0.54 using the PFT method.

Table 6-2. Monitoring Results For Loading 1, Run 1 (Day 7)

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	27.5	73.8	43.2
Kitchen	29.9	73.4	
Kitchen Duplicate	27.9		
Bedroom	20.1	73.2	41.0
Basement		68.5	
Ambient	1.0	56.9	60.2

Air Exchange Rate: 0.44 ACH (SF_6); 0.54 ACH (PFT)
Start: 04/26/95 @ 1216
End: 04/27/95 @ 1234

Run 2 measurements for the first loading (Table 6-3) were started 12 days after loading (May 1, 1995). Formaldehyde measurements using the DNPH method were close to 30 ppb upstairs as well as downstairs, and were above 25 ppb in the basement. As with run 1, indoor temperatures were between 73 and 74 °F. RH indoors was close to 45 percent. The whole-

house air exchange rate, as measured by the tracer-dilution method using SF_6, was 0.44 ACH as compared to 0.54 ACH using the PFT method.

Table 6-3. Monitoring Results For Loading 1, Run 2 (Day 12)

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	29.6	73.8	46.2
Kitchen	31.3	73.6	
Bedroom	29.9	73.4	43.2
Basement	26.5	66.7	
Ambient	7.0	52.4	76.8

Air Exchange Rate: 0.44 ACH (SF_6); 0.54 ACH (PFT)
Start: 05/01/95 @ 1228
End: 05/02/95 @ 1250

Additional formaldehyde samples were collected between run 2 and run 3. However, these were restricted to the CA method, to conserve resources. Results are given in Appendix A.

Results for run 3 of the first loading, which started 28 days after loading (May 17, 1995), are shown in Table 6-4. Formaldehyde measurements using the DNPH method were about 10 ppb higher than for runs 1 and 2, both upstairs and downstairs. Outdoor humidity levels were very high during this run, resulting in above 60 percent RH indoors. A dehumidifier had been added to the conventional house for this run. The whole-house air exchange rate, as measured by the tracer-dilution method using SF_6, was 0.40 ACH as compared to 0.54 ACH using the PFT method.

Table 6-4. Monitoring Results For Loading 1, Run 3 (Day 28)

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	41.7	75.1	63.1
Kitchen	43.9	75.0	
Bedroom	36.3	74.9	60.1
Basement	28.2	71.1	
Ambient	2.1	69.6	93.9

Air Exchange Rate: 0.40 ACH (SF$_6$); 0.54 (PFT)
Start: 05/17/95 @ 1159
End: 05/18/95 @ 1213

Results for the DNPH method under run 4 (Table 6-5), starting 33 days after loading (May 22, 1995), were slightly lower than for run 3, indicating that the formaldehyde concentrations in the conventional house may have reached a secular equilibrium within 28 days after loading. (This apparent trend can be seen more clearly from the summary of DNPH results across the four runs in Table 6-6.) The precision, based on duplicates in the living room, was close to ±1percent. The indoor RH level was at 50 percent.   The whole-house air exchange rate, as measured by the tracer-dilution method using SF$_6$, was 0.40 ACH as compared to 0.57 ACH using the PFT method.

Table 6-5. Monitoring Results For Loading 1, Run 4 (Day 33)

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	36.8	75.5	50.4
LR Duplicate	37.1		
Kitchen	39.4	74.8	
Bedroom	31.1	73.4	49.8
Basement		73.1	
Ambient	1.7	66.0	60.6

Air Exchange Rate: 0.40 ACH (SF$_6$); 0.57 ACH (PFTs)
Start: 05/22/95 @ 1333
End: 05/23/95 @ 1358

Table 6-6. Summary of Monitoring Results for the DNPH Method for Loading 1

Location	Formaldehyde Concentration, ppb			
	Run 1 (7)*	Run 2 (12)	Run 3 (28)	Run 4 (33)
Living Room	27.5	29.6	41.7	36.8
Kitchen	29.9	31.3	43.9	39.4
Bedroom	20.1	29.9	36.3	31.1
Basement	--	26.5	28.2	--
Ambient	1.0	7.0	2.1	1.7

*( ) indicates number of days after loading

Although it was apparent from the collective evidence provided by runs 1-4 that the house may have reached a secular equilibrium within one month after the first loading, additional DNPH samples were collected 50 days (June 8-9) and 78 days (July 6-7) after loading as a verification step. These runs were labeled B and C, respectively. As shown in Table 6-7, the run B results appear to be higher than for runs 3 and 4 but the indoor humidity level was substantially elevated during run B. The run C results, with RH levels between 55 and 60 percent, were essentially identical to those from run 4.

Table 6-7. Results for Supplemental Sampling for Loading 1

Location	DNPH Results, ppb	Temperature, °F	Relative Humidity, %
Loading 1, Run B (day 50)			
Living Room	51.3	76.6	71.2
Kitchen	46.5	76.0	
Bedroom	45.1	77.4	62.5
Basement	22.5	76.1	
Ambient	1.6	75.9	73.7
Loading 1, Run C (day 78)			
Living Room	37.4	75.4	58.0
Kitchen	38.1	73.1	
Bedroom	32.4	73.9	56.0
Basement	29.5	75.1	
Ambient	1.8	76.3	89.0

6.1.3 Second Baseline

Results for the second baseline period (August 3-4, 1995), prior to the second loading of the conventional house), are summarized in Table 6-8. Formaldehyde levels in the house were between 20 and 25 ppb as measured with the DNPH method.   Indoor temperatures were generally within ±1 °F of the target (75 °F) on the first and second floors, and the indoor humidity level was between 50 and 55 percent. The air exchange rate, as measured by the SF_6 method, was 0.39 ACH. PFT measurements were not conducted for the second baseline case.

The second baseline, with formaldehyde levels in the vicinity of 25 ppb, was considerably higher than the first baseline (close to 10 ppb). This difference may be due partly to low humidity levels at the first baseline, to re-emitting sinks that were partly or fully loaded at the second baseline as a result of the first loading of the house, or to some combination of these two factors.

Table 6-8. Monitoring Results for Second Baseline

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	23.0	75.2	54.5
Kitchen	23.7	73.1	
Bedroom	22.1	74.3	52.3
Basement	25.7	77.0	
Ambient	2.8	84.4	80.3

Air Exchange Rate: 0.39 ACH (SF_6)
Start: 08/03/95 @ 1200
End: 08/04/95 @ 1211

6.1.4 Second Loading

The conventional house was loaded with UF-bonded wood products on August 7-9, 1995. This "high" loading included new materials identical to those used in the "medium" first loading (underlayment on the first floor -- less the kitchen and bathroom areas -- plus kitchen and bathroom cabinets and interior doors) as well as underlayment for the second floor and twelve sheets of paneling. Results for the first run, starting seven days after completion of the second loading (August 16), are given in Table 6-9. The DNPH results indicated indoor formaldehyde levels approaching 60 ppb on the first and second floors and 40 ppb in the basement. The precision, based on duplicates in the bedroom, was close to ±2% (ratio of the standard deviation to the mean for the duplicate set). Temperature was maintained near the 75 °F setpoint, and indoor relative humidity was between 55 and 60 percent. The whole-house air exchange rate, as measured by the tracer-dilution method using SF_6, was 0.38 ACH as compared to 0.61 ACH using the PFT method.

Table 6-9. Monitoring Results For Loading 2, Run 1 (Day 7)

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %

Living Room	60.1	75.3	57.1
Kitchen	60.8	73.5	
Bedroom	60.5	74.5	55.5
Bedroom Duplicate	59.2		
Basement	39.7	76.2	
Ambient	2.9	81.5	88.2

Air Exchange Rate: 0.38 ACH (SF$_6$); 0.61 ACH (PFT)
Start: 08/16/95 @1200
End: 08/17/95 @ 1158

Results for the second run, which started on August 21, are given in Table 6-10. The DNPH results again indicated indoor formaldehyde levels in the vicinity of 60 ppb on the first and second floors (but slightly lower than the first run) and 40 ppb in the basement. The precision, based on duplicates in the living room, was close to ±2%. Temperature was maintained between 73 and 75 °F with indoor relative humidity close to 50 percent. The whole-house air exchange rate, as measured by the tracer-dilution method using SF$_6$, was 0.38 ACH as compared to 0.71 ACH using the PFT method.

Table 6-10. Monitoring Results For Loading 2, Run 2 (Day 12)

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	55.8	75.1	50.9
LR Duplicate	54.3		
Kitchen	58.1	73.4	
Bedroom	54.7	74.3	49.3
Basement	40.0	75.4	
Ambient	2.3	80.1	74.1

Air Exchange Rate: 0.38 ACH (SF$_6$); 0.71 ACH (PFT)
Start: 08/21/95 @1148
End: 08/22/95 @ 1149

Results for the third run, which started on September 6, are given in Table 6-11. The DNPH results indicated that indoor formaldehyde levels were lower than in the previous run, in the vicinity of 50 ppb on the first and second floors and 40 ppb in the basement. The precision, based on duplicates in the kitchen, was close to ±2%. Temperature was maintained between 73 and 75 °F with indoor relative humidity close to 50 percent downstairs and 45 percent upstairs. The whole-house air exchange rate, as measured by the tracer-dilution method using SF_6, was 0.36 ACH as compared to 0.59 ACH using the PFT method.

Table 6-11. Monitoring Results For Loading 2, Run 3 (Day 28)

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	46.7	74.4	50.7
Kitchen	48.5	73.9	
Kitchen Duplicate	50.1		
Bedroom	53.3	75.6	43.8
Basement	38.0	75.7	
Ambient	1.4	75.4	71.2

Air Exchange Rate: 0.36 ACH (SF_6); 0.59 ACH (PFT)
Start: 09/06/95 @1153
End: 09/07/95 @ 1150

Results for the fourth run, which started on September 11, are given in Table 6-12. The DNPH results indicated indoor formaldehyde levels in the vicinity of 30 to 40 ppb, reinforcing the trend observed from the third run. The precision, based on duplicates in the basement, was in the range of ±10%. Temperature was maintained between 73 and   74 °F with indoor relative humidity close to 50 percent downstairs and 45 percent upstairs. The whole-house air exchange rate, as measured by the tracer-dilution method using SF_6, was 0.39 ACH as compared to 0.60 ACH using the PFT method. The summary of DNPH results in Table 6-13 shows clearly that concentrations measured during runs 3 and 4 were lower than those measured during runs 1 and 2.

Table 6-12. Monitoring Results For Loading 2, Run 4 (Day 33)

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	39.0	73.4	51.6
Kitchen	40.8	73.2	
Bedroom	48.1	73.2	43.2
Basement	30.7	73.6	
Basement Duplicate	26.3		
Ambient	0.9	63.1	71.6

Air Exchange Rate: 0.39 ACH (SF$_6$); 0.60 ACH (PFT)
Start: 09/11/95 @1200
End: 09/12/95 @ 1200

Table 6-13. Summary of Monitoring Results for the DNPH Method for Loading 2

Location	Formaldehyde Concentration, ppb			
	Run 1 (7)*	Run 2 (12)	Run 3 (28)	Run 4 (33)
Living Room	60.1	55.8	46.7	39.0
Kitchen	60.8	58.1	48.5	40.8
Bedroom	60.5	54.7	53.3	48.1
Basement	39.7	40.0	38.0	30.7
Ambient	2.9	2.3	1.4	0.9

*( ) indicates number of days after loading

6.1.5 Third Baseline

Results for the third baseline period (September 22-23, 1995), prior to the third loading of the conventional house, are summarized in Table 6-14. Like the second baseline period, formaldehyde levels in the house were near 25 ppb as measured with the DNPH method. Indoor temperatures were about two degrees lower than the target of 75 °F. The indoor humidity level was about 55 percent downstairs and 45 percent upstairs. The air exchange rate, as measured by the SF$_6$ method, was 0.39 ACH. PFT measurements were not conducted for the third baseline case.

Table 6-14. Monitoring Results for Third Baseline

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	26.0	73.3	54.9
Kitchen	25.8	72.8	
Bedroom	27.7	73.3	44.3
Basement	25.0	73.3	
Ambient	<1.2	61.4	85.0

Air Exchange Rate: 0.39 ACH (SF_6)
Start: 09/22/95 @ 1330
End: 09/23/95 @ 1325

6.1.6 Third Loading

The conventional house was loaded with UF-bonded wood products on September 25-28, 1995. The "high" loading included new materials identical to those used in the "medium" first loading (underlayment on the first floor -- less the kitchen and bathroom areas -- plus kitchen and bathroom cabinets and interior doors) as well as underlayment for the second floor and twelve sheets of paneling. Results for the first run, which started on October 10, are given in Table 6-15. The DNPH results indicated indoor formaldehyde levels of 65 to 75 ppb on the first and second floors and 40 ppb in the basement. The precision, based on duplicates in the kitchen, was in the range of ±10% (ratio of the standard deviation to the mean for the duplicate set). Indoor temperatures were about two degrees below the target of 75 °F, and indoor relative humidity was above 60 percent both upstairs and downstairs. The whole-house air exchange rate, as measured by the tracer-dilution method using SF_6, was 0.39 ACH as compared to 0.69 ACH using the PFT method.

Table 6-15. Monitoring Results For Loading 3, Run 1 (Day 7)

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	71.9	72.5	62.7
Kitchen	76.1	73.2	
Kitchen Duplicate	66.7		
Bedroom	65.6	72.5	65.3
Basement	42.6	73.6	
Ambient	1.1	76.1	95.1

Air Exchange Rate: 0.39 ACH (SF_6); 0.69 ACH (PFT)
Start: 10/05/95 @1250
End: 10/06/95 @ 1251

Results for the second run, which started on October 10, are given in Table 6-16. The DNPH results indicated indoor formaldehyde levels in the vicinity of 55 ppb on the first and

second floors and 40 ppb in the basement. The precision, based on duplicates in the living room, was close to ±8%. Temperature was maintained around 72 °F with indoor relative humidity slightly below 50 percent. The whole-house air exchange rate, as measured by the tracer-dilution method using SF_6, was 0.36 ACH as compared to 0.64 ACH using the PFT method.

Table 6-16. Monitoring Results For Loading 3, Run 2 (Day 12)

Location	Formaldehyde (DNPH), ppb	Temperature, °F	Relative Humidity, %
Living Room	53.8	72.3	49.7
LR Duplicate	48.2		
Kitchen	55.2	72.4	
Bedroom	54.7	72.0	47.1
Basement	29.9	70.7	
Ambient	1.1	60.3	86.7

Air Exchange Rate: 0.36 ACH (SF_6); 0.64 ACH (PFT)
Start: 10/10/95 @1110
End: 10/11/95 @ 1124

Results for the third run, which started on October 26, are given in Table 6-17. The DNPH results indicated that indoor formaldehyde levels were lower than in the previous run, in the vicinity of 40 to 45 ppb on the first and second floors and 20 ppb in the basement. The precision, based on duplicates in the bedroom, was in the range of ±1%. Temperature was maintained near 75 °F with indoor relative humidity close to 45 percent. The whole-house air exchange rate, as measured by the tracer-dilution method using SF_6, was 0.42 ACH as compared to 0.62 ACH using the PFT method.

Table 6-17. Monitoring Results For Loading 3, Run 3 (Day 28)

Location	Formaldehyde (DNPH), ppb	Temperature, $^\circ$F	Relative Humidity, %
Living Room	43.2	74.4	43.8
Kitchen	46.2	73.9	
Bedroom	39.5	75.6	43.7
Bedroom Duplicate	39.1		
Basement	20.3	75.7	
Ambient	1.1	75.4	71.2

Air Exchange Rate: 0.42 ACH (SF_6); 0.62 (PFT)
Start: 10/26/95 @1204
End: 10/27/95 @ 1204

Results for the fourth run, which started on October 31, are given in Table 6-18. The DNPH results indicated indoor formaldehyde levels in the vicinity of 40 to 45 ppb on the first and second floors, reinforcing the trend observed from the third run. The precision, based on duplicates in the basement, was close to ±3%. Temperature was maintained near 72 $^\circ$F on the first floor with indoor relative humidity close to 45 percent. The whole-house air exchange rate, as measured by the tracer-dilution method using SF_6, was 0.35 ACH as compared to 0.53 ACH using the PFT method. The summary of DNPH results in Table 6-19 shows clearly that, as with the second loading, concentrations measured during runs 3 and 4 were lower than those measured during runs 1 and 2.

Table 6-18. Monitoring Results For Loading 3, Run 4 (Day 33)

Location	Formaldehyde (DNPH), ppb	Temperature, $^\circ$F	Relative Humidity, %
Living Room	42.3	71.7	46.1
Kitchen	40.4	71.9	
Bedroom	44.1	70.7	44.9
Basement	22.8	66.9	
Basement Duplicate	23.8		
Ambient	1.4	71.7	88.8

Air Exchange Rate: 0.35 ACH (SF_6); 0.53 ACH (PFT)
Start: 10/31/95 @1220
End: 11/01/95 @ 1251

Table 6-19. Summary of Monitoring Results for the DNPH Method for Loading 3

Location	Formaldehyde Concentration, ppb			
	Run 1 (7)*	Run 2 (12)	Run 3 (28)	Run 4 (33)
Living Room	71.9	53.8	43.2	42.3
Kitchen	76.1	55.2	46.2	40.4
Bedroom	65.6	54.7	39.5	44.1
Basement	42.6	29.9	20.3	22.8
Ambient	<1.0	1.1	1.1	1.4

*( ) indicates number of days after loading

6.1.7 Continuous Monitoring of Formaldehyde, Temperature and Humidity

The continuous formaldehyde analyzer is subject to variable zero drift and to significant span drift (i.e., loss of resolution over time). To quantitate the variable zero drift, the instrument was automatically "zeroed" through the DAS at three-hour intervals. The span drift, although significant, is largely linear over time. To quantitate span drift the instrument was spanned at approximately weekly intervals.

Calibration of the resultant data is a cumbersome process, requiring estimation of (assumed) linear span drift and consideration of the zero response every three hours. The instrument has been found to respond to carbon dioxide (CO_2) and, to a lesser extent, to sunlight (and associated warning of the instrument). Figure 6-1 shows an example of the instrument response to CO_2, which was introduced from a known source at concentrations of 1,000 and 2,000 ppm (with no formaldehyde in the source). As shown in the figure, these levels of CO_2 caused a negative instrument response on the order of 150 ppb. The conventional house was unoccupied during most of the study period, with the general exception of technician visits for loading/unloading or for sample deployment/retrieval, and therefore typically experienced ambient CO_2 levels assumed to be on the order of 350 ppm.

The plots in Figure 6-2 provide an example of the response to increased instrument temperature due to sunlight over a four-day period beginning at midnight on Julian day 127 (May 7, 1995). Solar radiation data shown in the upper plot indicate that the first two days were sunny, the third day was partially cloudy, and the fourth day had significant cloud cover. The formaldehyde measurements, shown in the lower plot, have brief spikes around midnight that cannot readily be explained; the important point, however, is the apparent response to sunlight. The formaldehyde levels recorded by the analyzer began to rise around 7:30 a.m. on the first two days and to a lesser extent on the third day, but not on the fourth day. The time of increasing concentration corresponds to the rising sun shining through windows into the living room where the analyzer was located.
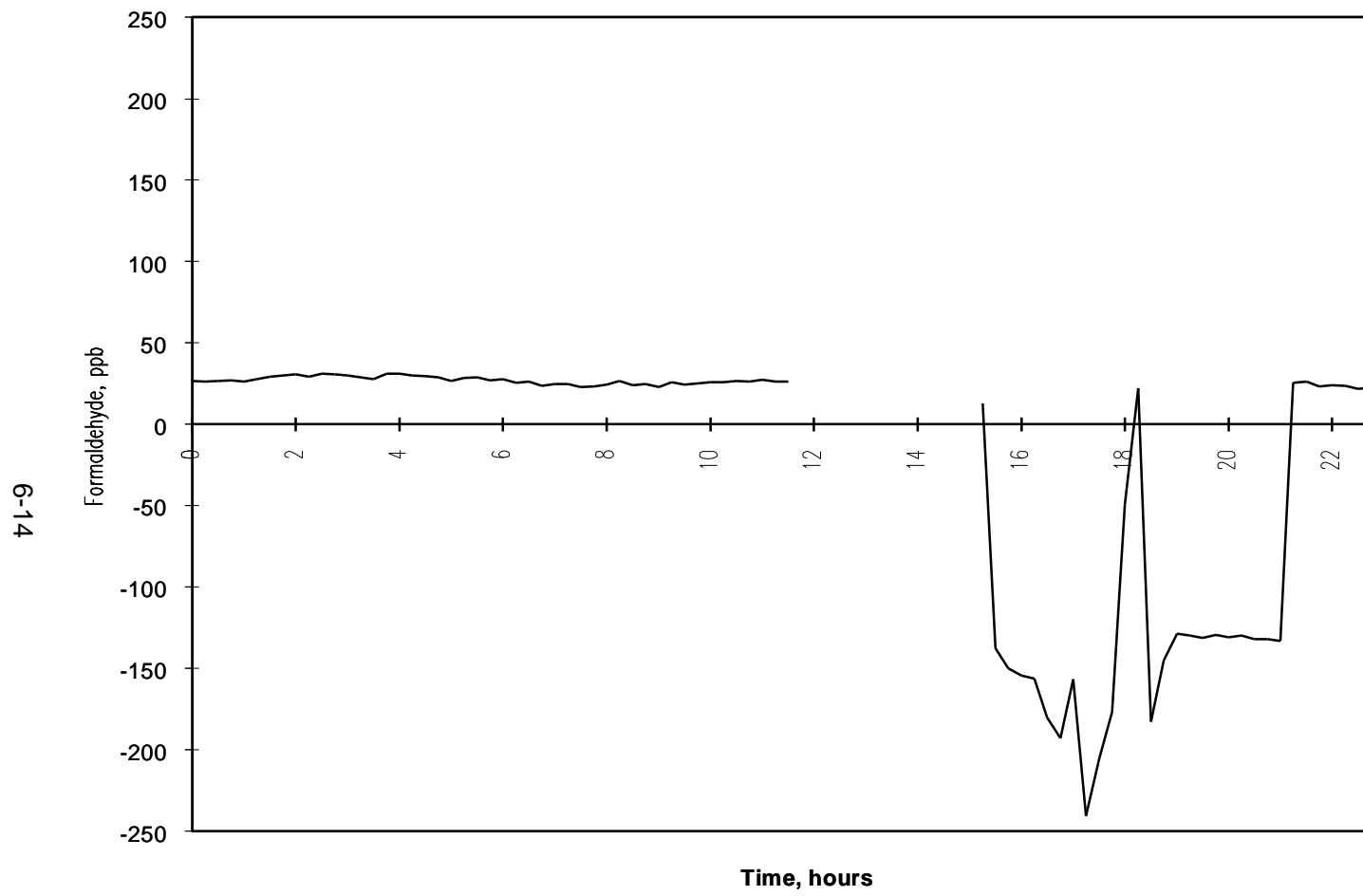
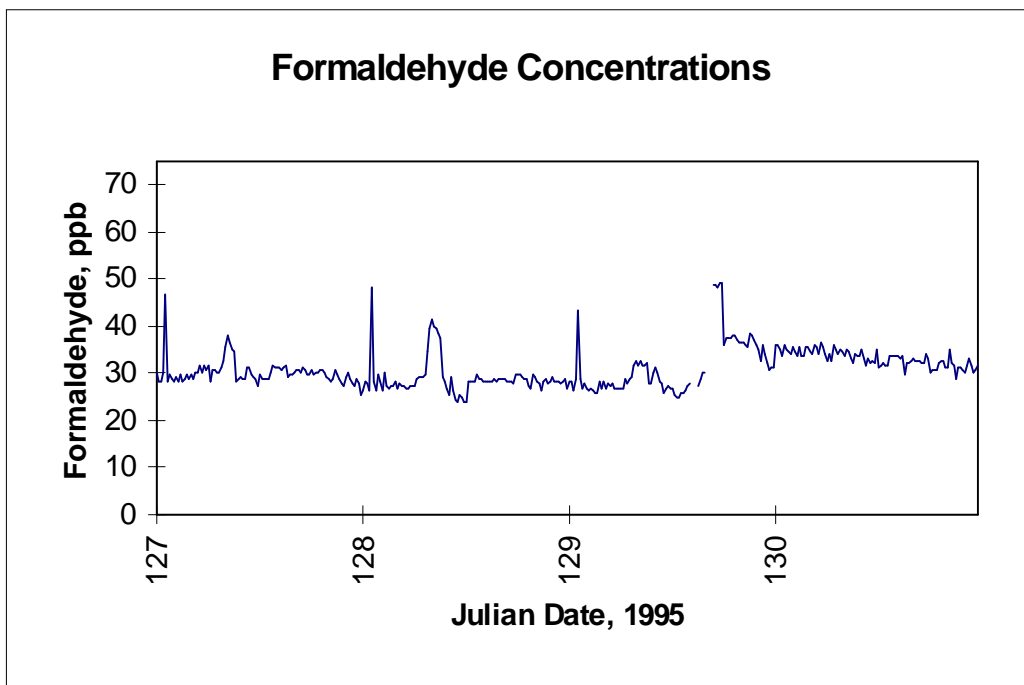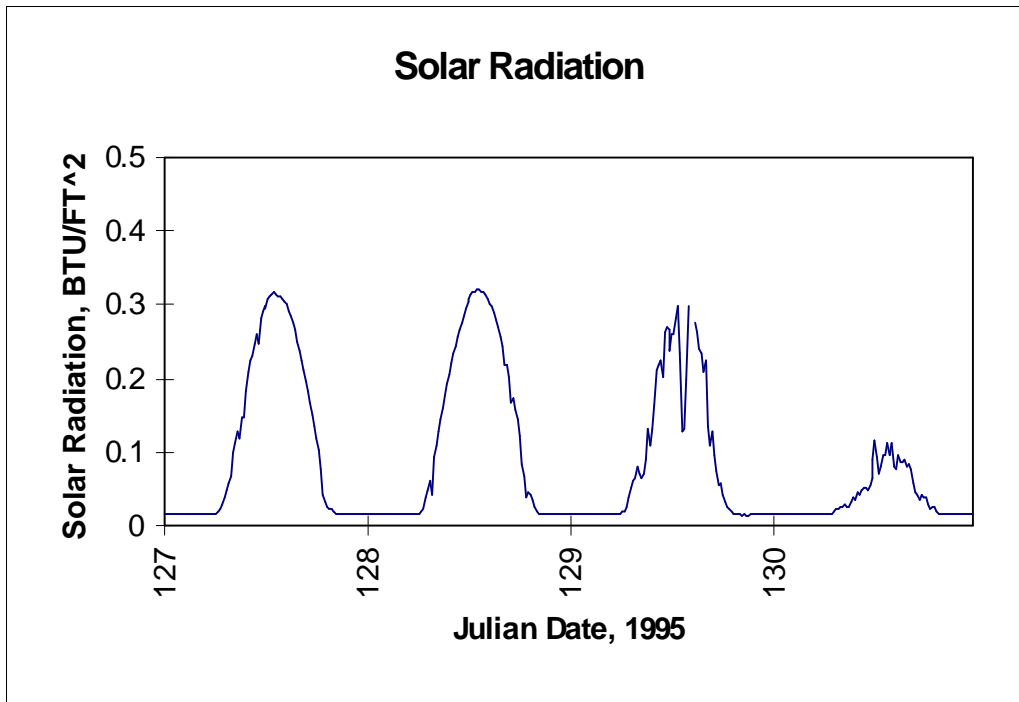Figure 6-1. Interscan Response to Carbon Dioxide.

Figure 6-2. Interscan Response to Sunlight (Temperature Effect) Over a Four-day Period.

Daily averages were computed from the analyzer output to help dampen the shorter-term fluctuations in response. Time series of the averages are plotted in Figures 6-3 to 6-5 for the three loadings of the house, respectively. For the first loading (Figure 6-3) that began on Julian day 108 (April 18, 1995), the response rose rapidly to about 30 ppb, then continued to rise at a gradual rate thereafter. At the time of the last DNPH measurements, on Julian day 142 (May 22), the continuous analyzer recorded daily averages in the range of 30-35 ppb, similar to but slightly lower than those measured by the DNPH method. Although DNPH measurements indicated that formaldehyde concentrations in the house had "leveled off" by this time, the continuous analyzer indicated that the concentrations continued to rise. However, the data after Julian day 160, and especially those after Julian day 175, are suspect due to aging of the electrochemical cell and associated poor resolution (see Figure 5-1 in Section 5.4).

For the second loading (Figure 6-4) that began on Julian day 219 (August 7, 1995), the analyzer response initially rose from a baseline below 30 ppb to about 40 ppb during the ten days thereafter. This response, however, is considerably lower than DNPH measurements in the range of 55-60 ppb during this time. The data are highly suspect following an adjustment to the potentiometer on day 241 (see Figure 5-1) but appear to be more reliable following installation of a new electrochemical cell on day 257. With the new cell the response near the end of the second loading was in the range of 40-50 ppb, generally consistent with the last set of DNPH results (run 4) for this loading.

For the third loading (Figure 6-5) that began on Julian day 268 (September 25, 1995), the analyzer response initially rose to about 50 ppb, or about 20 ppb below levels indicated by the DNPH method. The analyzer response was fairly level thereafter, generally in the range of 50-60 ppb, whereas the DNPH results showed a declining trend following the first measurement period about ten days after the loading was started. The results collectively indicate that the continuous analyzer can detect relative changes associated with loading and unloading the house, but also that at this low end of its analytical range it cannot readily detect more subtle changes over time.

More detailed information on the instrument response during the first and second loadings, in the form of a time series of 15-minute averages, is presented in Figures 6-6 and 6-7. Prior to the first loading (Figure 6-6), the instrument reported formaldehyde levels very close to zero. The concentration then rose rapidly to about 20 ppb as loading commenced around 9:00 a.m. The negative values around noon may reflect temporary instrument instability associated with increased air exchange (due to open doors) or increased CO_2 (due to presence of technicians). For the second loading (Figure 6-7), the measured concentration again rose rapidly by about 20 ppb as loading commenced around noon, then rose gradually thereafter but also experienced several periods of apparent instability.

Daily average temperatures and humidities during the study period are plotted in Figures 6-8 and 6-9, respectively. The daily average temperature (Figure 6-8) rose from a low of 50 °F at the beginning of the period to highs around 80 °F during the summer, then returned to around 50 °F toward the end of the study. The indoor temperature was generally maintained within a few degrees of the target of 75 °F throughout the study period. Although relative humidity (Figure 6-9) generally was maintained in the target
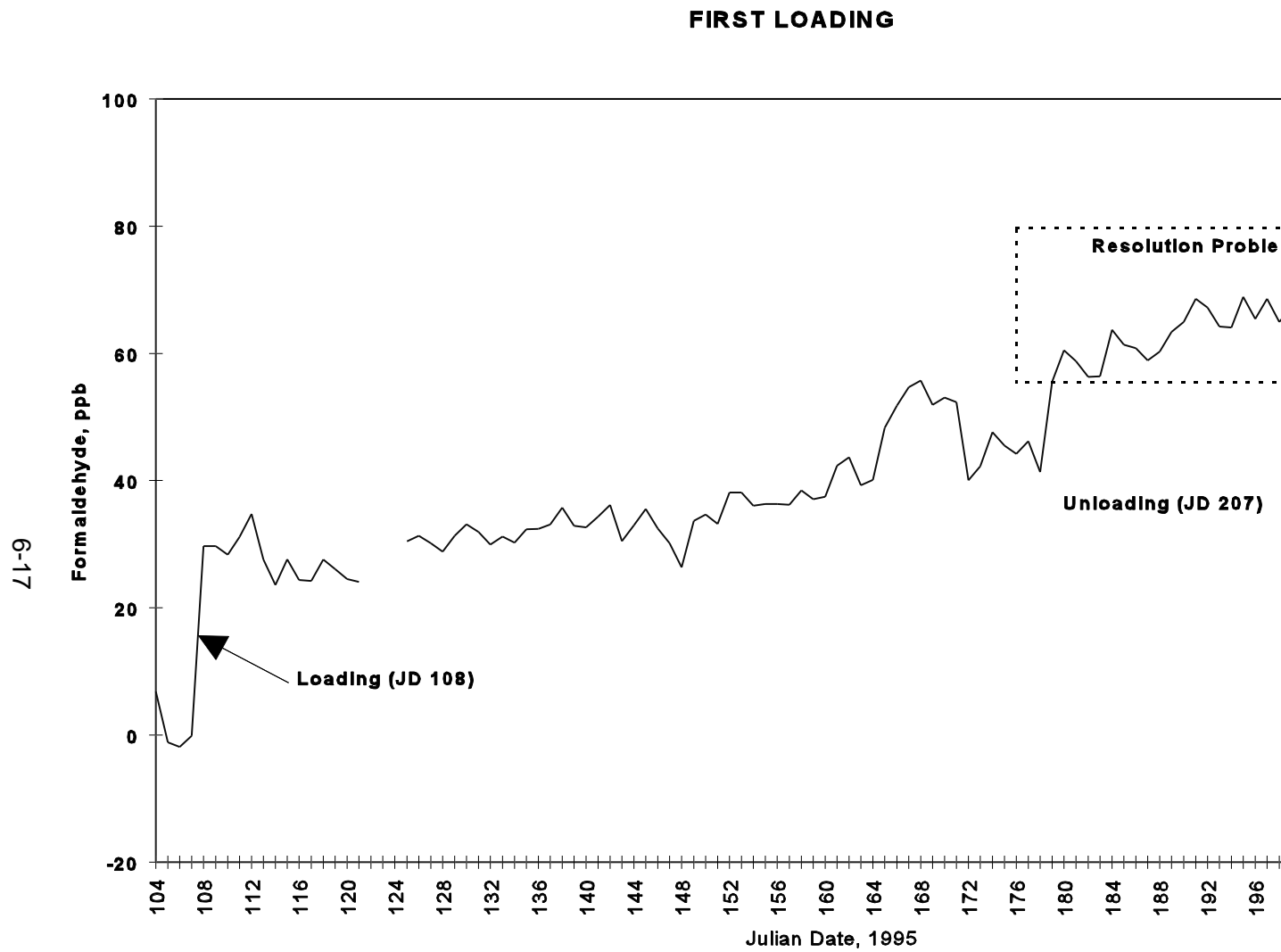
FIRST LOADING

Figure 6-3. Daily Averages from the Continuous Formaldehyde Analyzer During the First Lo
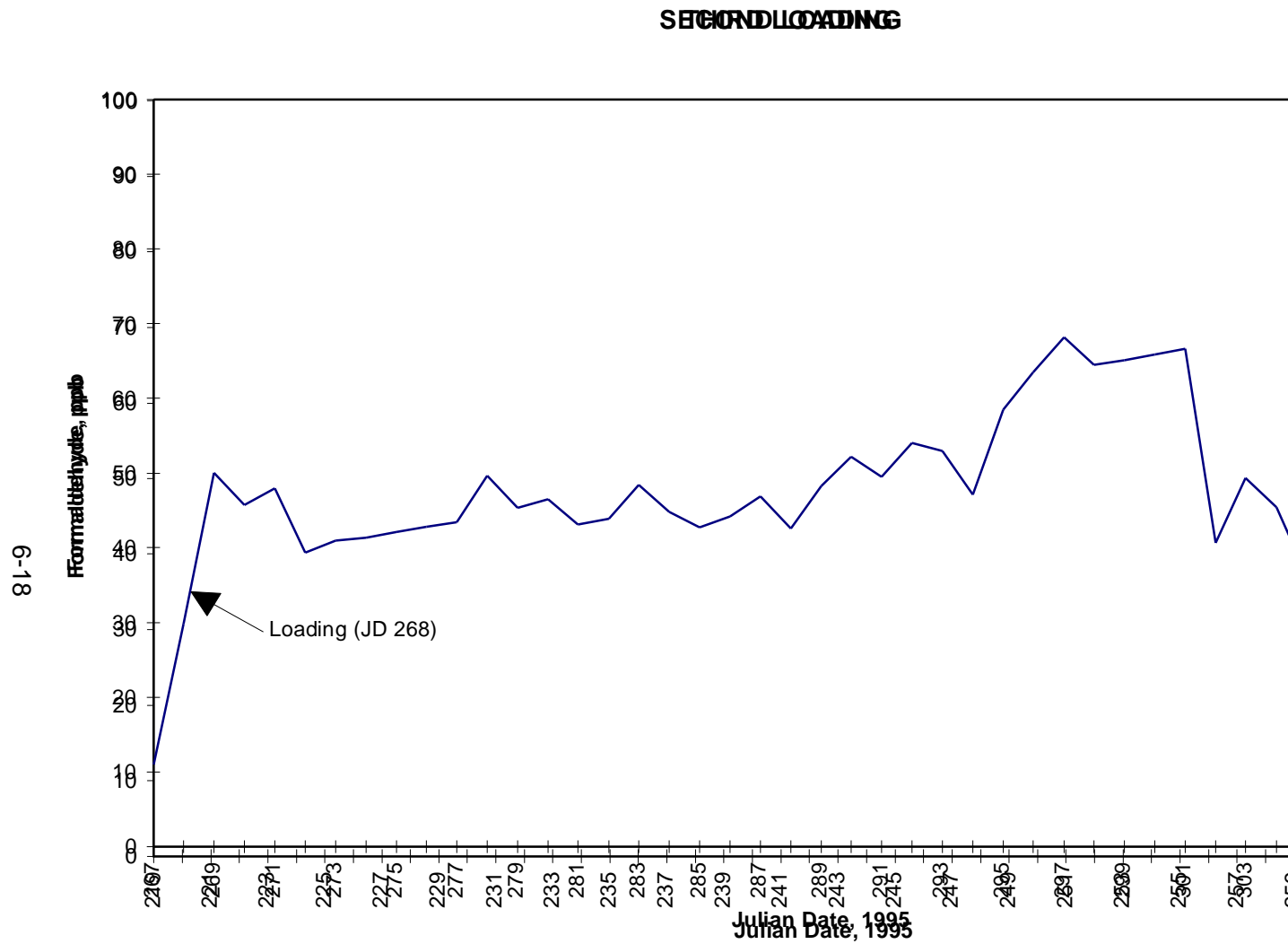
Figure 6-5. Daily Averages from the Continuous Formaldehyde Analyzer During the Third Loading

Figure 6-4. Daily Averages from the Continuous Formaldehyde analyzer During the Second Loading

Detailed Data for the First Loading (JD 108-111)
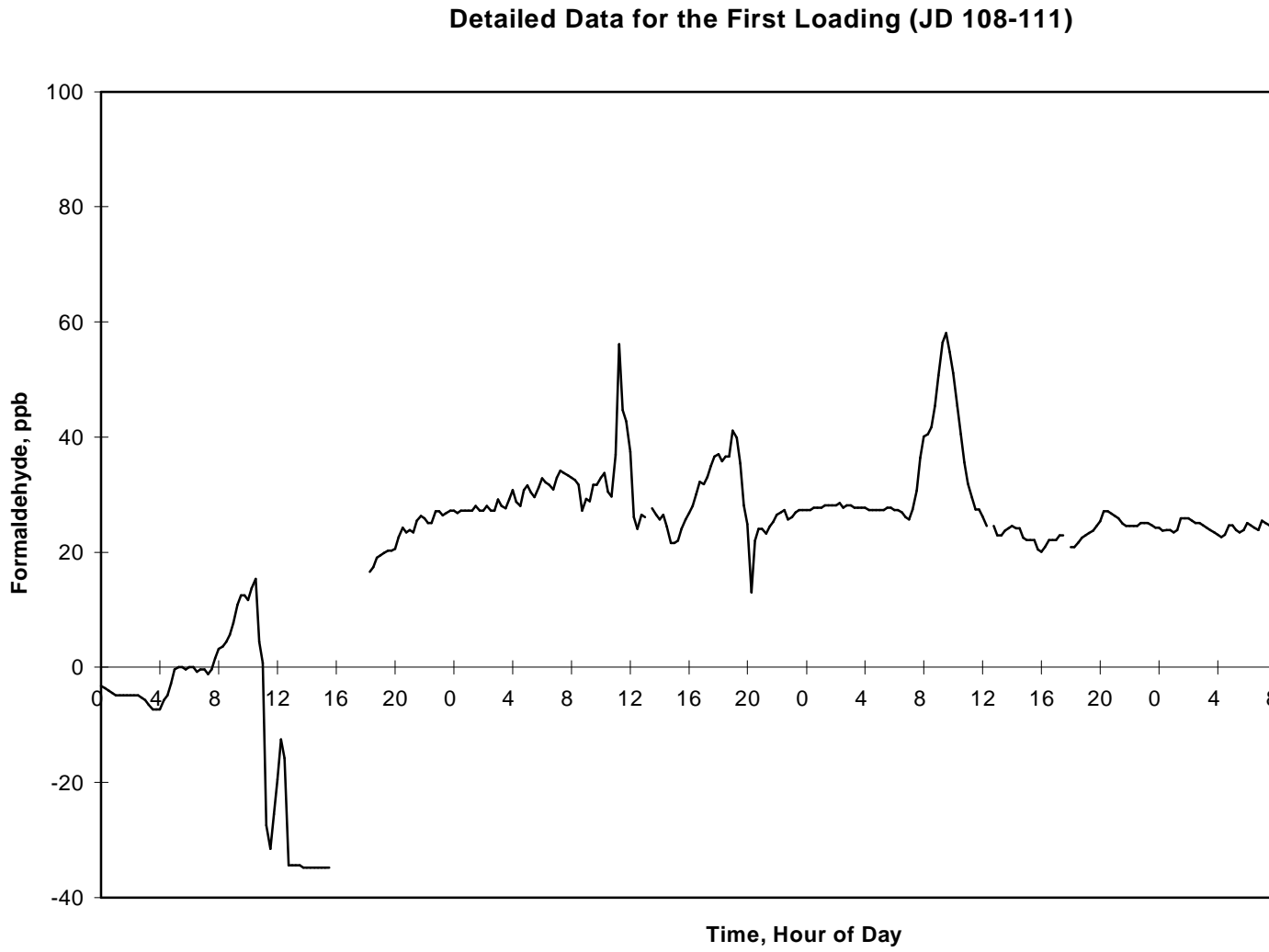
Figure 6-6. 15-minute Averages from the Continuous Formaldehyde Analyzer During the First l

Detailed Data for the Second Loading (JD 219-221)
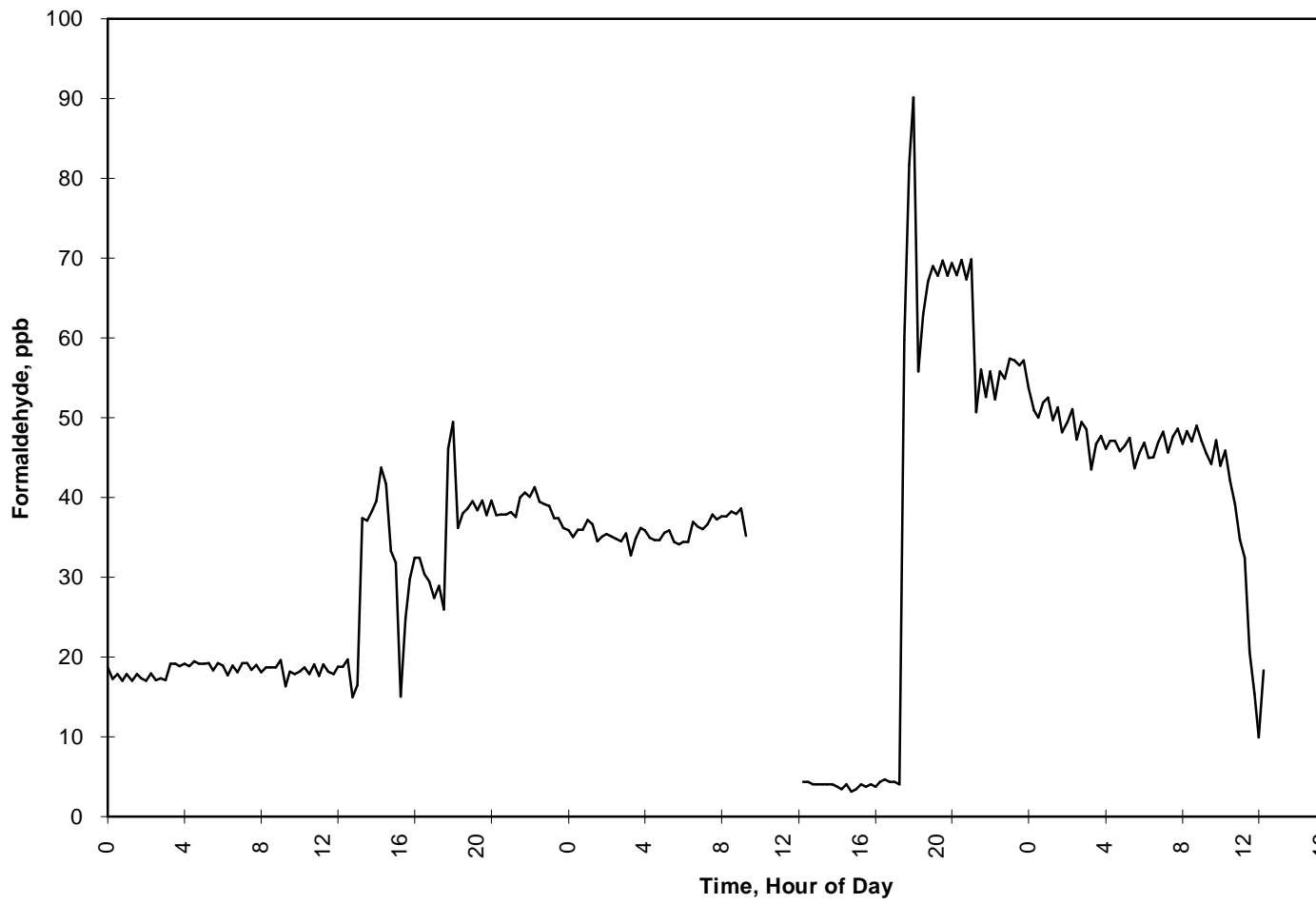
Figure 6-7. 15-Minute Averages from the Continuous Formaldehyde Analyzer During the Second Lo
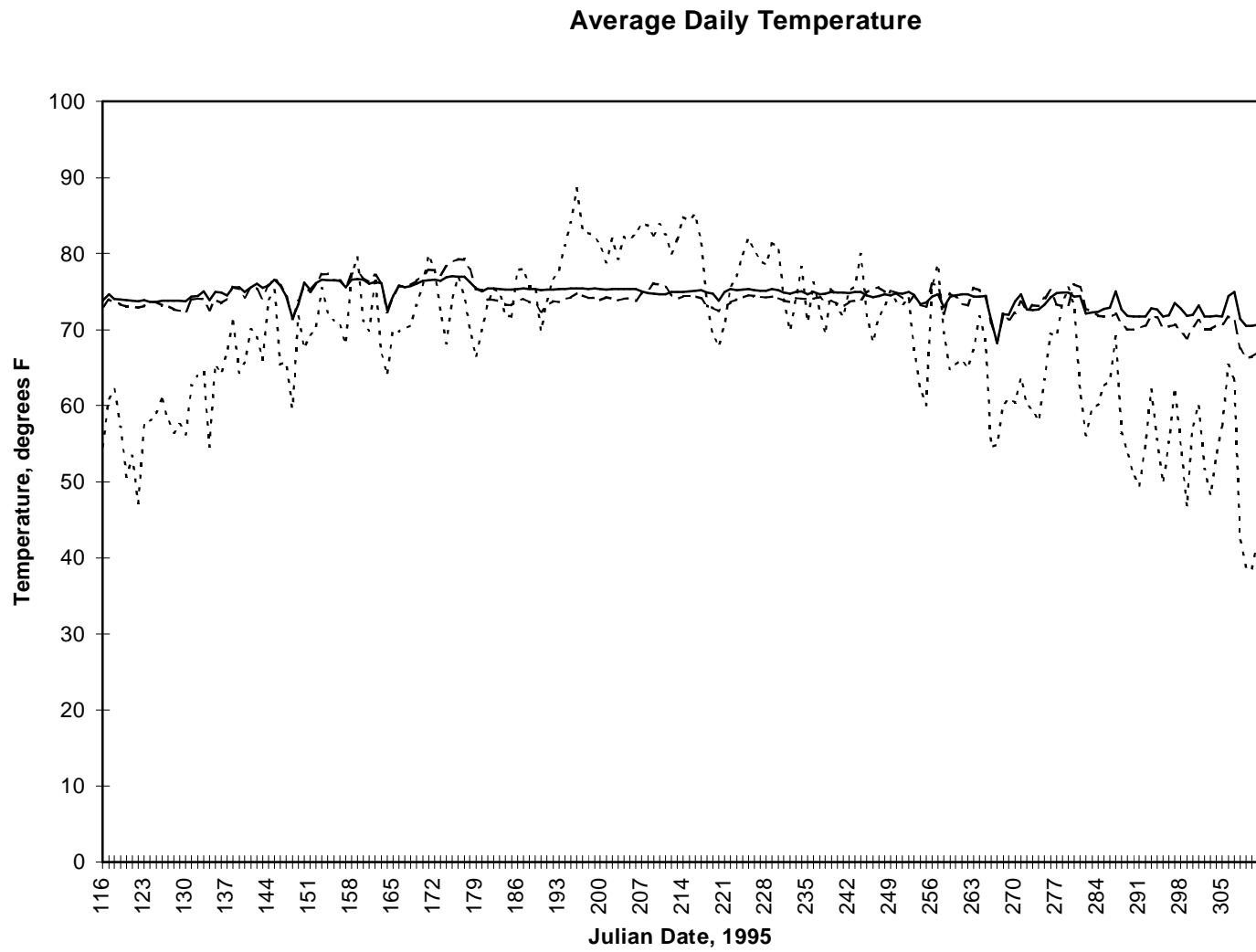
Average Daily Temperature

Figure 6-8. Daily Average Temperatures During the Study Period.

Average Daily Relative Humidity
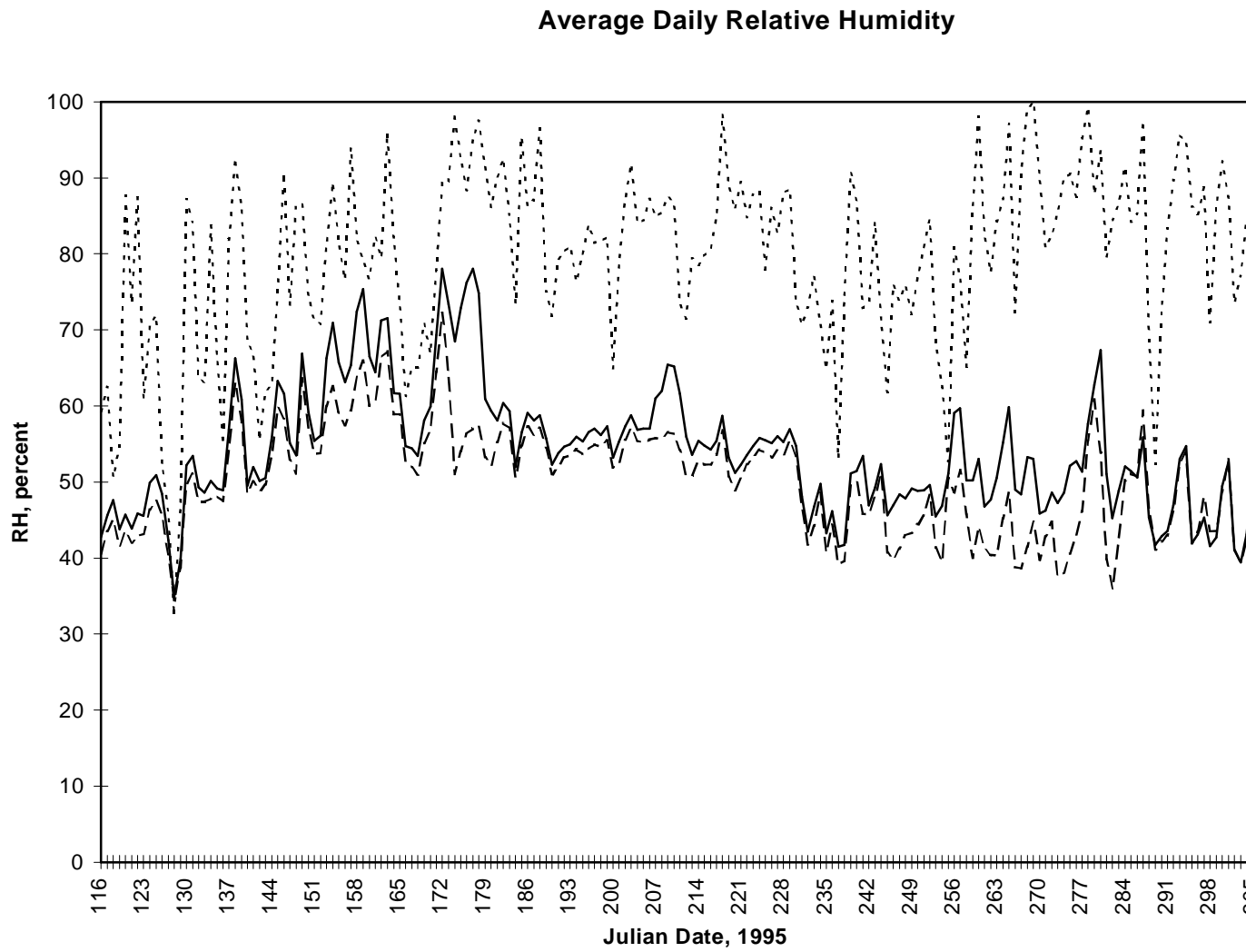

Figure 6-9. Daily Average Relative Humidities During the Study Period.

range of 50% ± 10%, there were periods in the late spring or early summer, around Julian days 150 to 180, where the humidity level sometimes exceeded 60% and occasionally rose above 70% on the first floor. DNPH measurement results adjusted to the target conditions of 75 °F and 50% relative humidity are presented in Appendix B.

6.1.8 Summary and Discussion of Conventional House Testing Results

The results of formaldehyde, temperature, humidity and air-exchange measurements during the formal "runs" associated with each loading, as well as their respective baseline periods, are compiled in Table 6-20. The formaldehyde results collectively indicate that monitored levels for loadings 2 and 3 generally were consistent with one another and that these "high" loadings had higher levels (but also a higher baseline) than for the "medium" loading (loading 1).

Living-room measurements for the three loadings are plotted in Figure 6-10 against elapsed time after UF-bonded wood products were installed. The results for loading 1 include the supplemental measurements (see Table 6-7) that were taken after day 33. The curvature of the lines is due to the spline fit that was applied, and is not meant to imply that values between measurement points can be readily interpolated. The figure illustrates the general consistency across loadings 2 and 3 and their differences from loading 1. Although loading 1 levels are similar to those from loadings 2 and 3 toward the end of their respective test periods, indoor humidity levels were fairly high near the end of loading 1.

Differences in baseline levels and in the general shape of the time series for run 1 versus runs 2 and 3 can be partly explained by the wallboard sink effect (see small-chamber test results on sink-effects in Section 6.3). The wallboard sink was largely empty at the outset of run 1 but largely "pre-loaded" at the outset of runs 2 and 3. The time series for runs 2 and 3 have a shape consistent with that of an exponentially declining emitter, as would be expected when the dominant sink (wallboard) is pre-loaded and becomes a "net zero emitter," such that the declining rate of emission from aging wood products drives the concentration profile. For loading 1, however, this profile is dampened by the relatively large mass being absorbed by this unloaded sink. Some of the difference in baseline values for run 1 versus runs 2 and 3 can also be explained by the low humidity level at the time when baseline measurements were taken for run 1.

The key measurement parameter for the study, formaldehyde by the DNPH method, was in control across all measurement periods. The QA spikes indicated that recoveries were consistently in the range of 90 to 110 percent, well within the accuracy goal of ±20 percent. Results of duplicate DNPH samples shown earlier in this section demonstrated a combined sampling/analytical precision of ±10 percent or better, again well within the corresponding data quality objective. A draft of the statistical analysis on these data by Battelle is presented in Appendix E. One of the major findings from this analysis is that the standard deviation across the high loadings, for measurements at the same location and at the same elapsed time since loading of UF-bonded wood products, was not much larger than that for duplicate measurements (i.e., at the same time and location within any given loading). This finding points to the repeatability of high-loading results for the conventional house, after the sinks were pre-loaded as a result of the preceding medium loading.

Table 6-20. Summary of Monitoring Results for Loadings 1, 2, and 3

| Run | DNPH Results, ppb | | | | | Temperature, °F | | | | | RH, % | | | Air Exchange |
	LR	KIT	BR	BSMT	AMB	LR	KIT	BR	BSMT	AMB	LR	2ND	AMB	SF₆
Loading 1 (medium)														
Base	9.1	9.8	9.5	9.1	1.3	75.7	75.8	74.0	63.4	49.0	22.8	24.4	55.2	--
1	27.5	29.9	20.1	--	1.0	73.8	73.4	73.2	68.5	56.9	43.2	41.0	60.2	0.44
2	29.6	31.3	29.9	26.5	7.0	73.8	73.6	73.4	66.7	52.4	46.2	43.2	76.8	0.44
3	41.7	43.9	36.3	28.2	2.1	75.1	75.0	74.9	71.1	69.6	63.1	60.2	93.9	0.40
4	36.8	39.4	31.1	--	1.7	75.5	74.8	73.4	73.1	66.0	50.4	49.8	60.6	0.40
Loading 2 (high)														
Base	23.0	23.7	22.1	25.7	2.8	75.2	73.1	74.3	77.0	84.4	54.5	52.3	80.3	0.39
1	60.1	60.8	60.5	39.7	2.9	75.3	73.5	74.5	76.2	81.5	57.1	55.5	88.2	0.38
2	55.8	58.1	54.7	40.0	2.3	75.1	73.4	74.3	75.4	80.1	50.9	49.3	74.1	0.38
3	46.7	48.5	53.3	38.0	1.4	74.4	73.9	75.6	75.7	75.4	50.7	43.8	71.2	0.36
4	39.0	40.8	48.1	30.7	0.9	73.4	73.2	73.2	73.6	63.1	51.6	43.2	71.6	0.39
Loading 3 (high)														
Base	26.0	25.8	27.7	25.0	<1.0	73.3	72.8	73.3	73.3	61.4	54.9	44.3	85.0	0.41
1	71.9	76.1	65.6	42.6	1.1	75.0	73.2	72.5	73.6	76.1	62.7	65.3	95.1	0.39
2	53.8	55.2	54.7	29.9	1.1	72.3	72.4	72.0	70.7	60.3	49.7	47.1	86.7	0.36
3	43.2	46.2	39.5	20.3	1.1	71.7	71.8	69.5	66.6	49.1	43.8	43.7	87.2	0.42
4	42.3	40.4	44.1	22.8	1.4	71.7	71.9	70.7	66.9	55.4	46.1	44.9	88.8	0.35

Legend: LR = living room;
            KIT = kitchen;
            BR = bedroom;
            BSMT = basement;
            AMB = ambient;
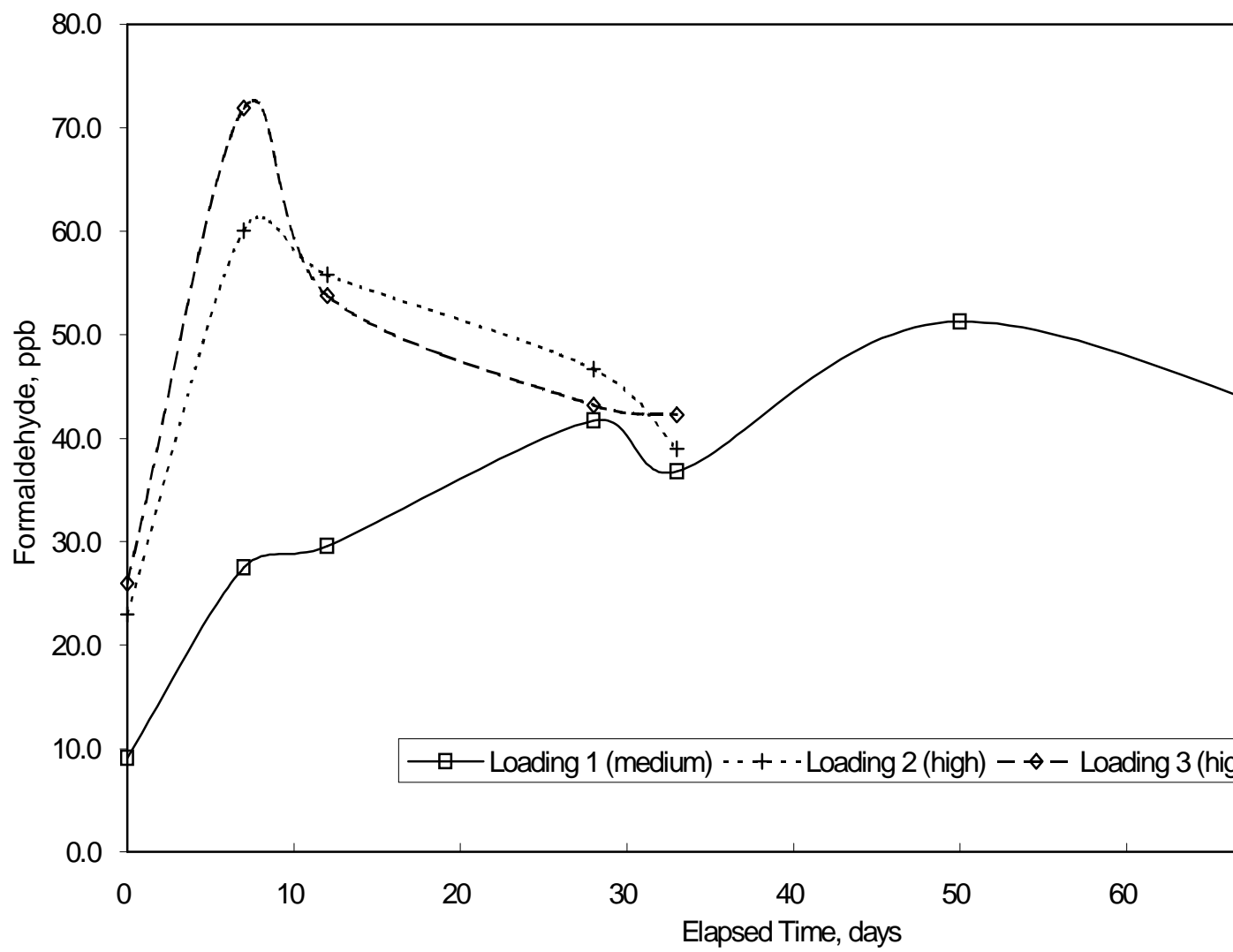   2ND = second floor.

Figure 6-10. Summary of DNPH Results (Living Room Values) for the Three Loadings of the Conver

Figure 6-11 shows a comparison of the SF_6 and PFT air-exchange results across the pilot study period (detailed PFT results are given in Appendix F). Although the collective results generally are in target range of 0.4 to 0.6 ACH, the PFT estimates are consistently higher. One possible reason for the discrepancy is the inherent difference between the two measurement technologies. The SF_6 method involves periodic injection and mixing of the tracer through the HAC system, followed by real-time analysis of the concentration decline due to dilution by infiltrating outdoor air. The PFT method relies on near-constant release of tracers from multiple locations near the perimeter of the house, accompanied by time-integrated sampling over a 24-hour period. Further insights cannot be obtained without additional, more intensive studies.

Although steps were taken to isolate the basement from the upstairs levels of the house (through various sealing processes and by closing the interior door at the top of the stairs to the basement throughout the study period), it was observed that SF_6 tracer gas released into the upstairs levels did migrate to the basement. An example of this behavior, across three SF_6 injections during a 24-hour period, is given in Figure 6-12. The SF_6 not only migrated to the basement but eventually climbed to higher levels in the basement than the upper floors, indicative of the relative airtightness of the basement zone. The PFT results in Appendix F support the apparent air communication between the basement and upper floors, with airflows on the order of 100 m^3/h in either direction. The implication is that some of the formaldehyde emissions from UF-bonded wood products migrated to the basement, but the basement readings may also reflect contributions from potential sources such as the plywood subfloor with exposed surface area facing the basement.

6.2 LARGE CHAMBER EMISSION TESTING

Results pertaining to tests by industry for underlayment, paneling, cabinets and doors are provided in Sections 6.2.1 to 6.2.4, respectively. NPA studies on underlayment samples from the conventional house, using a dynamic microchamber (DMC), are given in Appendix G. Further details on the large chamber test results presented in this section appear in Appendix H. Related studies by NPA on time-related decay in underlayment emissions and on wallboard absorption/desorption are given in Appendices I and J, respectively.

6.2.1 Particleboard Underlayment

As shown in Table 6-21, chamber test results under standard conditions (77 °F, 50% RH, 0.5 ACH) for the particleboard underlayment were generally within the range established for "medium emitting" wood panel products through the screening test. For particleboard specimens used in the pilot study, a decreasing trend is evident for products used in the three loadings as stored sublots aged in the wrapper.

SF6:PFT Comparison

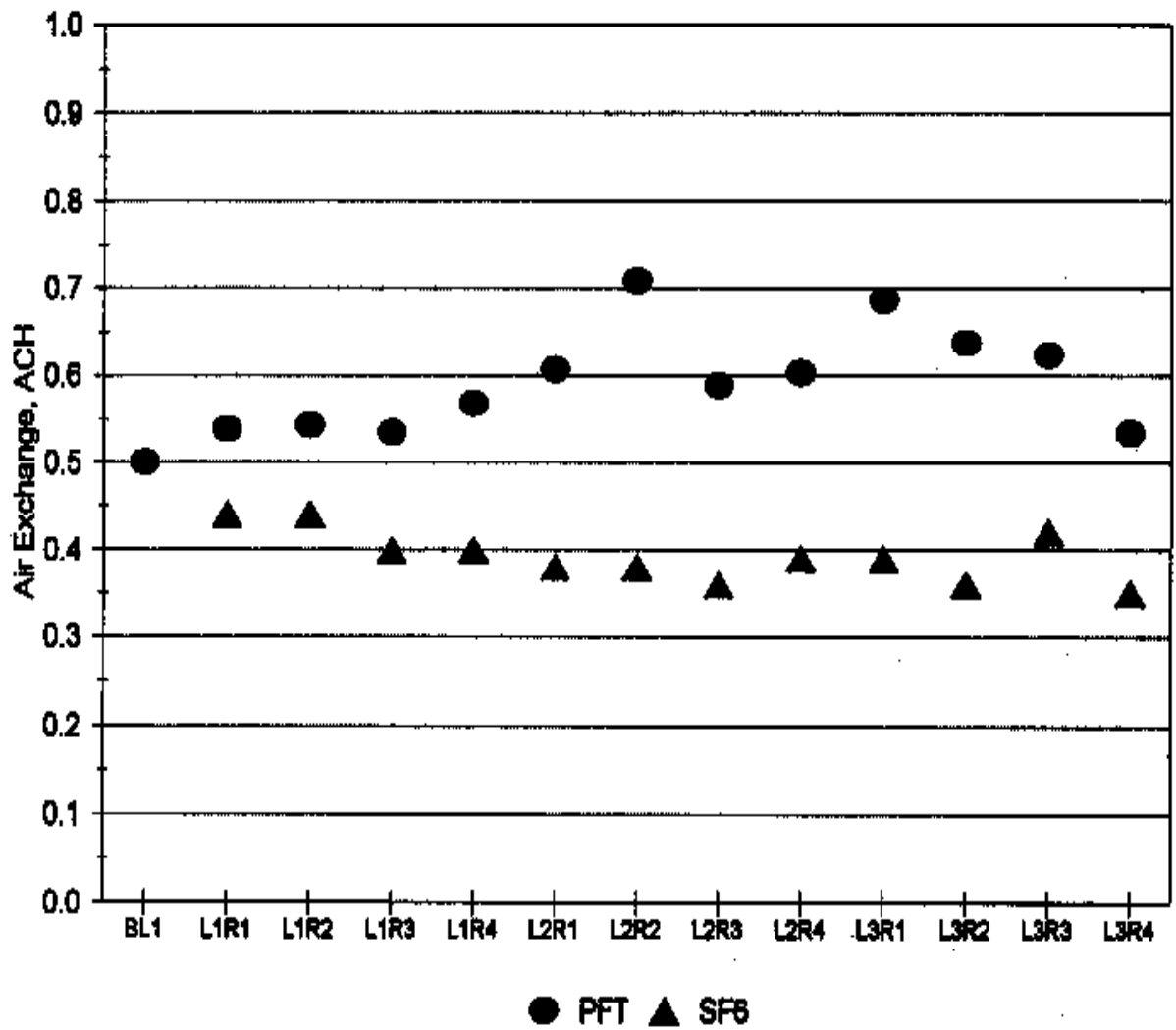Figure 6-11. Comparison of SF$_6$ and PFT Results Across the Study Period.

6-28
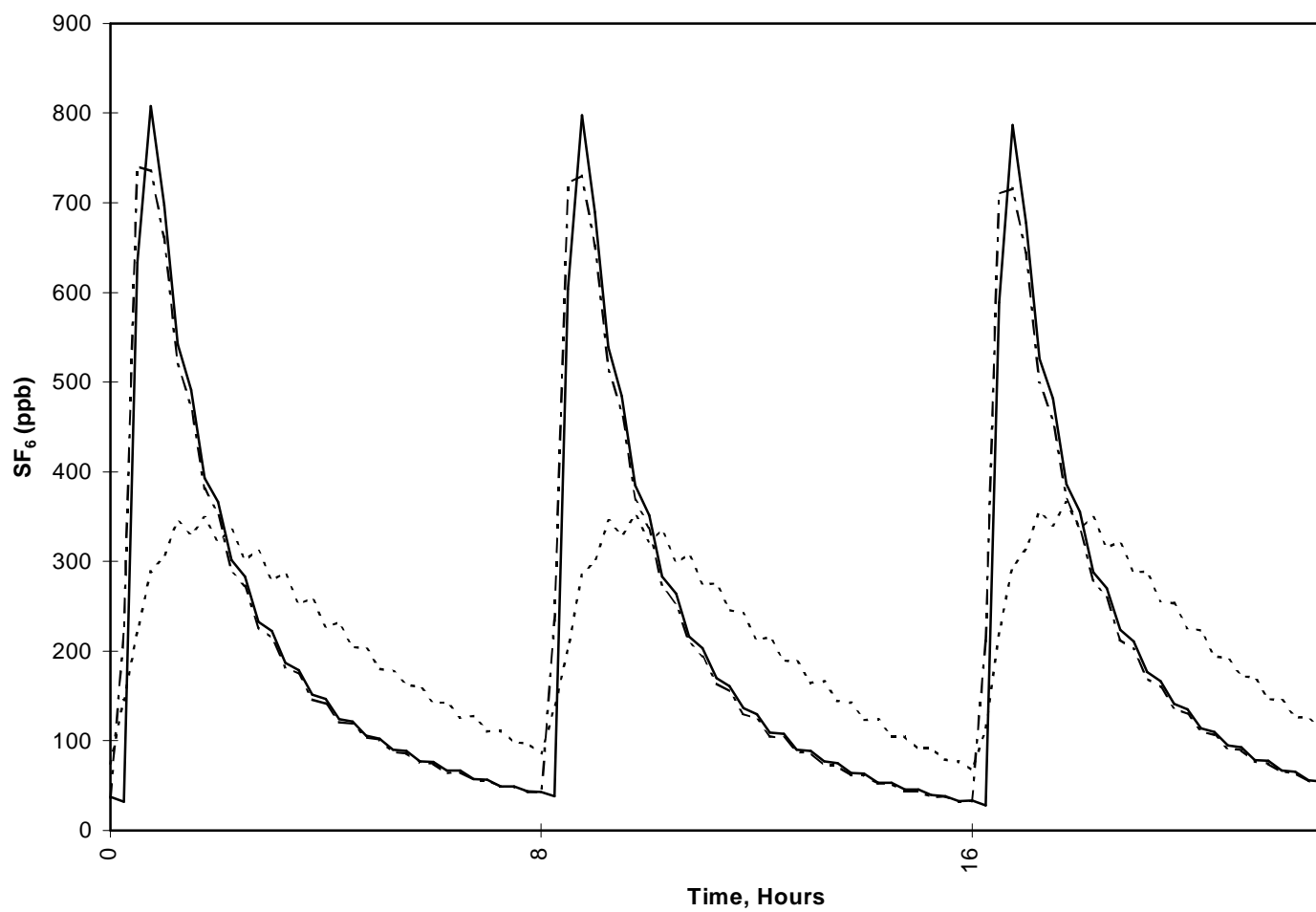
Figure 6-12. SF$_6$ Concentration Profiles at Three Sampling Locations (Living Room, Bedroom #3 and Bas... Following Three Injection Periods on August 21, 1995.

Table 6-21. Large Chamber Test Results[a] for Particleboard Underlayment

| | Air Exchange (ACH) | Temperature (°F) | RH (%) | Measured Formaldehyde | | | Adjusted[b] (ppm) |
				First (ppm)	Second (ppm)	Average (ppm)	
Screening	0.50	77.5	50	0.148	0.148	0.148	0.144
Loading 1	0.25	77.2	51	0.150	0.152	0.151	0.147
	0.50	77.1	51	0.128	0.127	0.128	0.125
	1.01	77.2	51	0.078	0.081	0.080	0.077
Loading 2	0.25	77.1	51	0.143	0.142	0.143	0.139
	0.50	77.0	50	0.113	0.115	0.114	0.114
	0.99	77.0	51	0.073	0.072	0.073	0.071
Loading 3	0.24	76.5	48	0.123	0.124	0.124	0.132
	0.51	76.6	48	0.098	0.096	0.097	0.103
	1.01	76.5	48	0.062	0.061	0.062	0.066

[a] With a loading rate of 0.13^2 ft^2/ft^3.

[b] Adjustment to standard conditions of 77 °F, 50% RH as per ASTM E-1333.

6.2.2 Hardwood Plywood Wall Paneling

As shown in Table 6-22, chamber test results under standard conditions (77 °F, 50% RH, 0.5 ACH) for the hardwood plywood wall paneling were generally within the range established for "medium emitting" wood panel products through the screening test. For paneling used in the pilot study, a decreasing trend is evident from loading 2 to loading 3 as stored sublots aged in the wrapper. Hardwood plywood wall panels were not incorporated into the first loading scenario; chamber tests were conducted only in association with the second and third loadings.

Table 6-22. Large Chamber Test[a] Results for Hardwood Plywood Wall Paneling

| | Air Exchange (ACH) | Temperature (°F) | RH (%) | Measured Formaldehyde | | | Adjusted[b] (ppm) |
				First (ppm)	Second (ppm)	Average (ppm)	
Screening	0.50	77.1	50	0.114	0.116	0.115	0.114
Loading 1	Not Used In Loading 1						
Loading 2	0.25	77.1	52	0.138	0.139	0.139	0.133
	0.50	76.9	50	0.111	0.112	0.112	0.112
	0.99	77.0	50	0.080	0.084	0.082	0.082
Loading 3	0.25	77.0	49	0.101	0.099	0.100	0.102
	0.50	76.8	48	0.085	0.083	0.084	0.088
	1.01	77.0	49	0.058	0.057	0.058	0.059

[a] With a loading rate of 0.29 ft^2/ft^3.

[b] Adjustment to standard conditions of 77 °F, 50% RH as per ASTM E-1333.

6.2.3 Kitchen Cabinets

As shown in Table 6-23, chamber test results under standard conditions (77 °F, 50% RH, 0.5 ACH) for the kitchen cabinets were in the range of 0.05 ppm. A decreasing trend is evident for products used in subsequent loadings as stored sublots aged in the wrapper. Screening tests were not conducted for kitchen cabinets.

Table 6-23. Large Chamber Test Results[a] for Kitchen Cabinets

| | Air Exchange (ACH) | Temperature (°F) | RH (%) | Measured Formaldehyde | | | Adjusted[a] (ppm) |
				First (ppm)	Second (ppm)	Average (ppm)	
Loading 1	0.17	77.5	51	0.098	0.099	0.099	0.094
	0.51	77.5	48	0.053	0.052	0.053	0.053
	1.00	75.0	50	0.026	0.026	0.026	0.029
Loading 2	0.24	77.4	50	0.068	0.068	0.068	0.066
	0.50	77.4	52	0.052	0.052	0.052	0.049
	0.99	77.3	50	0.026	0.027	0.027	0.026
Loading 3	0.25	77.2	54	0.070	0.069	0.070	0.064
	0.50	77.0	49	0.048	0.047	0.048	0.048
	1.01	77.0	50	0.026	0.026	0.026	0.026

[a] With a loading rate of 0.13 ft^2/ft^3.

[b] Adjustment to standard conditions of 77 °F, 50% RH as per ASTM E-1333.

6.2.4 Interior Partition Doors

        As shown in Table 6-24, chamber test results under standard conditions (77 °F, 50% RH, 0.5 ACH) for the interior partition doors were in the range of 0.05 ppm. Loading from interior doors was held constant across all three loading scenarios; chamber tests were conducted only in association with the first and third loadings to conserve resources. For products used in the pilot study, a decreasing trend is evident from loading 1 to loading 3 as stored sublots aged in the wrapper.

Table 6-24. Large Chamber Test Results[a] for Interior Partition Doors

| | Air Exchange (ACH) | Temperature (°F) | RH (%) | Measured Formaldehyde | | | Adjusted[b] (ppm) |
				First (ppm)	Second (ppm)	Average (ppm)	
Loading 1	0.24	76.7	50	0.074	0.076	0.075	0.076
	0.50	76.7	50	0.051	0.051	0.051	0.052
	1.00	76.5	54	0.029	0.029	0.029	0.028
Loading 2	Not Tested						
Loading 3	0.25	77.0	49	0.069	0.069	0.069	0.070
	0.51	77.1	48	0.046	0.046	0.046	0.047
	1.00	77.0	49	0.026	0.025	0.026	0.026

[a] With a loading rate of 0.13 ft^2/ft^3.
[b] Adjustment to standard conditions of 77 °F, 50% RH as per ASTM E-1333.

6.2.5 Emission Rates for UF-Bonded Wood Products

Emission rates were computed for UF-bonded wood products using the adjusted formaldehyde concentration results from Tables 6-21 to 6-24 and the following relationship that applies under assumed steady-state conditions:

$$C_{ss} = \frac{S}{aV}$$

where C_{ss} = steady-state formaldehyde concentration in the chamber (μg/m^3)
  S = emission rate (μg/h)
  a = air exchange rate (1/h)
  V = chamber volume (m^3).

The emission rate, then, is the product of the formaldehyde concentration times the air exchange rate and chamber volume. Division of the emission rate by the exposed surface area yields an emission rate per unit surface area, in units of μg/m^2-h. Loading rates and air exchange rates are given in the previous tables. The volume of the test chamber was 1080 ft^3, or 30.6 m^3.

The results of the calculation described above are presented in Table 6-25. At an air exchange rate of 0.5 ACH that corresponds to the target setting for the conventional house, the emission rate is on the order of 100 μg/m^2-h for underlayment and close to 50 μg/m^2-h for the other UF-bonded wood products. As the air exchange rate is increased, the emission rate also increases, but at a rate that is less than proportional to the increase in air exchange; this trend is indicative of a concentration feedback effect.

Table 6-25. Computed Emission Rates for UF-Bonded Products,
Based on Adjusted Large Chamber Concentration Results

6-31

Loading	Emission Rate, μg/m^2-h			
	Underlayment	Paneling	Cabinets	Doors
At Target ACH = 0.25				
1	70.2	Not Used	44.9	36.3
2	66.4	28.5	31.5	Not Tested
3	63.1	21.8	30.6	33.4
At Target ACH = 0.50				
1	119.4	Not Used	50.6	49.7
2	108.9	48.0	46.8	Not Tested
3	98.4	37.7	45.9	44.9
At Target ACH = 1				
1	147.1	Not Used	55.4	53.5
2	135.7	70.2	49.7	Not Tested
3	126.1	50.5	49.7	49.7

6.2.6 Other House Constituents

The manufacturer of the paint used on the wallboard and interior doors at the conventional house was contacted by the EPA WAM to obtain data on formaldehyde content. The manufacturer's data indicated that the wallboard paint contains 0.001% formaldehyde by weight and the door paint contains 0.007% formaldehyde.

A carpet and padding sample was collectively sent to EPA's Air and Energy Engineering Research Laboratory (AEERL) in Research Triangle Park for small-chamber testing. Results of the chamber tests, conducted at 0.5-0.55 ACH, 74 °F and 55-60% RH, indicated an emission rate of 1.4 μg/m^2-h for the carpet and the same rate for the padding (after subtracting the chamber background) at an elapsed time of 24 hours following insertion in the chamber, or an emission rate of 2.8 μg/m^2-h for these two constituents combined. The combined emission rate is one to two orders of magnitude lower than that for UF-bonded wood products.

6.3 SMALL CHAMBER SINK AND BARRIER TESTS

Initial tests were conducted using an inert tracer gas (CO_2) to verify adequate mixing in the chamber and a formaldehyde input (with no sinks in the chamber) to verify that formaldehyde losses to the chamber lining were minimal (Section 6.3.1). The next set of tests addressed sink effects of carpet/padding (Section 6.3.2) and gypsum board (Section 6.3.3). The final set of tests addressed the potential barrier effects of carpet/padding when placed over underlayment (Section 6.3.4).   The results of the completed sink tests were used to estimate adsorption/desorption rate parameters for use in future modeling efforts (Section 6.3.5).

The Interscan real-time analyzer results for each chamber test were adjusted for instrument drift assuming linear drift throughout the duration of any given test. The formaldehyde feedstream was typically spanned several times during each experiment. In addition, several zeros (formaldehyde-free feedstreams) were typically performed, including a pure nitrogen stream and a scrubbed air supply stream. Using data collected during the spans, the measured data were adjusted using linear regression analysis of the spans of the known formaldehyde

input concentrations. A consistent zero drift was not identified in the data, and therefore the data were adjusted only for the zero offset.

6.3.1 Initial Small Chamber Tests

Initial chamber tests were conducted to verify the degree of mixing in the GEOMET small chamber. Controlled concentrations of CO_2 were metered at a constant rate through the supply port of the chamber and concentrations were monitored at the outlet using a continuous analyzer (Horiba non-dispersive infrared, calibrated using NIST-traceable gases). Separate tests were conducted for air exchange rates of 0.5, 1.0, and 1.5 ACH in the chamber with a nominal feedstream concentration of 4600 ppm CO_2 (concentrations varied slightly from experiment to experiment, but were constant within a given run). Theoretical expectations for each run were developed based on mass-balance calculations. As shown in Figure 6-13, results were marginally acceptable for the 0.5 ACH case, agreeing to within 10 percent with theoretical expectations. For the higher air exchange cases, however, any disagreement was indistinguishable from measurement errors associated with the instrumentation, indicating that adequate mixing was attained. Formal sink testing was conducted at the highest air exchange rate (1.5 ACH).

Further chamber tests were conducted to determine whether the chamber is a sink for formaldehyde. Formaldehyde was delivered to the chamber at a constant rate of 1.5 ACH and a concentration of 0.2 ppm. The chamber concentration was continually monitored at the outlet using an Interscan real-time analyzer. Theoretical concentrations were calculated using the solution to the mass-balance equation for a single compartment. A comparison of the measured and theoretical concentrations, shown in Figure 6-14, indicates agreement well within the precision of the instrument. The results show conclusively that the chamber is not a substantial sink for formaldehyde.

6.3.2 Carpet Sink Tests

Another set of tests was conducted during October 1995 and January 1996 to evaluate the sink characteristics of the carpet and padding. Two tests were conducted under identical air exchange rates of 1.5 ACH, but with different formaldehyde concentrations in the input stream. Two different concentrations were used because the

Figure 6-13. Preliminary Chamber Tests to Verify Mixing

FIRST CHAMBER TEST WITH NO SINKS

Start Ingrowth Period: Julian Date (1995) = 279; Time = 16:50

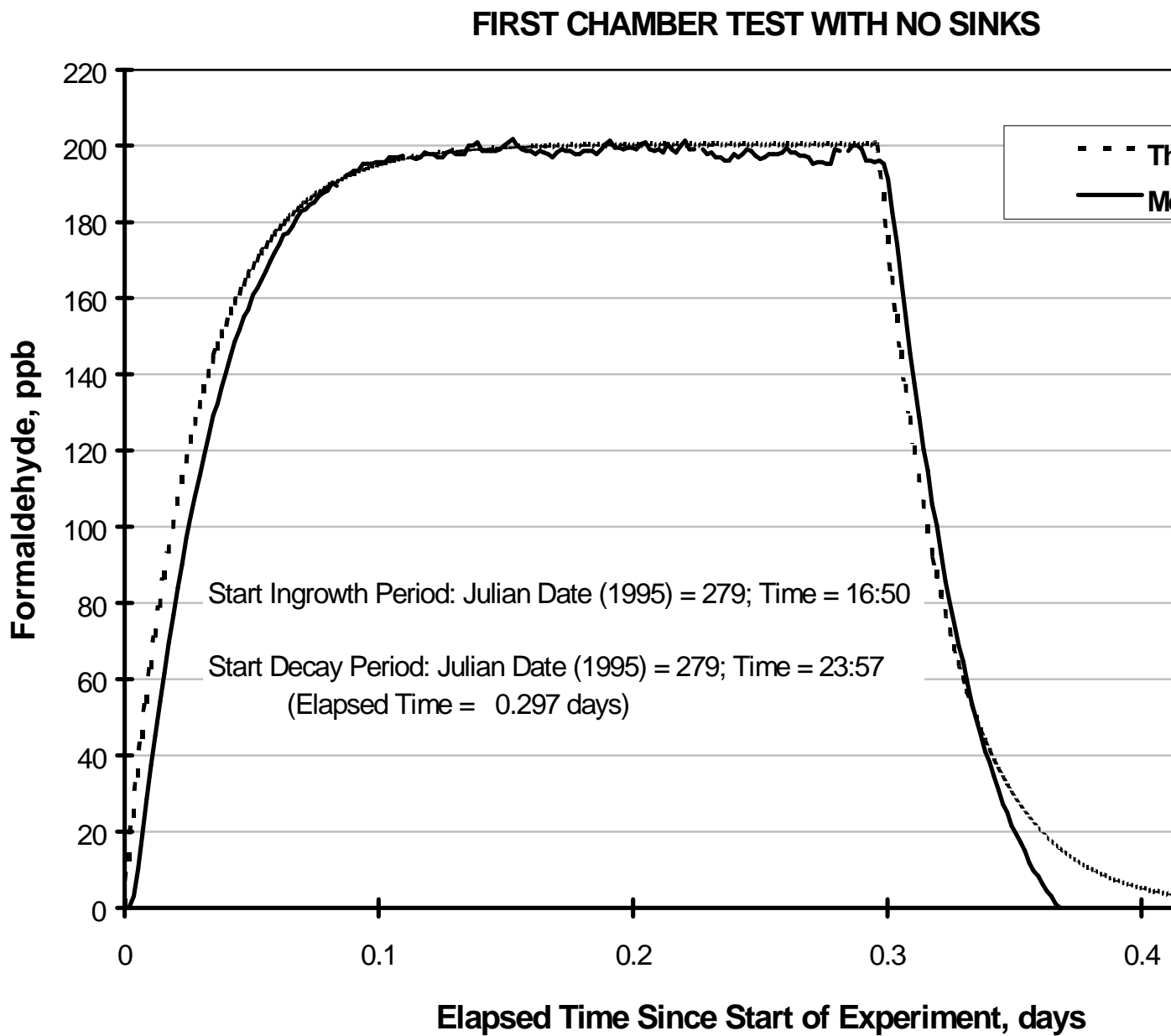Start Decay Period: Julian Date (1995) = 279; Time = 23:57
(Elapsed Time =   0.297 days)

Figure 6-14. Comparison of the Theoretical and Measured Formaldehyde Concentrations for the First Chamb

carpet is believed to be a sink for formaldehyde, and the rate of adsorption to the sink is suspected to be a function of the air concentration.
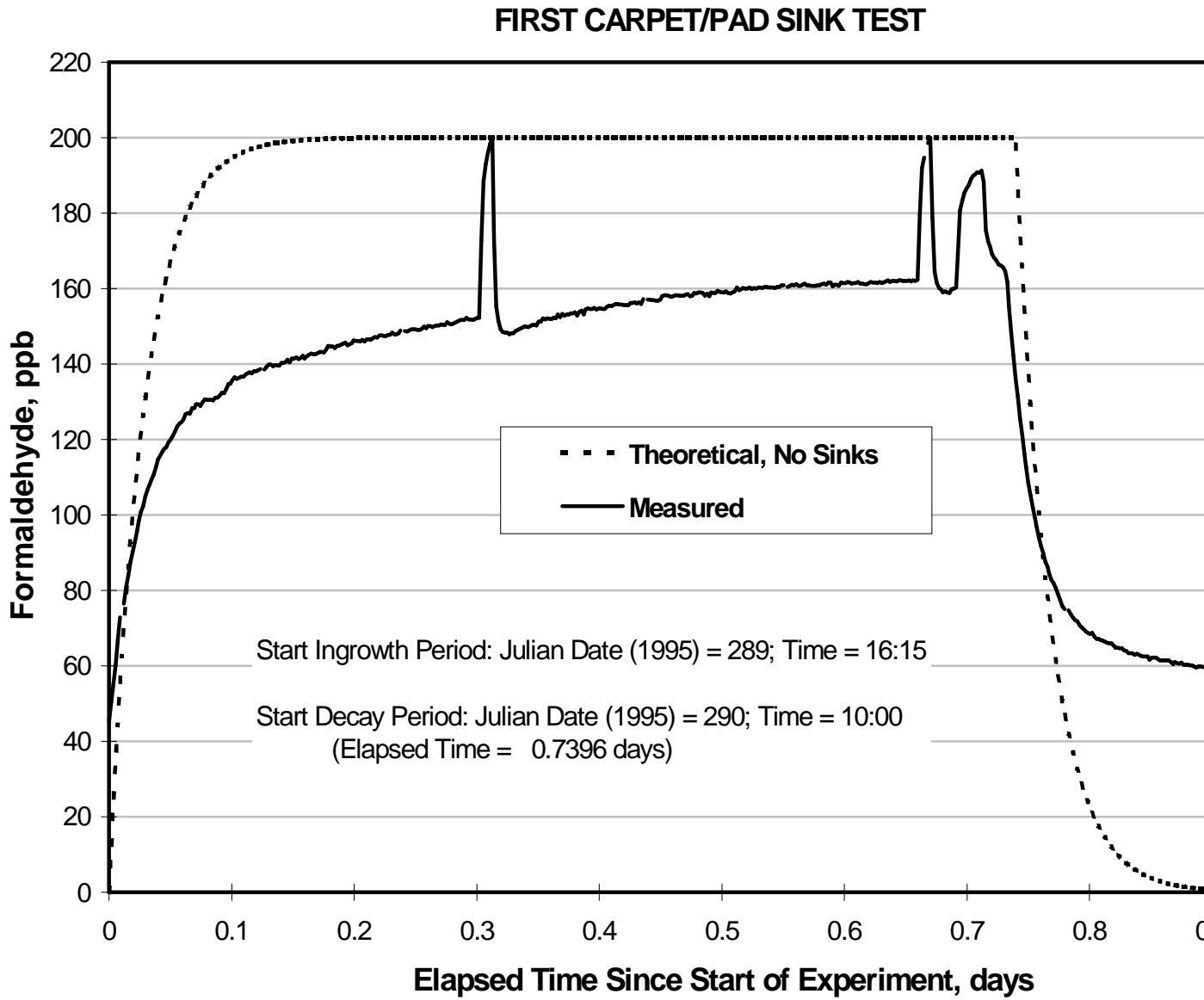
In both tests, a 7.1-inch square piece of carpet and padding was placed in a tight-fitting aluminum pan with edges equal to the depth of the carpet and padding. The pan containing the carpet and pad were then placed horizontally on the chamber floor. The chamber was then sourced with the formaldehyde stream of 0.2 ppm during the first test, and 0.12 ppm during the second. The resulting data for the first and second tests, adjusted for instrument drift and compared to the theoretical concentration if no sinks were present, are shown in Figures 6-15 and 6-16. Comparison of the theoretical (concentration that would be expected in the absence of sinks) and the measured indicates that a substantial amount of formaldehyde is adsorbed by the carpet. The trend in the data appears to be the result of a first-order removal process. Calibration spans at several points throughout the experiment are apparent in the data.

The data presented in Figure 6-16 show a noticeable decline after the span and zero at the end of the first day. This response is believed to be due to a combination of several factors. The first factor is that the chamber air flow is in suspension (0 ACH) during the span and zero. The formaldehyde continues to adsorb to the carpet/padding during this period, lowering the chamber concentration. Additionally, the Interscan has been observed to respond adversely to the large variations in concentrations that occur during the span and zero, leading to a response "conditioned" by the immediate concentration history. Therefore, the low concentration during the zero is believed to cause the lower output immediately thereafter. An added disturbing factor is the flat slope during the next hour period, which is also likely due to the instrument, but is presently not understood.

6.3.3 Wallboard Sink Tests

The chamber tests for gypsum wallboard were conducted to evaluate the sink characteristics of formaldehyde to wallboard. As with the carpet tests, these two tests were conducted under identical conditions with the exception of the formaldehyde feedstream concentration, to evaluate the effect of concentration on the rate of mass transfer to and from the wallboard. For each test, two 10.5-inch square pieces of painted wallboard were securely fastened back-to-back and edge sealed, leaving a total of 220.5 square inches of exposed wallboard surface area. The edges were sealed with sodium silicate. The wallboard was then placed in the center of chamber in a vertical position, supported by stainless steel wire.

The chamber was then sourced with the formaldehyde stream of 0.2 ppm during the first test, and 0.12 ppm for the second, at 1.5 ACH. The resulting data for the first and second tests, adjusted for instrument drift, are compared to the expected concentration if no sinks were present in Figures 6-17 and 6-18. The comparison indicates that the sink effect is even more pronounced for the wallboard. Calibration spans at several points throughout the experiment are apparent in the data. The time period during which a DNPH sample was taken to verify the measurement of the Interscan is also shown in Figure 6-17. The concentration of 0.112 ppm from the DNPH sample compares favorably with the average Interscan reading of 0.12 ppm over the same period.

FIRST CARPET/PAD SINK TEST

Start Ingrowth Period: Julian Date (1995) = 289; Time = 16:15

Start Decay Period: Julian Date (1995) = 290; Time = 10:00
(Elapsed Time = 0.7396 days)

Legend:
- - - - Theoretical, No Sinks
——— Measured

Formaldehyde, ppb (y-axis)

Elapsed Time Since Start of Experiment, days (x-axis)

6-15. Comparison of the Theoretical and Measured Formaldehyde Concentrations for the First Carpet/Pad Sin

SECOND CARPET/PAD SINK TEST

Start Ingrowth Period: Julian Date (1996) = 26; Time = 17:15

Start Decay Period: Julian Date (1996) = 27; Time = 23:50
(Elapsed Time = 1.274 days)

Legend:
- - - - **Theoretical, No S**
——— **Measured**

Y-axis: **Formaldehyde, ppb** (0 to 220)

X-axis: **Elapsed Time Since Start of Experiment, days** (0 to 2)

Figure 6-16. Comparison of the Theoretical and Measured Formaldehyde Concentrations for the Second Ca

FIRST WALLBOARD SINK TEST
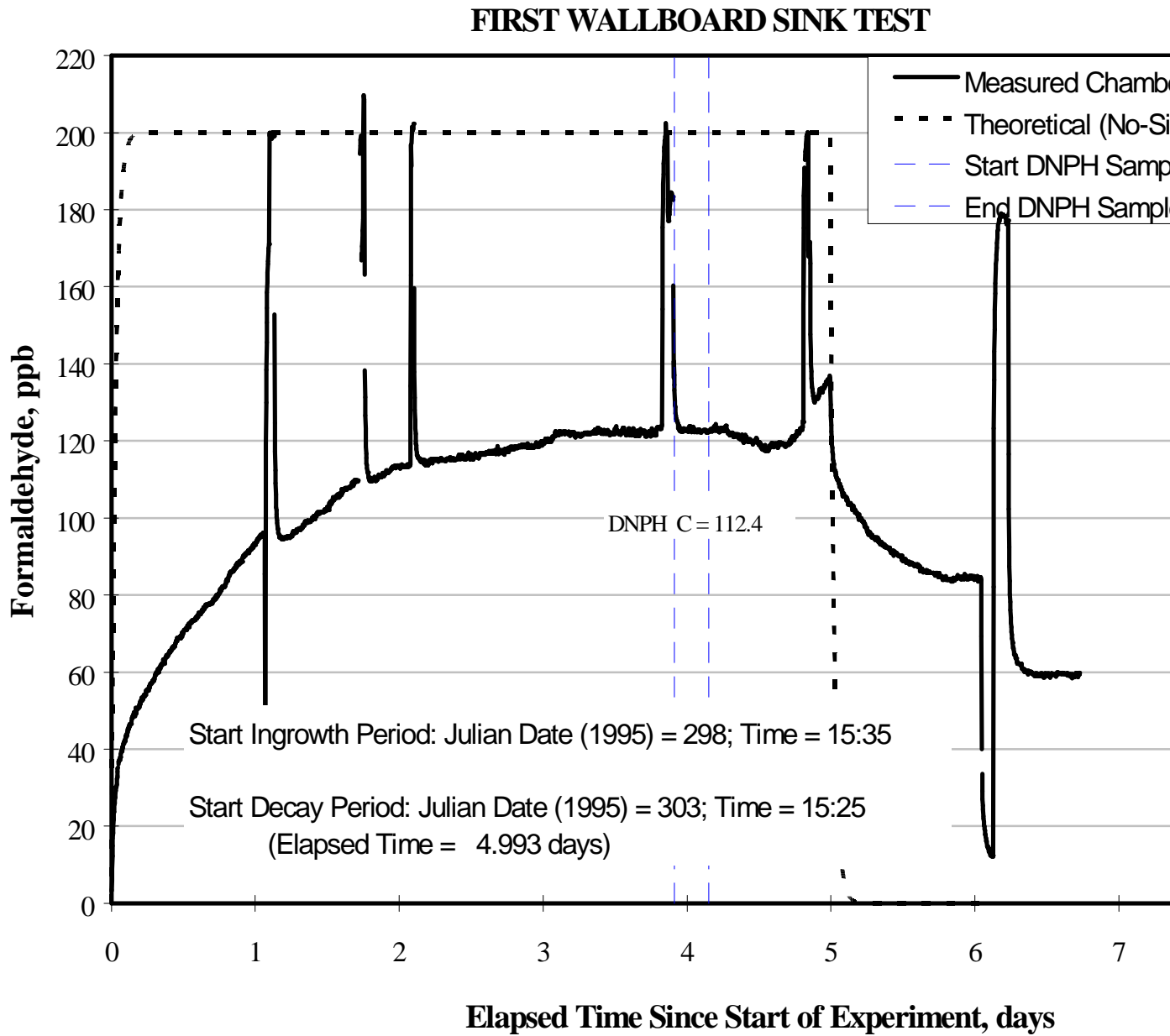
Figure 6-17. Comparison of the Theoretical and Measured Formaldehyde Concentrations for the First Wa

SECOND WALLBOARD SINK TEST

Start Ingrowth Period: Julian Date (1996) = 20; Time = 23:50

Start Decay Period: Julian Date (1996) = 24; Time = 2:0
   (Elapsed Time =   3.090 days)

Measured

Theoretica

Formaldehyde, ppb

Elapsed Time Since Start of Experiment, days
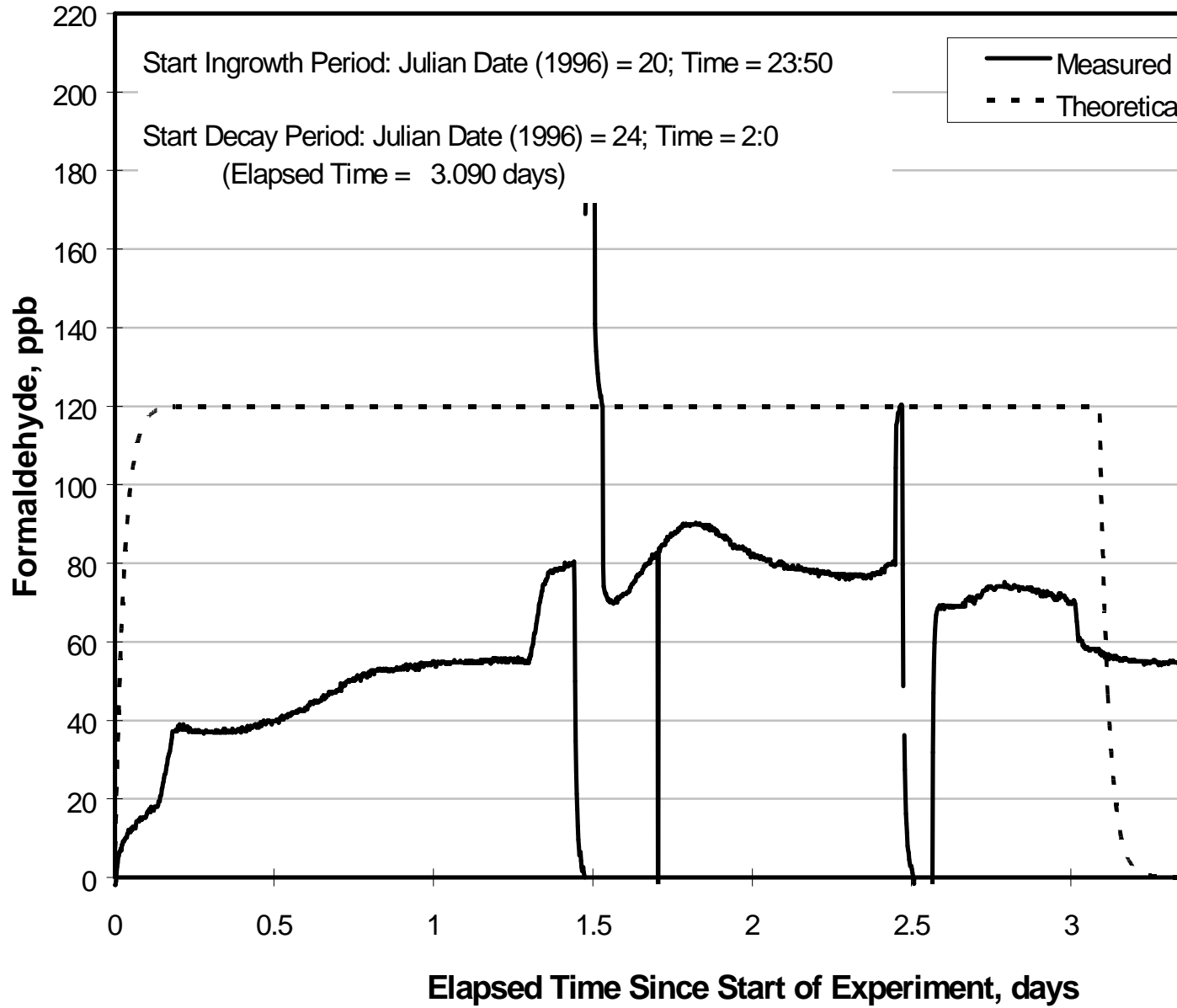
Figure 6-18. Comparison of the Theoretical and Measured Formaldehyde Concentrations for the Second W

The data presented in Figure 6-18 exhibit noticeable fluctuations at several points during the experiment. This behavior has not been thoroughly evaluated, but several of the fluctuations are known to be responses of the Interscan to variations in temperature of the room in which the instrument resides.

6.3.4 Carpet Barrier Tests

A set of tests to evaluate the behavior of the underlayment both with and without a carpet and padding barrier were conducted under identical chamber conditions. In both tests, a tight-fitting aluminum pan with edges equal to the depth of the underlayment, carpet and padding was used. In the first test, a 7.1-inch square piece of underlayment was placed in the pan with nothing on top of it. In the second test, a 7.1-inch square piece of underlayment was placed in the pan with an equally sized piece of padding and carpet placed on top of it. For both tests, the pan was then placed horizontally on the chamber floor, and chamber was monitored using the Interscan.

The resulting data for the first and second tests, adjusted for instrument drift, are shown in Figure 6-19. The data indicate that the underlayment is releasing formaldehyde. While it is tempting conclude from these data that the carpet and padding have no effect on the emission of formaldehyde, the carpet sink test presented earlier in this section indicates otherwise. The imprecision of the instrument and the temperature effects make it difficult to understand the long-term trend in the emission profile. This temperature effect is discussed later, in section 6.3.6.

6.3.5 Parameter Estimation

The behavior of surfaces found in the indoor environment is known to affect the concentration of indoor air pollutants (Tichenor *et al.,* 1991). Understanding the behavior of the various materials used in the test house regarding adsorption and desorption of formaldehyde is an important factor in applying the results of the chamber tests to interpret the data collected at the house. Consequently, the chamber data were analyzed and used to estimate the adsorption/desorption rate parameters for formaldehyde to the various materials.
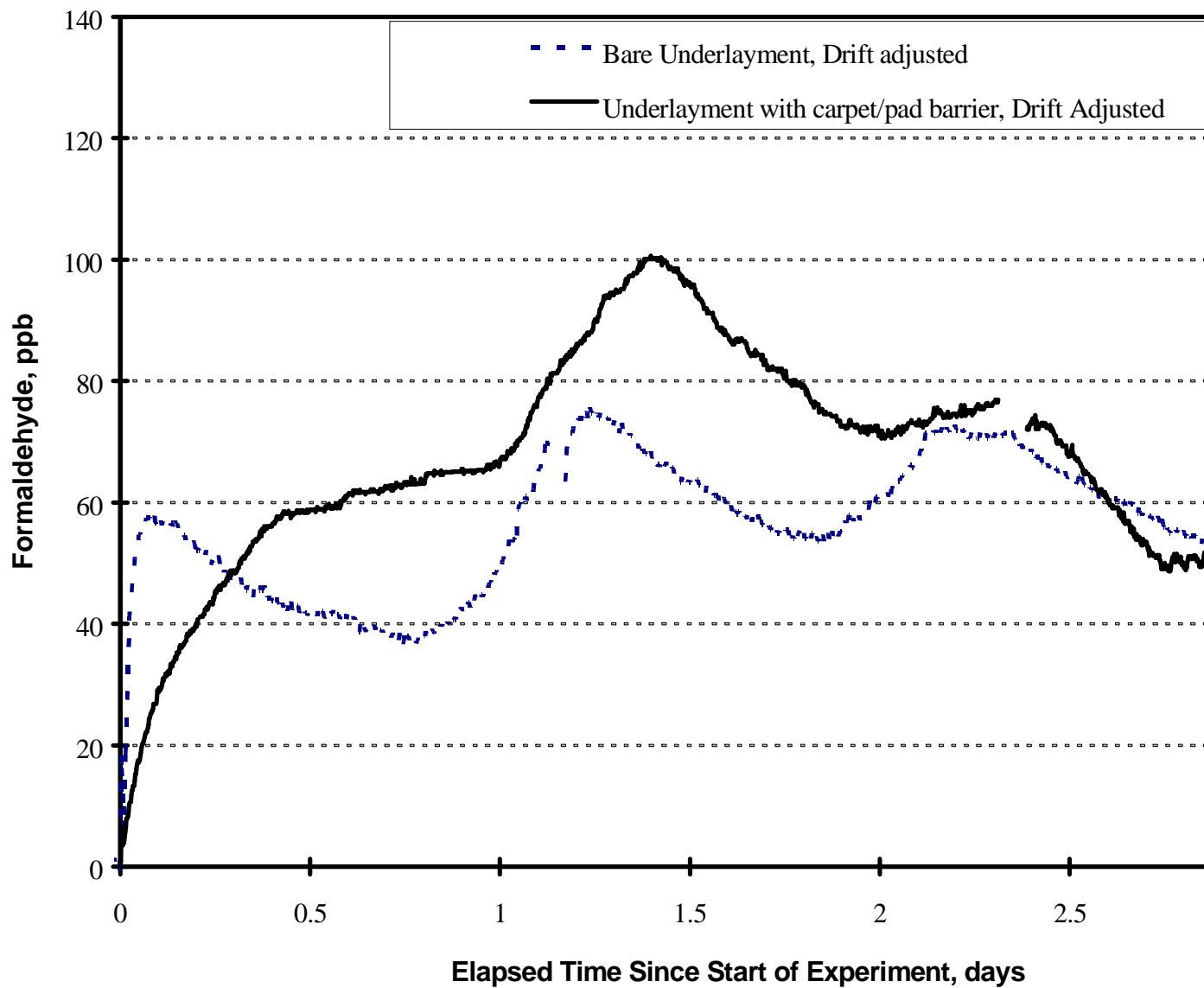
Figure 6-19. Comparison of Concentration Profiles for Bare Underlayment and Underlayment Covered by C

Several sink models have been proposed to describe adsorption/desorption on material surfaces. The Langmiuir isotherm description has been shown to provide a reasonable representation of the adsorption/desorption of compounds with carpet (Tichenor *et al.,* 1991). The mass-balance equation using the Langmiur isotherm for the chamber is as follows:

$$V\frac{dC}{dt} = R(t) - NVC - k_a AC + k_d AM \qquad (1)$$

or:

$$\frac{dC}{dt} = \frac{R(t)}{V} - NC - k_a LC + k_d LM \qquad (2)$$

where:

C	=	chamber air concentration, mg/m^3
t	=	time, h
V	=	chamber volume, m^3
R(t)	=	emission rate of the source, mg/h
N	=	air exchange rate, h^{-1}
k$_a$	=	adsorption rate constant, m/h
k$_d$	=	desorption rate constant, h^{-1}
A	=	area of the sink, m^2
M	=	mass per unit area of sink, mg/m^2
L	=	ratio of sink area to chamber volume, m^{-1}

The mass-balance equations using the Langmiur isotherm for the carpet is as follows:

$$A\frac{dM}{dt} = k_a AC + k_d AM \qquad (3)$$

or:

$$\frac{dM}{dt} = k_a C + k_d M \qquad (4)$$

The above equations were implemented as a finite difference computer model. A parameter estimation algorithm using a least-squares error convergence criterion was also implemented for use with the model to estimate the parameters for a given data set.

The parameters for the model were estimated for the first carpet/pad sink test described above (Section 6.3.2). Figure 6-20 compares the resulting model predictions to the data set along with the estimated parameters. The estimated parameters were then applied to the second carpet/pad sink test described above (Section 6.3.2), adjusting only the input stream concentration to the experimental value used during the second test (0.12 ppm). The resulting model predictions are compared to the measured data in Figure 6-21.

FIRST CARPET/PAD SINK TEST

LANGMUIR ISOTHERM MODEL

Adsorption rate Constant (m/hr), ka = 1.304

Desorption rate Constant (1/hr), kd = 0.196

Input Stream Concentration (ppb) = 200

Predicted Concen

Measured Concen

Formaldehyde, ppb

Elapsed Time Since Start of Experiment, days
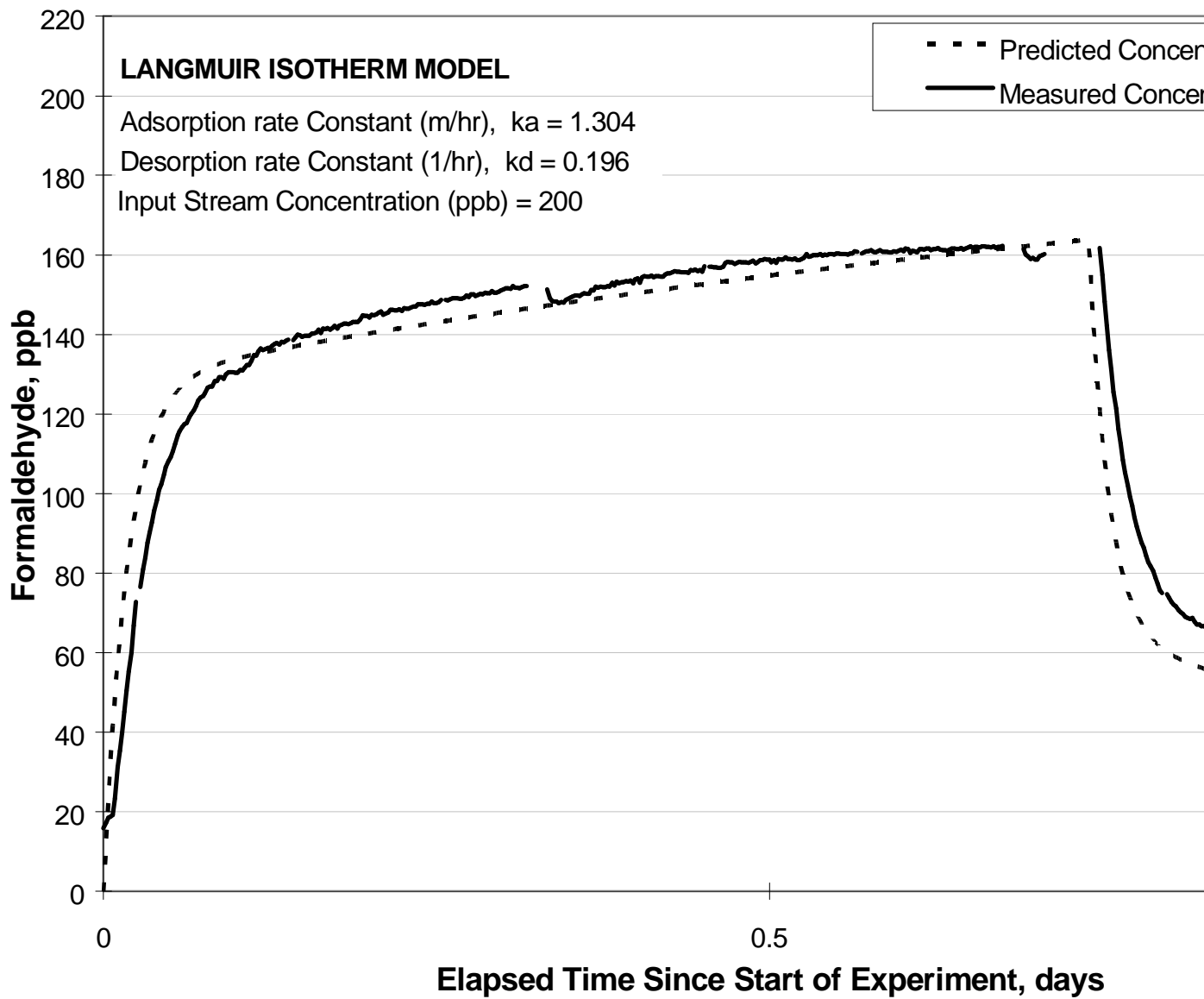
Figure 6-20. Comparison of the Measured and Predicted Formaldehyde Concentrations for the First Carpet/Pad

SECOND CARPET/PAD SINK TEST

LANGMUIR ISOTHERM MODEL

Adsorption rate Constant (m/hr), ka = 1.304

Desorption rate Constant (1/hr), kd = 0.196

Input Stream Concentration (ppb) = 120

Predicted Concentrati

Measured Concentrat

Formaldehyde, ppb

Elapsed Time Since Start of Experiment, days
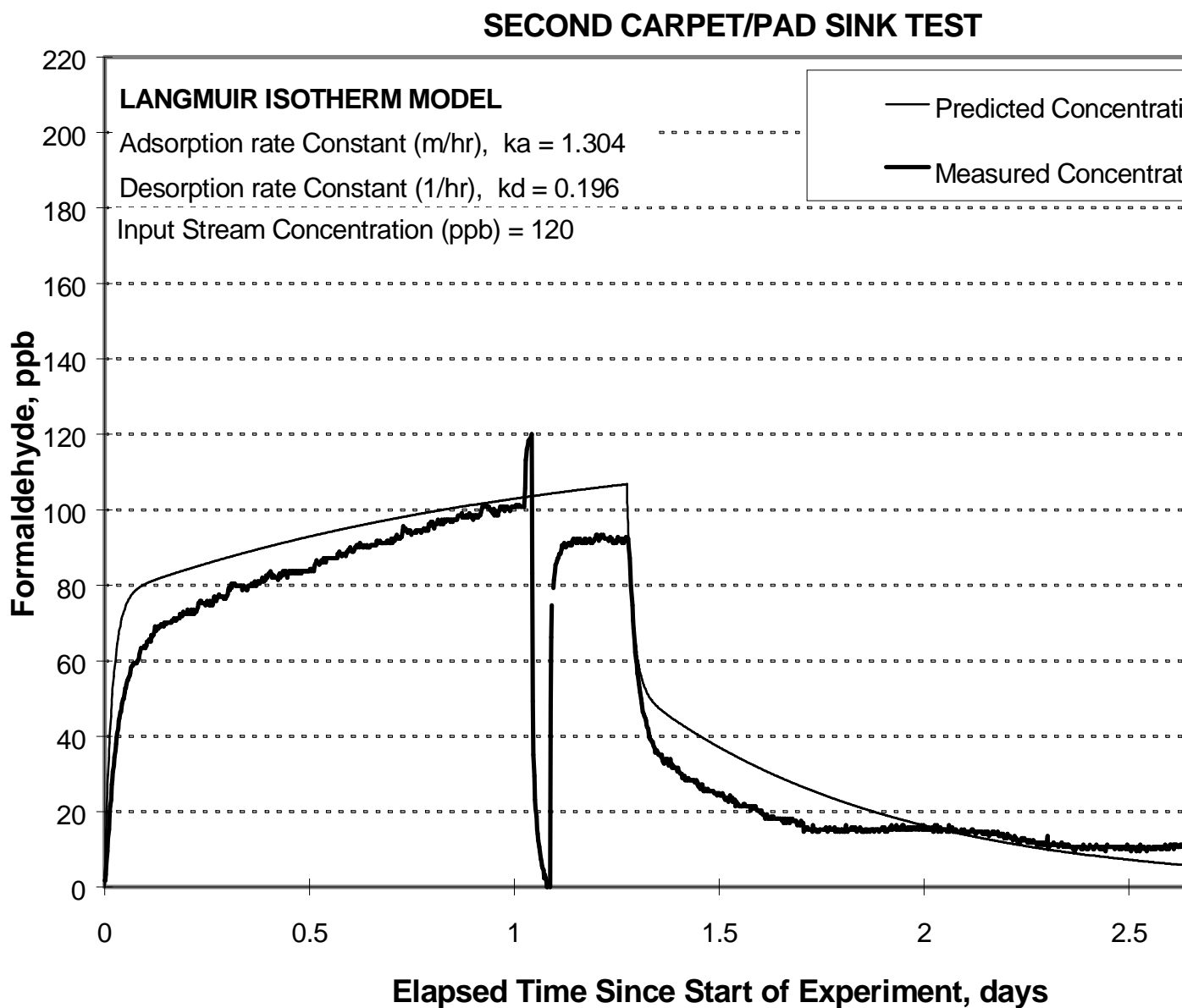
Figure 6-21. Comparison of the Measured and Predicted Formaldehyde Concentrations for the Second Ca

The model predictions generally resemble the data set and are well within the range of instrument precision, with the possible exception of the period immediately following a span and/or a zero. The Langmiur isotherm description provides a reasonable representation of the data sets from both chamber tests, and therefore is believed to be valid over a range of concentrations. The ratio of chamber loading rate to air exchange rate is approximately equal to that used in the test house, and therefore, this model is expected to provide a reasonable representation of the carpet behavior at the house.

The theoretical mass accumulated in the carpet during each test is shown in Figure 6-22. The difference between the curves for the first and the second tests are the result of the different feed concentrations (0.2 ppm and 0.12 ppm, respectively), and the shorter time period allowed for ingrowth during the first test. The accumulation of formaldehyde in the carpet during each test was continuing until the decay period was initiated, indicating that an equilibrium condition was not reached. The slight downward curvature observed in the plot for each test indicates that the adsorption rate relative to the desorption rate is decreasing, but the system is still well removed from the adsorption/desorption equilibrium condition.

The Langmiur isotherm description was also applied to the wallboard sink tests described in Section 6.3.2. However, the model was unable to achieve a reasonable fit to the data. This is likely due to the more complex nature of the wallboard. The Langmiur model is based on the assumption that the surface is homogeneous and composed of independent and identical sorption sites. Carpet more closely approximates this assumption. However, wallboard is a relatively complex integration of a porous paper surface and a porous gypsum interior, offering innumerable, tortuous paths to differing sorption sites.

Several other models have been proposed in the technical literature to better represent the processes that occur in more complex systems. In particular, models that better represent the diffusion through the boundary layer, and models that provide alternative representations of the sorption phenomena, have exhibited a greater ability to represent the adsorption/desorption behavior of chemicals to wallboard. Models describing the diffusion through the boundary layer and diffusion through the porous sink material-- the (BLDC Boundary Layer Diffusion Controlled) and BLPD (Boundary Layer Porous Diffusion) models--have been proposed (described by Axley, 1993) and have been shown to provide a reasonable representation of this behavior. Several representative adsorption isotherm models have also been proposed (Axley, 1993), with varying degrees of success dependent on the sorbate (the chemical) and the sorbent (the building material).

These models offer varying degrees of complexity and quality of fit to the data. The appropriate model is likely an adequately complex model to represent the data without requiring large parameter sets. The BLDC model, in combination with the Linear or the Langmuir adsorption isotherm models, has been shown to provide a reasonable representation of the formaldehyde adsorption/desorption to wallboard data without excessive numbers of parameters (Axley, 1993). The BLDC model represents adsorption/ desorption dynamics by assuming that the boundary layer transport rate is the limiting factor, and that instantaneous equilibrium with the sorbent is achieved.

Comparison of Theoretical Mass in Sink
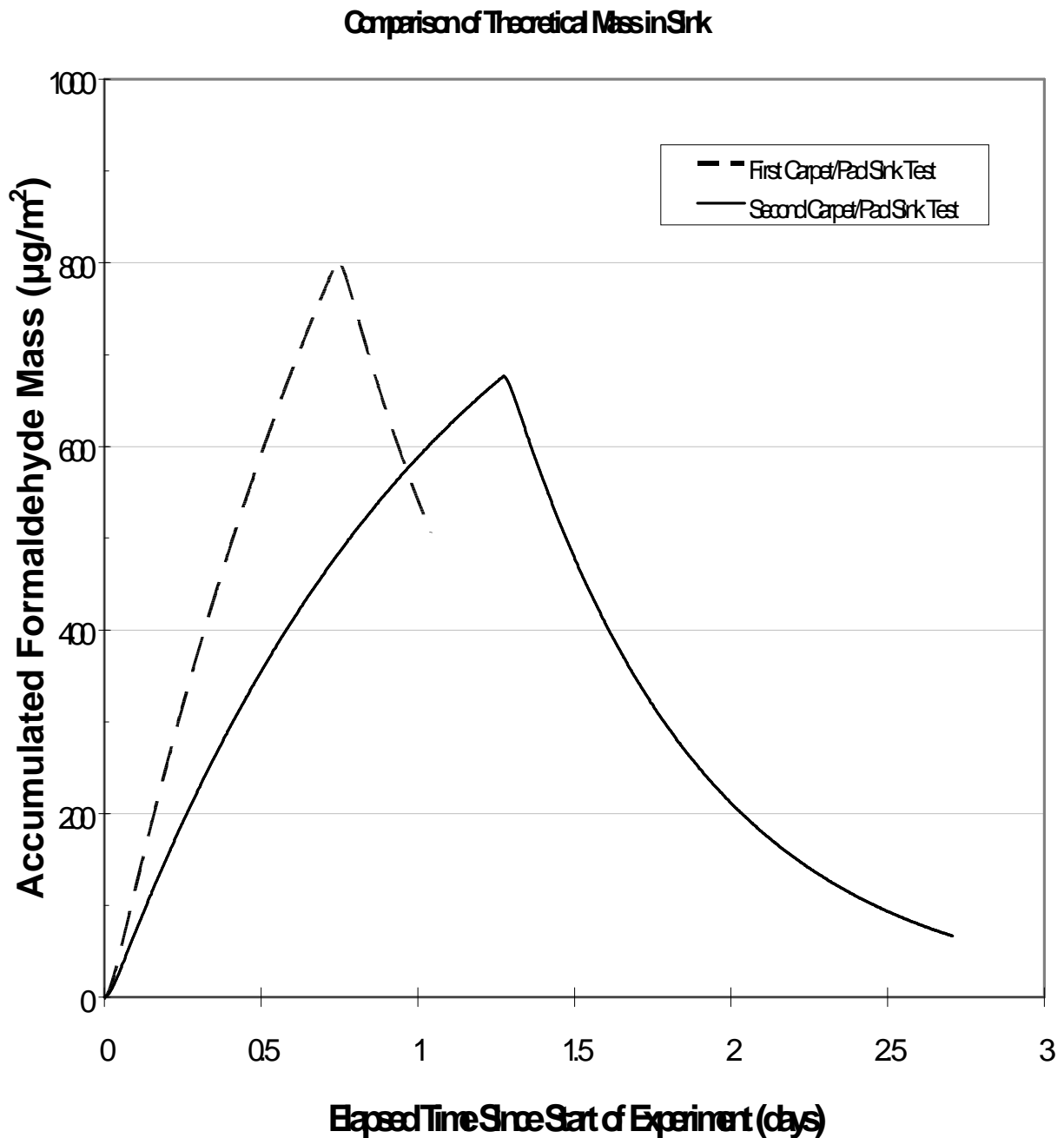
Figure 6-22. Comparison of the Theoretical Accumulated Formaldehyde Mass During the Two Carpet/Pad Sink Tests.

One possible fit for the BLDC model applied to the first wallboard test is shown in Figure 6-23. The fit appears to capture the general trend in the data, but it is unclear whether there is an additional process occurring that is not captured by the model. The measured data are not adequately precise to support a conclusion regarding the applicability of the model.

The fit presented in Figure 6-23 is the result of a search of the likely parameter space. No attempt was made to force the parameter estimates to resemble the estimated values for these parameters from the Axley study. Although the resulting parameters differ from those reported by Axley, they are not significantly different after adjusting to the appropriate chamber volume and gypsum board size. Further investigations are needed to pursue avenues of model improvement and to identify theoretical limits of application. Additional chamber tests to capture a broader range of conditions would be fundamental to such investigations.

The BLDC model and other models show promising predictive capability. These models have been applied to a very specific set circumstances, in isolation of complicating factors such as variability in air exchange rates, interzonal flows, temperature, and humidity. How well these models can be unified and applied to other real-world conditions, such as the test house, is presently unknown.

6.3.6 Interscan Behavior

The Interscan output has been observed to alter in response to temperature around the instrument, carbon dioxide concentration, and solar radiation. The temperature response is fairly strong. One example of this behavior is shown in Figure 6-24; the temperature of the instrument and the output of the instrument appear to be highly correlated. This is an effect that needs to be better understood; during any future use of the Interscan, it is highly recommended that the instrument be placed in a temperature-controlled environment (e.g., ±1 °F).

HCHO: Model run for the BLDC (Boundary Layer Diffusion Controlled) sorption model Langmuir isotherm case

Kl*Cso*Mgyp (g) = 5775;   hm*p*Agyp (g/h)=273.18913104

Where: Kl = Lamgmuir isotherm coefficient (g air/g Formaldehyde)   Mgyp = Mass of gypsum board (g)

Cso = Sorbed-phased concentration corresponding to complete coverage by a single layer (g Formaldehyde/g air)

hm = Average film mass transfer coefficient (m/s);   p = Air density (g air/m3);   Agyp = Projected surface area of

Input Stream Concentration (µg/m3) =245.4

Predicted Concentration (ppb)

Actual Concentration (ppb)

Formaldehyde, ppb

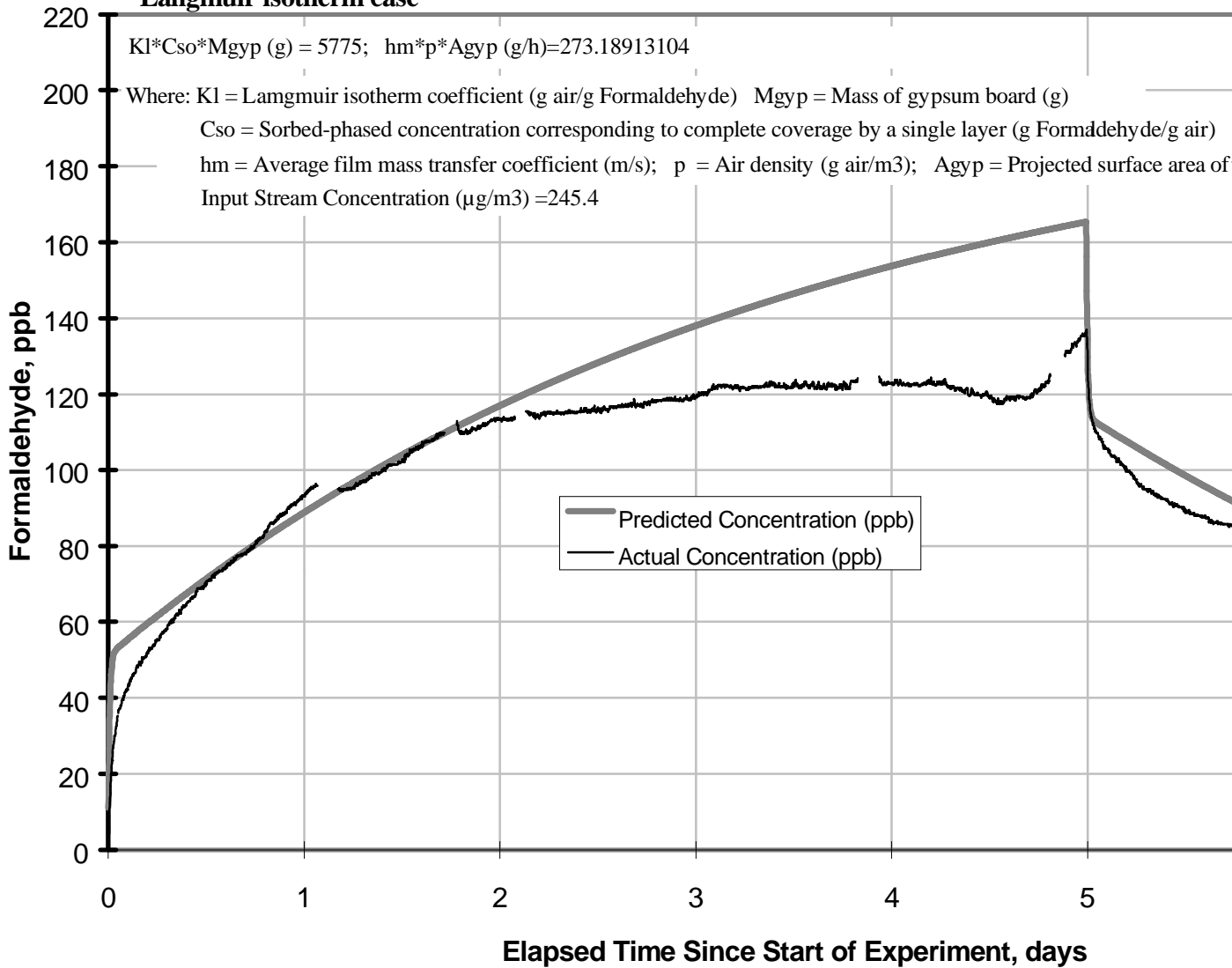**Elapsed Time Since Start of Experiment, days**

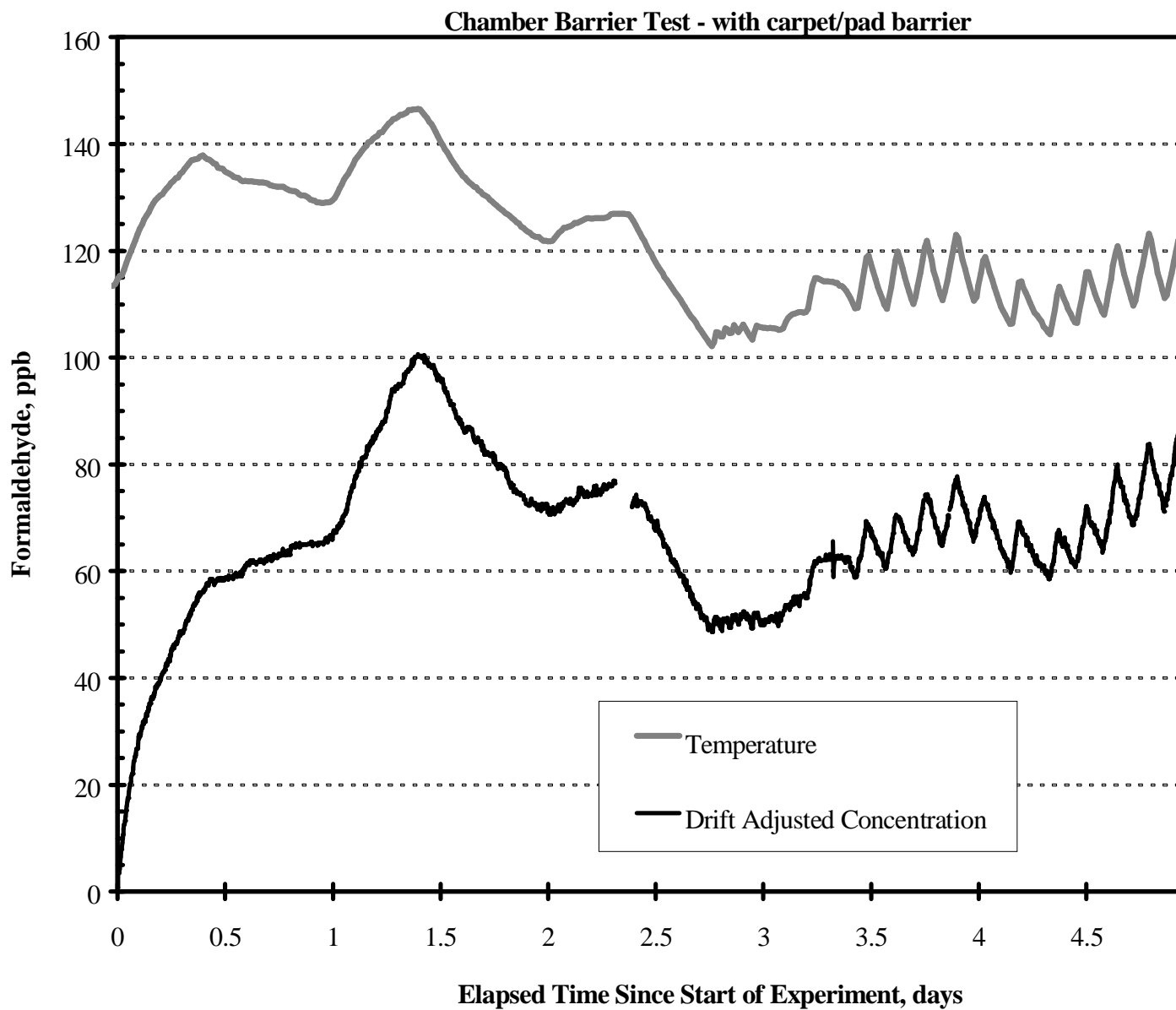Figure 6-23. Comparison of the Measured and Predicted Formaldehyde Concentrations for the Second Ca

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Figure 6-24. Example of Interscan Response to Temperature.

7.0 CONCLUSIONS

The conclusions presented below relate primarily to the pilot study objectives listed in Section 1.2.

Several logistical difficulties were encountered that prevented the pilot study from being completed as o Among the greatest difficulties were (1) locating a house for the study, (2) preparing and characterizing the hous humidity levels in the house within the prescribed range. The remote location of the conventional house ultimat study meant a significant investment in driving time for technicians and made it difficult to undertake certain rou otherwise would have required less than a day's work. Such inefficiencies, together with significant front-end w peculiarities of the house and initial difficulties with the pre-monitoring interlaboratory comparison, resulted in pr expenditures beyond those originally anticipated for this portion of the study. As a result, certain aspects of the had to be sacrificed--only three of the four loading configurations planned for the conventional house could be c logistics of manufactured-house testing could not be evaluated beyond initial discussions with manufacturers. T drop manufactured houses from the study was related to financial resources rather than logistical difficulties, as manufacturer was identified.

On the other hand, logistical aspects such as acquiring, storing and accessing the materials associated house loading went remarkably smoothly. This success was partly due to the high level of cooperation from var representatives and their close working relationship with the study team. Difficulties were encountered, howeve target temperature at the storage facility, in part because this facility included some office space and the tempe responded primarily to the thermostat in the office area.

Little difficulty was encountered in controlling most experimental variables at the conventional house. Th product loading rate, emission rate, temperature and air exchange--all were generally kept within their respectiv decay was evident in the emissions of wood products stored for successively later loadings. The greatest chall maintaining relative humidity levels in the target range of 40 to 60 percent, especially during the transition from s from summer to fall. Humidity was not a primary experimental variable for the study, but was considered to be a that should be tightly controlled.

It was demonstrated that different test results could be obtained across different experimental condition precision in measurement response could be obtained. Differences across experimental conditions (medium ve could be distinguished, although the differences were partially dampened by the substantial sink effect of the gy Appropriate precision was obtained largely because of the consistently high resolution (minimum detection limit (90 to 110 percent) and precision (± 10 percent or better) for the DNPH method with a 24-hour sampling duratio

The data from the conventional house were marginally sufficient for estimating the extent of variability o variation with changes in experimental conditions. There were sufficient duplicate DNPH samples to obtain a g combined sampling/analytical precision, as a baseline for comparison with other sources of variation. There we

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sampling events to estimate the room-to-room component of variation. The limited number of loadings (three ra
were planned), coupled with the unique circumstances of the first loading (little mass in the indoor sinks at the o
to properly estimate the variance component associated with repeats of the same loading configuration. Howev
demonstrated that the variance across repeats of the high loading, for a specific sampling location at the same
loading of the house, was only marginally higher than the variance for duplicate DNPH samples.

    Formaldehyde carryover between successive tests at the conventional house, due to inherent sinks, wa
effect, due largely to absorption of formaldehyde by painted gypsum wallboard, was not eliminated by the presc
conventional house. Replacing the wallboard between successive runs would likely be expensive, time consum
The monitoring results did suggest that baseline formaldehyde values are reasonably reproducible once the hou
with UF-bonded wood products. Thus, removing the potential confounding effect of sinks is perhaps best accor
loading" them before formal collection of data, or through modeling efforts. The success of such modeling effo
ability to properly estimate rates of mass transfer to and from the sinks, which were partially addressed in this s
chamber tests.

    The ability to control and vary the air exchange rate of the conventional house using a heat recovery ve
demonstrated. This ability was demonstrated for two of the three target air exchange rates (0.2 and 0.5 ACH) p
study; the third target (1.2 ACH) could not be addressed because the HRV lacked suffucient capacity. Achievin
0.2 ACH was primarily accomplished by sealing procedures that substantially reduced the air leakage of the hou
sensitivity of its air exchange rate to weather conditions.

    Considerable attention was required to maintain the continuous formaldehyde monitor and calibrate the
are two primary reasons for this difficulty: (1) the concentration levels monitored for this study are at the lower
instrument; and (2) the resolution becomes increasingly poor as the electrochemical cell ages. Zero and span
complications but, in retrospect, some of this difficulty might have been overcome by a different auto-zeroing str
hour auto-zero every six hours. The performance of this instrument for chamber testing of sink effects, on the c
encouraging. This improved performance is most likely attributable to a more stable operational environment c
requirements that limit the aging of the cell. Sensitivity of the instrument to temperature is also a concern, but f
can be overcome by keeping the instrument in a temperature-controlled environment.

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