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**Application of a Multi-zone Airflow and  
Contaminant Dispersal Model to Indoor Air  
Quality Control in Residential Buildings**

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## Synopsis

A new multizone airflow and contaminant dispersal model CONTAM93 is described, along with a demonstration of its application in a study of ventilation and contaminant control in single-family residential buildings. While CONTAM93 is based on existing theory of network airflow analysis and contaminant dispersal, the model employs a unique graphic interface for data input and display. The interface uses a sketchpad to describe the connections between zones and icons to represent zones, openings, ventilation system components, and contaminant sources and sinks. The model, its graphic interface and plans for its further development are described.

As a demonstration of the capabilities of CONTAM93, the paper describes a study of ventilation and contaminant control in eight single-family residential buildings. The overall objective of the effort is to study the impact of residential HVAC systems on indoor air quality (IAQ). This paper describes the study and the use of CONTAM93 to calculate whole building air change rates for a range of weather conditions and to simulate fan pressurization and tracer gas decay tests in the houses.

### 1. Introduction

Airflow rates in buildings are determined by the interaction of the building structure, its HVAC system, and weather conditions. Indoor pollutant concentrations depend on these airflow rates, pollutant source and sink characteristics, and outdoor concentrations. A whole-building, multizone approach, accounting for all of these factors, is required to study many important issues in building airflow and IAQ and has been implemented in many multizone airflow and IAQ models. A survey of multizone models, all of which provide at least some of the required modeling capabilities, is described by Feustel and Dieris (1). This paper describes a new multizone airflow and pollutant transport program CONTAM93 (2), which is the latest in the series of multizone IAQ modeling programs developed at the National Institute of Standards and Technology (NIST).

To demonstrate the use and capabilities of CONTAM93, its application in a residential IAQ modeling study is also discussed (3). In this study, CONTAM93 is being used to predict contaminant concentrations in a number of single-family dwellings as a function of weather conditions and HVAC system configurations for several contaminant sources. The study design and the use of CONTAM93 in this effort is described, but the results of the contaminant simulations are not presented in this paper. Fan pressurization tests were simulated with CONTAM93 to characterize the airtightness of the houses modeled in the study. The program was also used to calculate whole building air change rates for a range of weather conditions and to simulate tracer gas decay measurements of whole building air change rates. These air change rates were compared to each other and to air change rates calculated with the single-zone LBL infiltration model (4).

## 2. CONTAM93

### 2.1 General Description

CONTAM93 is an easily used contaminant analysis program combining the best available algorithms for modeling the airflow and contaminant dispersal in multizone buildings. It employs a graphic interface and is usable on commonly available small computers. Over the past several years, NIST has developed a series of public domain computer programs for calculating airflow and contaminant dispersal in multizone buildings. The earliest such program was ASCOS (Analysis of Smoke Control Systems) (5). Another program, TARP (Thermal Analysis Research Program) (6, 7), used multizone airflow calculations to estimate the portion of building thermal load due to infiltration and perform a simple contaminant migration analysis. Programs developed specifically for the study of contaminant dispersal included CONTAM86 (8) and CONTAM87 (9). NBSAVIS/CONTAM88 (10) added multizone airflow analysis capability, based on the program AIRMOV (11), and a menu-driven interface to CONTAM87. Improvements in the airflow calculation algorithm were implemented in the AIRNET program (12). CONTAM93 combines a new graphic interface with the contaminant simulation capabilities of CONTAM88 and the airflow analysis method of AIRNET.

CONTAM93 requires a 286-class (or higher) PC compatible computer with math coprocessor, VGA graphics, and MS-DOS. CONTAM93 consists of two programs: CONTAM and CONTAMX. CONTAMX is a non-interactive program which computes the airflows and/or contaminant concentrations in a building from information on the building, its HVAC system, ambient conditions, contaminant sources, and contaminant removal mechanisms. CONTAMX can perform steady-state, transient (up to 24 hour), and 24-hour cyclic simulations with a user specified time step. CONTAM is an interactive program for processing the required CONTAMX input and for displaying or exporting the CONTAMX output. Both CONTAM and CONTAMX operate under the 640K-byte memory limit of MS-DOS, which is sufficient for simulating buildings with several hundred zones and multiple contaminants.

### 2.2 Graphic Interface

When using CONTAM93, the user does not directly access the data files describing the building. All access to the building description is done through the CONTAM program and its graphic interface. The description of the building is created (or modified) in the SketchPad. The SketchPad consists of an invisible array of about 3600 small cells into which the user places various symbols representing building features relevant to the calculation of contaminant dispersal. This produces a simple illustration which has been chosen intentionally to represent the simplicity of the underlying mathematical model. The SketchPad is used to establish the geometric relationships of the relevant building features. It is not intended to produce a scale drawing of the building. Instead, it is used to create a simplified model where the walls, zones, and airflow paths are topologically similar to the actual building. The SketchPad allows the entry and display of the data in an intuitive manner. The SketchPad will bring up various data entry screens needed to define the

mathematical characteristics of the various building features (e.g. leakage areas and contaminant source strengths). After performing the simulation, the flows and pressure drops at each opening are presented on the SketchPad. Transient contaminant concentrations can also be displayed.

The CONTAM93 SketchPad is designed to simplify the data input and analysis processes for a multi-zone airflow and contaminant dispersal simulation. It is still up to the user to decide how best to idealize the building as a multizone system based on the building layout and the objectives of the simulation. The user must also determine which contaminant dispersal processes are important and appropriate input values for the building being simulated. The required input values can be numerous and include the following: airtightness of exterior envelope and interior partition components, ventilation system airflow rates, wind pressure coefficients, ambient weather and contaminant concentrations, indoor contaminant source strengths and sink characteristics, contaminant reaction rates, and filter efficiencies. Values of these quantities can be determined from the published literature and field measurement.

Once the user has decided how to represent the building as a multizone system and has determined appropriate input values, the building data is entered into the SketchPad. Building data is organized by *levels* with data entry beginning at the lowest level. A level would typically be a building floor, but a suspended ceiling acting as a return air plenum or a raised floor acting as a supply plenum may also be treated as a level leading to multiple levels per floor. Each level is divided by *walls* into separate regions of uniform air temperature, pressure, and contaminant concentration called *zones*. Walls include the building envelope and internal partitions with a significant resistance to air flow, and are drawn as either horizontal or vertical lines. There is a set of implicit walls (generally floors) separating the zones on different levels. A default ambient zone surrounds the building. Other zones can be designated as ambient to represent, for example, a courtyard. An airflow *path* indicates some building feature by which air can move from one zone to another. Such features include cracks in the building envelope, open doorways, and exhaust fans. Path symbols placed on the walls are used to represent openings between zones or to ambient; any other placement represents an opening in the floor to the zone on the level below. Contaminant source (or sink) symbols may be placed in any zone. These represent any feature (within the list of available models) which produces or removes a contaminant. A simple model of an air handling system is available with supply and return point symbols placed within the appropriate zones. All supply and return airflows follow user defined schedules.

Figure 1 shows the floor plan of a ranch style house modeled for the residential IAQ study discussed in this paper, and Figure 2 shows the CONTAM93 SketchPad representation of this house. In this case the representation closely mimics the floor plan. Airflow paths are represented by the diamond-shaped symbols on the walls. The zone symbols are squares with X's inside; the contaminant sources are boxes with C's inside. The air handling system, system supply points, and system return points are represented by a bold S, squares with dots inside, and squares with dashes inside, respectively.

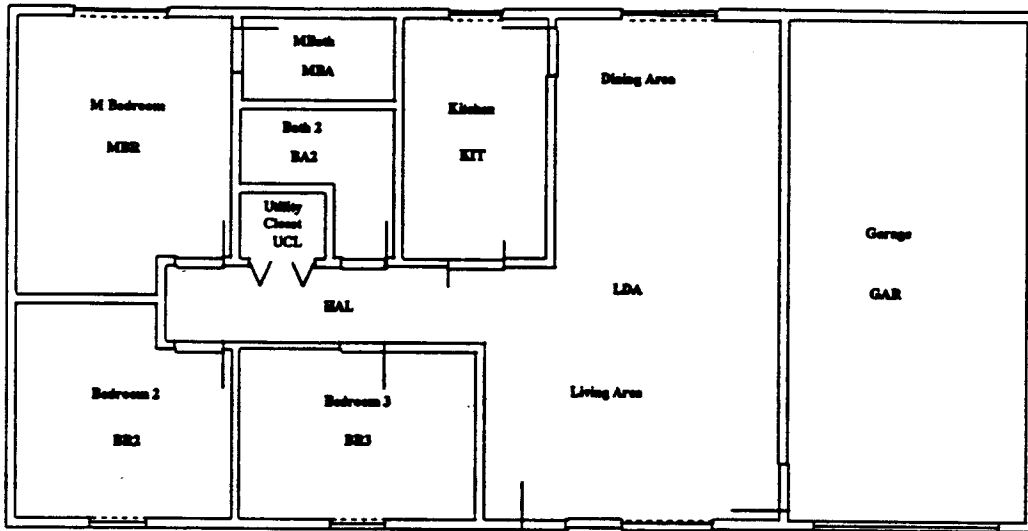


Figure 1 - Miami ranch house floorplan and zones

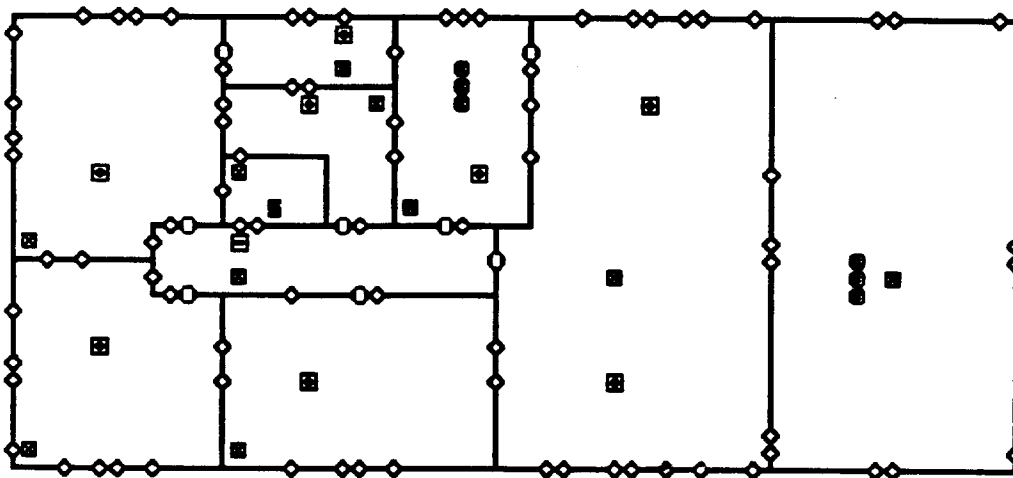


Figure 2 - Miami ranch house in CONTAM93 Sketchpad

### 2.3 Future Development Plans

Work is presently in progress to improve the user interface and to extend the range of features that can be simulated. The logic of the interface is being made more similar to common graphic interface standards, although the next version of the program will still run

under DOS. A DOS extender is being used to allow merging of the I/O processor and the simulation programs into a single program and to let the size of the SketchPad be user definable with a maximum of about 32,600 cells. This extender will limit the program to 386-class and higher PC's. The program is being modified to include libraries of airflow paths and contaminant source/sink models. Extensions in the simulation capabilities will include ductwork, exposure analysis, non-linear contaminant chemistry, and aerosol transport.

### 3. Example Application of CONTAM93: A Residential IAQ Study

As a demonstration of the capabilities of CONTAM93, this section describes its application in a study of IAQ in single-family residential buildings (3). The houses are described in terms of how they are represented in CONTAM93. The results of using CONTAM93 to analyze airflow in the houses with three approaches (simulated fan pressurization tests, calculated whole building air change rates, and simulated tracer gas decay measurements of whole building air change rates) are also presented.

#### 3.1 Project Description

As interest and concern about residential IAQ increases, whole building modeling has the potential for improving our understanding of many important issues. Most of the research to date has employed simple models of the building and its systems, ignoring the multizone nature of the airflows involved and some important mechanisms of contaminant transport. Whole building analysis, using multizone approaches, is needed to advance our understanding of the impact of HVAC systems on residential IAQ and the possibility of using these and other systems to mitigate some IAQ problems. This section describes such a study being performed at NIST using CONTAM93. A detailed description of the study plan is contained in reference 3.

The overall objective of the project is to study the impact of residential HVAC systems on IAQ. The study involves simulations in eight single-family residential buildings. The buildings include a ranch house and a two-story house, each located in a hot (Miami, Florida) and a cold (Minneapolis, Minnesota) climate and each modeled with typical and tight levels of envelope air leakage. These houses are described briefly later in this paper and in detail in reference 3.

The pollutant sources used in the study were selected based on a literature review of pollutants relevant to the residential environment. The pollutants include total volatile organic compounds (VOC), nitrogen dioxide (NO<sub>2</sub>), carbon monoxide (CO) and fine and coarse particulates. The VOC sources include a constant source with a generation rate proportional to floor area in each room, simulating a flooring material, and so-called burst sources with a constant generation rates lasting 30 minutes, simulating use of a consumer product. An individually identifiable burst source is released in each room, once in the morning and once in the afternoon. CO, NO<sub>2</sub> and fine particulates are generated by an oven in the kitchen area at a constant rate for 30 minutes in the morning and one hour in the evening. These same combustion products are generated by a portable heater in the garage

or basement for a three-hour period in the morning and a two-hour period in the evening. Outdoor concentrations for these pollutants are specified, with the levels of CO and NO<sub>2</sub> becoming elevated in the morning and early evening.

In addition to the airflow component inputs described in this paper, the contaminant modeling required additional inputs. These include numerical values to characterize reversible VOC sinks, NO<sub>2</sub>, and particle deposition rates, and HVAC system filter particulate-removal efficiencies. These values were determined based on information available in the literature.

The strategy in the study was to perform 24 hour simulations of airflow and contaminant concentrations for each of the eight houses subject to each of the contaminant sources. These simulations were performed for a typical hot, mild and cold day for each of the two cities. The results of these so-called baseline simulations were concentrations of the simulated contaminants at 15 minute time steps over each day. The simulations are then repeated with one of three IAQ control technologies installed in the HVAC system of each house. These technologies include an electrostatic particulate filter, a heat recovery ventilator and an outdoor air intake damper on the forced-air system return. Although there are many other options for controlling residential contaminants, these particular controls were selected based on their ability to be installed in existing forced-air systems.

### 3.2 Building Descriptions and CONTAM93 Input

This modeling study involves single-family residential buildings: a ranch house and a two story house, located in two sites (Miami and Minneapolis). Each building is modeled as a multizone airflow system, containing roughly ten zones, with air leakage elements connecting the zones to each other and the outdoors. Figure 1 is a schematic floor plan of the Miami ranch house. The Miami houses are slab-on-grade, while the Minneapolis houses have full basements. Each building was modeled with typical and low values of air leakage, making a total of eight buildings in the study. Reference 3 contains detailed descriptions of the layout and dimensions of each house, including schematic floorplans.

Detailed information on building component leakage of the houses is not available as the houses modeled were not based on real buildings. However, since there is no attempt to match predictions with experimental data, the building leakage modeled needs only to be reasonable in magnitude and distribution. Table 1 shows all of the leakage paths between zones for the Miami ranch house (see Figure 2 for the representation of the Miami ranch house in CONTAM93). Table 2 lists the values for those leakage paths for both typical and tight cases. The Table 2 leakage areas are for a reference pressure difference of 4 Pa and a discharge coefficient of 1.0 and are based on values listed in Table 23-3 of ASHRAE (4) unless otherwise noted. The typical values were generally based on "best estimate" and/or uncaulked entries in the ASHRAE table, while the tight values were based on minimum and/or caulked entries. All doors connecting zones other than closets were modeled as open. The same leakage values were used for the other houses, although the paths connecting the zones differed depending on the house configurations.

Table 1 - Miami ranch house airflow paths

	MBR	BR2	BR3	MBA	BA2	UCL	KIT	LDA	HAL	GAR	ATC
BR2	INTW OUTL										
BR3		INTW OUTL									
MBA	INTD INTW										
BA2	INTW OUTL			INTW OUTL							
UCL	INTW				INTW						
KIT				INTW OUTL	INTW OUTL						
LDA			INTW OUTL				INTW INTD OUTL				
HAL	INTD INTW	INTD INTW	INTD INTW OUTL		INTD INTW	CLD INTW	INTD INTW OUTL	HAD			
GAR								EXTD EXW OUTL			
ATC	CEIL CPEN	CEIL CPEN	CEIL CPEN	CEIL CPEN PIP	CEIL CPEN PIP	CEIL CPEN	CEIL CPEN	CEIL CPEN CPEN	CEIL ATD		
AMB	WIN EXW OUTL	WIN EXW OUTL	WIN EXW OUTL	EXV EXW OUTL	EXV		WIN EXV EXW OUTL	SGD EXTD WIN EXW OUTL		GAD GARF EXW	VNT
	MBR	BR2	BR3	MBA	BA2	UCL	KIT	LDA	HAL	GAR	ATC

The wind pressure distribution on a building's exterior surfaces depends on the wind direction, the building shape, and the location on the building exterior. For this study, the pressure coefficient values used for the building walls were based on Equation 23-8 of ASHRAE (4). The coefficient for the flat garage roof was based on Figure 14-6 of ASHRAE (4).

Each house was modeled with a central forced-air heating and cooling system. Features of the system design for the Miami houses include: equipment in a first floor utility closet, supply ducts in the attic and a central return for the ranch house; and interior supply ducts and one return on each floor for the two-story house. For the Minneapolis houses, features include: equipment located in the basement, interior supply ducts, and a return in each room. Guidelines published by the National Association of Home Builders (15) were used to design the heating and cooling systems. Detailed descriptions of the building HVAC systems are contained in Reference 2 and include the heating and cooling equipment types and descriptions, overall and individual supply and return flow design values for both heating and cooling, and drawings showing the system equipment and duct locations and duct sizes. CONTAM93 also requires information on the HVAC system operation, specifically, an on-off schedule.



Table 2 - Air leakage coefficients

Name	Description	Typical	Tight
ATD	Attic door	30 cm <sup>2</sup> /ea	18 cm <sup>2</sup> /ea
CEIL	Ceiling [Based on general ceiling]	1.8 cm <sup>2</sup> /m <sup>2</sup>	0.79 cm <sup>2</sup> /m <sup>2</sup>
CLD	Closet door (closed) [Based on interior door]	0.9 cm <sup>2</sup> /m	0.25 cm <sup>2</sup> /m
	Closet door frame [Based on general door frame]	25 cm <sup>2</sup> /ea	12 cm <sup>2</sup> /ea
CPEN	HVAC ceiling penetration [Based on kitchen vent with damper closed]	5 cm <sup>2</sup> /ea	1 cm <sup>2</sup> /ea
EXTD	Exterior door [Single]	21 cm <sup>2</sup> /ea	12 cm <sup>2</sup> /ea
	Door frame [Wood]	1.7 cm <sup>2</sup> /m <sup>2</sup>	0.3 cm <sup>2</sup> /m <sup>2</sup>
EXV	Bathroom exhaust vent	20 cm <sup>2</sup> /ea	10 cm <sup>2</sup> /ea
	Kitchen exhaust vent	40 cm <sup>2</sup> /ea	5 cm <sup>2</sup> /ea
EXW	Ceiling-wall joint	1.5 m <sup>2</sup> /m	0.5 m <sup>2</sup> /m
	Floor-wall joint	4 cm <sup>2</sup> /m	0.8 cm <sup>2</sup> /m
	Wall-wall joint [Based on ceiling-wall joint]	1.5 m <sup>2</sup> /m	0.5 m <sup>2</sup> /m
GAD	Garage door [Based on general door (2 m x 4 m)]	0.45 cm <sup>2</sup> /m	0.31 cm <sup>2</sup> /m
	Garage door frame [Wood]	1.7 cm <sup>2</sup> /m <sup>2</sup>	0.3 cm <sup>2</sup> /m <sup>2</sup>
GARF	Garage roof [Based on general ceiling]	1.8 cm <sup>2</sup> /m <sup>2</sup>	0.79 cm <sup>2</sup> /m <sup>2</sup>
HAD	Hall doorway	2.4 m <sup>2</sup> /ea	2.4 m <sup>2</sup> /ea
INTD	Interior door (closed) [Based on Table 4.2 of Klotz and Milke (13)]	140 cm <sup>2</sup> /ea	75 cm <sup>2</sup> /ea
	Interior door (open)	2.1 m <sup>2</sup> /ea	2.1 m <sup>2</sup> /ea
INTW	Interior wall [Based on gypsum board on stud wall (14)]	2.0 cm <sup>2</sup> /m <sup>2</sup>	2.0 cm <sup>2</sup> /m <sup>2</sup>
OUTL	Outlet	2.5 cm <sup>2</sup> /ea	0.5 cm <sup>2</sup> /ea
PIP	Piping penetrations	6 cm <sup>2</sup> /ea	2 cm <sup>2</sup> /ea
SGD	Sliding glass door	22 cm <sup>2</sup> /ea	3 cm <sup>2</sup> /ea
VNT	Attic vent [Based on Table 21-1 of 4]	1 cm <sup>2</sup> / 300 cm <sup>2</sup>	1 cm <sup>2</sup> / 300 cm <sup>2</sup>
WIN	Double hung window	2.5 cm <sup>2</sup> /m	0.65 cm <sup>2</sup> /m
	Window framing [Wood]	1.7 cm <sup>2</sup> /m <sup>2</sup>	0.3 cm <sup>2</sup> /m <sup>2</sup>

Another important consideration for the HVAC systems is duct leakage. In CONTAM93, a leak can be modeled by including an additional system supply or return point and reducing the other supply and return flows by the corresponding amount. For the Minneapolis houses, a 10% return leak was included for the return trunk in the basement. For the Miami ranch house, a 10% supply leak was included for the supply trunk in the attic. For the Miami two story house, all system ducts are located in a plenum between floors and no leaks were included.

### 3.2 Airflow modeling results

CONTAM93 was used to analyze airflow in the houses using three approaches: simulated fan pressurization tests, calculated whole building air change rates, and simulated tracer gas decay measurements of whole building air change rates. Based on the the fan pressurization test results, infiltration rates were also predicted using the LBL infiltration model (4).

Fan pressurization tests in the houses were simulated with CONTAM93 by including a constant flow element in the door of each house and adjusting the flow until pressure differences of 4 and 50 Pa was achieved. The airflow rates at 50 Pa were divided by the interior volumes of the houses to determine the 50 Pa air change rates, and the 4 Pa flows

were converted to effective leakage areas using Equation 27 in Chapter 23 of ASHRAE (4). The results of the fan pressurization simulations are shown in Table 3. The difference between the Miami and Minneapolis houses is due primarily to the existence of the basement in the Minneapolis houses. In terms of both measures of airtightness, the tight houses are about 66% tighter than the houses of typical leakage.

Table 3 - Fan pressurization simulation results

House	ach <sub>50</sub> (hr <sup>-1</sup> )	Leakage area (cm <sup>2</sup> )
Typical Miami ranch	13.2	680
Tight Miami ranch	4.1	220
Typical Minneapolis ranch	6.6	720
Tight Minneapolis ranch	2.2	230
Typical Miami 2 story	12.9	1120
Tight Miami 2 story	4.6	390
Typical Minneapolis 2 story	8.8	1170
Tight Minneapolis 2 story	3.1	410

CONTAM93 was used to calculate whole building air change rates for wind speeds from 0 to 10 m/s and indoor-outdoor temperature differences from -10 to 30 °C. The wind direction was held constant throughout the simulations. These simulations were performed with the HVAC systems both on and off. Whole building air change rates were calculated by adding the airflow entering the conditioned space of the house through all leakage paths. The results of these airflow simulations for the Miami ranch house are shown in Tables 4 and 5 for the system off.

Several general trends are shown by these results. Using 'tight' values for the airflow elements vs. 'typical' values reduced the whole building air change rate by up to a factor of four as compared to a factor of three for the fan pressurization results. Also, over the range considered here, the wind speed had a greater impact on the whole building air change rate than the temperature difference. However, the tight airflow elements reduced the impact of the wind speed more than the impact of the temperature difference.

Table 4 - Whole house air change rate for typical Miami ranch house (ach)

Im - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.33	0.21	0.00	0.22	0.35	0.46	0.57	0.67	0.76
2	0.40	0.32	0.33	0.38	0.47	0.54	0.65	0.74	0.84
4	0.75	0.78	0.82	0.85	0.89	0.94	1.00	1.08	1.15
6	1.31	1.34	1.38	1.42	1.46	1.50	1.54	1.61	1.67
8	1.92	1.96	2.01	2.06	2.11	2.16	2.21	2.27	2.33
10	2.57	2.63	2.69	2.75	2.81	2.87	2.94	3.01	3.08

Table 5 - Whole house air change rate for tight Miami ranch house (ach)

$T_m - T_{out}$ (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.10	0.07	0.00	0.07	0.11	0.14	0.17	0.20	0.23
2	0.11	0.09	0.08	0.10	0.14	0.17	0.20	0.23	0.26
4	0.18	0.18	0.19	0.21	0.22	0.24	0.26	0.28	0.31
6	0.30	0.31	0.32	0.33	0.34	0.36	0.38	0.39	0.42
8	0.44	0.46	0.47	0.48	0.49	0.51	0.53	0.54	0.57
10	0.60	0.61	0.63	0.64	0.65	0.67	0.69	0.71	0.73

Tables 6 and 7 show the results of the airflow simulations with the HVAC system on. Operation of the HVAC system increased the building air change rate as much as 0.31 ach at zero wind speed and temperature differences due to supply duct leakage in the attic. The effect of the system fan was less than 0.05 ach at high wind speeds ( $> 4$  m/s) and temperature differences ( $> 10$  °C).

Table 6 - Whole house air change rate for typical Miami ranch house with system fan on (ach)

$T_m - T_{out}$ (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.45	0.38	0.31	0.39	0.52	0.63	0.73	0.83	0.93
2	0.59	0.52	0.41	0.50	0.63	0.74	0.84	0.93	1.03
4	0.86	0.81	0.85	0.89	0.95	1.02	1.10	1.17	1.24
6	1.34	1.37	1.41	1.45	1.49	1.55	1.61	1.67	1.73
8	1.95	1.99	2.04	2.09	2.14	2.19	2.25	2.30	2.38
10	2.60	2.66	2.72	2.78	2.84	2.91	2.97	3.04	3.11

Table 7 - Whole house air change rate for tight Miami ranch house with system fan on (ach)

$T_m - T_{out}$ (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.33	0.37
2	0.32	0.31	0.31	0.31	0.31	0.31	0.32	0.36	0.39
4	0.39	0.37	0.35	0.32	0.32	0.33	0.37	0.41	0.44
6	0.47	0.45	0.44	0.42	0.40	0.41	0.43	0.46	0.49
8	0.56	0.54	0.52	0.51	0.53	0.55	0.57	0.58	0.61
10	0.65	0.63	0.64	0.66	0.69	0.71	0.73	0.75	0.77

CONTAM93 was also used to simulate tracer gas decay tests in the houses by setting an initial tracer gas concentration of 100, in arbitrary units, in all building zones except the garage and attic. Transient tracer gas concentrations were simulated for the same temperature-wind speed grid as above. Air change rates were calculated for each zone from the decay of the tracer gas concentration at 15 minutes after the start of the simulation. The whole house air change rate was calculated as the volume-weighted average of the individual zone air change rates. The simulation time step was chosen such that reducing it by half

resulted in an absolute average change of less than 1% in individual zone tracer gas concentrations at the 15 minute point.

The results of these simulations with the HVAC system off are shown in Tables 8 and 9. These simulations were repeated with the HVAC system on and the results are presented in Tables 10 and 11. The building air change rates based on the simulated tracer gas decay tests are, as expected, very similar to those determined with the building airflow calculations. The average absolute percent difference between the two methods is 5%. The largest differences occur at high temperature differences and high wind speeds due to decreased uniformity in individual zone tracer gas concentrations. These nonuniformities in tracer gas concentration result in an overestimation of the building air change rate as compared to the calculated values in Tables 4 through 7. The overestimation of the air change rates is larger at higher air change rates because the concentrations in the different zones diverge more at the 15 minute time interval. Also, the overestimation is larger at high wind speeds than at large temperature differences because the wind causes greater concentration nonuniformities among the zones.

Table 8 - Tracer gas decay simulation results for typical Miami ranch house (ach)

T <sub>m</sub> - T <sub>out</sub> (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.33	0.21	0.01	0.22	0.35	0.46	0.57	0.66	0.76
2	0.40	0.32	0.34	0.39	0.48	0.54	0.65	0.74	0.83
4	0.80	0.84	0.88	0.91	0.96	1.01	1.07	1.14	1.22
6	1.45	1.49	1.53	1.59	1.63	1.67	1.72	1.79	1.86
8	2.18	2.24	2.29	2.35	2.41	2.47	2.54	2.60	2.71
10	3.05	3.12	3.19	3.27	3.35	3.43	3.51	3.60	3.79

Table 9 - Tracer gas decay simulation results for tight Miami ranch house (ach)

T <sub>m</sub> - T <sub>out</sub> (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.10	0.07	0.00	0.07	0.11	0.14	0.18	0.21	0.24
2	0.11	0.09	0.08	0.10	0.14	0.17	0.20	0.23	0.26
4	0.18	0.18	0.19	0.21	0.22	0.24	0.26	0.28	0.31
6	0.31	0.32	0.33	0.34	0.35	0.37	0.39	0.40	0.43
8	0.46	0.47	0.48	0.50	0.51	0.53	0.54	0.56	0.58
10	0.62	0.64	0.65	0.67	0.68	0.70	0.72	0.75	0.76

Table 10 - Tracer gas decay simulation results for typical Miami ranch house with system fan on (ach)

T <sub>m</sub> - T <sub>out</sub> (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.41	0.35	0.30	0.39	0.52	0.63	0.72	0.82	0.91
2	0.56	0.50	0.40	0.49	0.62	0.73	0.82	0.92	1.00
4	0.88	0.84	0.88	0.93	0.98	1.05	1.13	1.20	1.27
6	1.41	1.46	1.50	1.54	1.58	1.64	1.71	1.77	1.83
8	2.10	2.16	2.21	2.27	2.32	2.38	2.44	2.50	2.58
10	2.92	2.99	3.06	3.14	3.21	3.29	3.37	3.46	3.55

Table 11 - Tracer gas decay simulation results for tight Miami ranch house with system fan on (ach)

$T_{in} - T_{out}$ (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.29	0.29	0.30	0.30	0.30	0.31	0.31	0.31	0.35
2	0.30	0.30	0.30	0.30	0.30	0.31	0.31	0.34	0.38
4	0.37	0.36	0.34	0.33	0.31	0.32	0.36	0.40	0.43
6	0.46	0.45	0.44	0.43	0.41	0.40	0.42	0.45	0.48
8	0.56	0.55	0.53	0.52	0.53	0.55	0.57	0.58	0.61
10	0.65	0.64	0.64	0.66	0.69	0.71	0.73	0.75	0.77

As expected, the zone tracer gas concentrations were more uniform for the simulations with the HVAC system on than for the simulations with the system off. This increased uniformity creates the appearance of decreased air change rates with the system on under certain conditions. For example, at a temperature difference of 30 °C and a wind speed of 10 m/s, turning the system on *reduced* the tracer gas-based estimate of the air change rate by 0.24 ach (from 3.79 in Table 8 to 3.55 in Table 10) while the actual air change rate was *increased* by 0.03 ach (from 3.08 in Table 4 to 3.11 in Table 5).

Whole building air change rates for the houses were also estimated using the single-zone LBL infiltration model described in ASHRAE (4). The airflow rate was calculated using Equation 23-32 of ASHRAE (with the effective leakage areas from Table 3 above and a wind coefficient for moderate local shielding) for the same temperature-wind speed grid as the CONTAM93 simulations above. The results for the Miami ranch house are shown in Tables 12 and 13. The average absolute percent differences between the LBL air change rates and the CONTAM93 air change rates are 32% and 19% for the typical and tight buildings, respectively. However, the LBL model estimates are much closer to the air change rates calculated with CONTAM93 at low wind speeds than at high wind speeds.

Table 12 - LBL model results for typical Miami ranch house (ach)

$T_{in} - T_{out}$ (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.37	0.26	0.00	0.26	0.37	0.45	0.52	0.59	0.64
2	0.45	0.37	0.26	0.37	0.45	0.52	0.58	0.64	0.69
4	0.63	0.58	0.51	0.58	0.63	0.69	0.73	0.78	0.82
6	0.86	0.81	0.77	0.81	0.86	0.90	0.93	0.97	1.00
8	1.09	1.06	1.03	1.06	1.09	1.12	1.15	1.18	1.21
10	1.34	1.31	1.29	1.31	1.34	1.36	1.39	1.41	1.44

Table B - LBL model results for tight Miami ranch house (ach)

$T_m - T_{out}$ (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.12	0.08	0.00	0.08	0.12	0.15	0.17	0.19	0.21
2	0.15	0.12	0.08	0.12	0.15	0.17	0.19	0.21	0.22
4	0.21	0.19	0.17	0.19	0.21	0.22	0.24	0.25	0.27
6	0.28	0.26	0.25	0.26	0.28	0.29	0.30	0.31	0.33
8	0.35	0.34	0.33	0.34	0.35	0.36	0.37	0.38	0.39
10	0.43	0.42	0.42	0.42	0.43	0.44	0.45	0.46	0.47

#### 4. Summary and Conclusions

CONTAM93 is an easily used contaminant analysis program combining the best available algorithms for modeling the airflow and contaminant dispersal in multizone buildings with a graphic interface. The models, the program interface, and planned future development were described. Also described was the application of CONTAM93 in a NIST study to assess the potential effectiveness of existing HVAC technology to reduce the levels of selected pollutants in single-family residential buildings with central forced-air heating and cooling systems. This description included the results of simulated fan pressurization tests, building airflow simulations for a range of weather conditions, and simulated tracer gas decay tests.

#### References

1. Feustel HE and Dieris J. "A Survey of Air Flow Models for Multizone Structures" (1992) *Energy and Buildings* 18:79-100.
2. Walton GN. *CONTAM93 - User Manual* (1994) NISTIR 5385, National Institute of Standards and Technology.
3. Emmerich SJ and Persily AK. *Indoor Air Quality Impacts of Residential HVAC Systems Phase I Report: Computer Simulation Plan* (1994) NISTIR 5346, National Institute of Standards and Technology.
4. ASHRAE. *1993 Handbook of Fundamentals* (1993) American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
5. Klote JH. *A Computer Program for Analysis of Smoke Control Systems* (1981) NBSIR 80-2157, National Bureau of Standards.
6. Walton GN. *Thermal Analysis Program Reference Manual* (1983) NBSIR 83-2655, National Bureau of Standards.

7. Walton GN. "A Computer Algorithm for Predicting Infiltration and Interroom Airflows" (1984) ASHRAE Transactions, Vol. 90, Part 1.
8. Axley J. *Indoor Air Quality Modeling Phase II Report* (1987) NBSIR 87-3661, National Bureau of Standards.
9. Axley J. *Progress Toward a General Analytical Method for Predicting Indoor Air Pollution in Buildings, Indoor Air Quality Modeling Phase III Report* (1988) NBSIR 88-3814, National Bureau of Standards.
10. Grot RA. *User Manual NBSAVIS CONTAM88* (1991) NISTIR 4585, National Institute of Standards and Technology.
11. Walton, GN. *A Computer Algorithm for Estimating Infiltration and Inter-Room Air Flows* (1983) NBSIR 83-2635, National Bureau of Standards.
12. Walton GN. *AIRNET - A Computer Program for Building Airflow Network Modeling* (1989) NISTIR 89-4072, National Institute of Standards and Technology.
13. Klote JH and Milke JA. Design of Smoke Management Systems (1992) American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. and Society of Fire Protection Engineers.
14. Shaw CY, Magee RJ, and Rousseau J. "Overall and Component Airtightness Values of a Five-story Apartment Building (1991) ASHRAE Transactions, Vol. 97, Pt. 2.
15. Yingling RK, Luebs DF, and Johnson RJ. *Residential Duct Systems - Selection and Design of Ducted HVAC Systems* (1981) National Association of Home Builders of the United States.