NT-87-06-1

# HVAC INTEGRATED SYSTEM ANALYSIS

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## ABSTRACT

This paper presents an advancement in HVAC system analysis, which is predicated on the electrical analogy to fluid systems. An integrated description of a building's HVAC system and rooms is constructed and may be used to support system testing and balancing, system performance analysis, capacity verification testing, and room interactions. Additional system simulation is useful to assess plant modifications and their impact on HVAC performance.

This method is applicable to any facility with a large or complex HVAC system configuration. These improved techniques will produce a major economy in costs of system balancing and other testing activities while reducing the overall time required to balance the system.

## INTRODUCTION

The method discussed here for HVAC integrated system analysis consists of a comprehensive set of tools for system modeling, analysis, and simulation developed from actual field experience gained during the balancing and start-up of HVAC systems at six nuclear units. These tools include isometric and network representations of the HVAC system, a microcomputer data conversion program, and a mainframe data analysis code.

This approach to HVAC analysis allows simplified modeling of complex ventilation networks utilizing the concepts of the electrical analogy to fluid systems. These complex networks can be subdivided into manageable "building blocks," which are analyzed independently and then assembled to form the complete integrated system.

These analytical tools can be applied to HVAC systems during design and prior to operation, simulating the performance of different component combinations. The tools can also be applied to operating systems for determining the adjustments necessary to balance the systems, thereby minimizing manual iteration of system balancing devices, such as dampers.

The major advantage of this method is the ability to integrate all active and passive system elements into one model. This model can then be used to predict the design conditions in all areas under differing operating scenarios. If maintained, the model forms a diagnostic tool for analyzing the effects of system modifications throughout the life of the plant.

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Today's HVAC design often relies heavily on the experience and judgment of the designer and analyst. Some individuals perceive HVAC design as more of an artform than a disciplined science. Actually, this perception reflects the complexity often encountered in the HVAC systems found in power plants and other large industrial systems.

For example, in nuclear power plants, many functional requirements are placed on the HVAC system. These include division of the system into accessible and nonaccessible areas because of the radioactivity, segregation of the building into fire and nonfire zones, operation of the system in normal and post-accident configurations, or combinations of these and other requirements. This multiplicity of requirements has led toward the use of independent modular design techniques to provide the proper treatment for each requirement.

The analytical method discussed here allows the several modular subsystems contained in a complex HVAC system to be described as a single unified model. This facilitates the assessment of the interaction between subsystems during the various modes of system operation.

## APPLICATIONS

The following examples highlight several of the applications for integrated system analysis.

### System Balancing

Once constructed, HVAC systems must be tested, adjusted, and balanced so that the installed assembly of fans and ductwork can provide design airflow rates, airflow directions, temperatures, and pressures to all areas served. This balancing process is typically accomplished by an iterative trial-and-error field procedure, which involves testing the system, adjusting the system's balancing devices, and then re-testing and re-adjusting until the desired conditions are obtained. The number of iterations required to balance a system, however, can be significantly reduced by employing a method of integrated system analysis.

This method computerizes the iterations, minimizing the time spent in the field on readjustments. Once the system resistances are determined and fan performance accounted for, effects of various component combinations can be determined without further testing.

An integrated model can be scaled to each selected application. Models can be constructed and applied to a single system or subsystem, such as a control room zone airflow study, or to a group of several interrelated systems such as a building ventilation system study for nuclear plant containment.

### Outage Planning

An integrated HVAC analytical model can be an invaluable tool in outage planning. The use of such a model facilitates outage planning in a manner that is analogous to the use of physical models. HVAC systems are interconnected, distributed throughout the entire power plant, and often have common points, such as plant general areas or the plant exhaust stack. Thus, there are many opportunities for system interactions.

### HVAC System Modifications

During a plant's lifetime, modifications are performed that add to or redistribute the heat loads within the plant. Examples are the expansion of laboratory facilities or the replacement of insulation systems. Such changes need to be properly assessed to avoid imbalances in the operation of HVAC systems that can adversely affect the performance of plant equipment, including the equipment qualified life. Electronic equipment is especially susceptible to adverse environmental effects.

In addition, minimizing in-plant trial-and-error adjustment of systems reduces field labor costs and the risk of exposing personnel to radiation. Thus, modification planning and post-modification checks are important applications of integrated HVAC models.

### System Design

In a sense, all uses of these modeling techniques are simulations. The term "simulation," however, is used here to denote those applications that focus on design or diagnostic activities rather than testing.

Design and construction activities typically involve the efforts of several HVAC engineers and occur over an extended period of time. Additionally, input from other engineering disciplines as well as construction interface must be accommodated as the design proceeds. Hence, a single model can consolidate the inputs and significantly enhance them.

Other design considerations require knowledge of gas composition as well as flow rate. For example, an indoor air quality assessment may require determination of the concentration of airborne pollutants, dust, smoke, or radiation. Simulation of an HVAC system can be used to predict its performance regarding these and other potential hazards. Simulations can be enhanced once performance parameters of the installed systems become available.

Degradation of performance, capacity, and efficiency of systems as a function of age and maintenance can be evaluated by adjusting the appropriate system elements in the simulation model and observing the resultant performance.

These methods can be applied to other fluid systems as well as to air systems. The ability to describe an incompressible fluid system has been incorporated to simulate hydronic systems, such as plant chilled water or component cooling systems. The balancing of the chilled water system in conjunction with balancing of the air-handling portions of the system is another useful application.

These techniques can be applied to other plant systems. For example, a fossil power plant can be represented by an integrated system model that includes representations of the furnace, forced draft and induced draft fans, air heaters, plant stack, and connecting ductwork. This requires the capability to include heat addition, heat transfer, and variation of gas composition in the simulation. Such a model can be used to simulate start up, normal and upset conditions. In addition, changes in pressure as well as airflow rate throughout the system can be predicted and used to verify the proper operation of the plant.

### Diagnostic Analysis

Diagnostic analyses allow us to gain a further grasp on HVAC system performance. Actual installed performance can vary from the desired design performance for both new and aging systems. An integrated model is an excellent tool for identifying the contributing factors for system performance below design expectations and for assessing possible corrective actions. To be effective, the integrated simulation model is constructed and then calibrated by field data so it describes the as-built configuration. A common example of performance deviation is the inaccuracy in assigning heat loads during the design process. The heat loads may differ appreciably from those actually occurring during plant operation. A more accurate value of the heat loads is vital in those cases where insufficient airflow or local hot spots have been identified or where additional heat loads may result from proposed modifications. By entering input from the measured area temperatures and airflow rates into the simulation model, the actual heat loads for given operating conditions can be calculated and used to assess corrective actions.

### System Configuration Studies

Another beneficial application of diagnostic simulation is in the performance of system configuration studies. As previously stated, the set of HVAC systems for a large facility is complex and has many potential interface permutations. The design process usually does not attempt an exhaustive evaluation of all possible combinations but rather addresses given criteria and design operating modes. On occasion, the plant can be placed in an unanticipated configuration with undesirable results. These types of upset conditions are more easily studied using a computerized system model.

## TECHNICAL APPROACH

Given this overview of the wide range of applications of integrated HVAC system analysis, it is appropriate to discuss the technical approach involved in developing and implementing such models.

## System Model Development

The flow of fully turbulent air in the ductwork system can be represented by the following relationship:

$$R = \frac{\Delta P_T}{\rho Q^2} \qquad (1)$$

where:

$R$ = resistance of the ductwork system

$\Delta P_T$ = loss in total pressure

$Q$ = airflow rate

$\rho$ = density

This is analogous to Ohm's law of electric circuits, where resistance is proportional to voltage drop divided by current. This electrical analogy to fluid systems, shown in Figure 1, is exploited to assemble a network of paths and nodes representing the HVAC ductwork system. Using symbology derived from the analysis of DC circuits, the mechanical elements of a ductwork segment, a fan, and a damper can be represented as the electrical elements of fixed resistance, a current source, and a variable resistance, as shown in Figure 2. The network diagram can represent each element in the ductwork system or complex system elements can be combined in accordance with rules similar to those for the equivalent resistance of series and parallel electric circuits.

Series Resistances $$R_T = \sum_{i=1}^{n} R_i \qquad (2)$$

Parallel Resistances $$R_T = \left[\sum_{i=1}^{n} (R_i)^{-1/2}\right]^{-2} \qquad (3)$$

The typical fan performance curve and ductwork system interaction is represented as an equivalent network with a voltage source in series with a resistance. Once the network diagram representing the HVAC system has been constructed, the value of each resistance element in the network is determined by microcomputer analysis of field test data.

It is customary industry practice to calculate in-duct airflow rates from the mean velocity within the duct based upon a pitot tube velocity pressure traverse, assuming a "Standard Air" density rather than the system design density.

Many of the plant HVAC systems provide 100% outdoor air ventilation where the density variation could be more than 10% depending upon the time of year. Since a system could be tested at any time during the year, the airflow rate test data must be corrected to the design conditions for proper comparison. Correction factors are only applied when the air density varies from the "Standard Air" valve by more than 10% AABC (1982).

In order to provide a baseline for comparative analysis and for repeatability of evaluated results, a comprehensive testing and balancing evaluation procedure was developed based upon the AMCA fan application manual (AMCA 1976). This procedure allows for the baselining of actual airflow rate data and an indication of actual fan performance.

This procedure has been codified into the microcomputer. The expected airflow rates at the design conditions are computed, based upon actual velocity pressures, and density at the traverse location and the density at the fan inlet. In addition, several diagnostics that assess the quality of the collected data are performed. The microcomputer program has been most effective when utilized with an on-site microcomputer system which allows for rapid determination of airflow rate and system pressure data. Once the actual airflow rates and pressures are determined, the actual resistance of the duct system elements are calculated These resistances are used as input to a mainframe node-path computer code, which analyzes th performance of the system and determines the adjustments necessary. This code is discussed in detail in the Appendix.

## SAMPLE APPLICATION

The sample application chosen is the use of these methods in the testing, adjusting, and balancing of HVAC systems. This method is currently being employed at two two-unit nuclear power stations in the testing and balancing of the auxiliary building HVAC system. The simplified auxiliary building HVAC system shown in Figure 3 processes approximately 260,000 cfm of air through 200 rooms on eight floor levels within each plant.

The complex supply and exhaust systems were separated into groups based upon the segregation of the building's use or ductwork location and further divided into manageable subsystems based upon the identity number of the main duct airflow measuring stations, as shown on Figure 4.

Individual isometric drawings were prepared for each subsystem. The development of these isometric drawings minimized the need to refer to the more than 100 physical drawings for the system. The isometric drawings provide a single reference drawing for planning of actual traverse locations and for reviewing the impact of test results on a subsystem basis. In addition, the isometric drawings provide an excellent summary of the installed system configuration that can be used throughout the life of the plant.

Once the individual isometric drawings were developed, individual HVAC network diagrams were prepared. These diagrams represent all major fixed and variable resistance as well as the airflow rate into each room. After each network diagram was reviewed against the physical drawings, the nodes and paths for the network were numbered. The network diagram was then reviewed to establish the pitot-tube traverse locations necessary to define the value of each system's resistance element. The traverse locations were then transferred to the respective isometric drawings. When all traverse locations were identified, a field walkdown was performed to ensure accessibility.

Actual testing was usually performed on the night shift to minimize worker interferences and problems inherent with daytime plant activities. The collection of data proceeded on a subsystem basis. This approach allowed for the maximum control of the testing and balancing process.

The resistances for all existing paths were calculated on the microcomputer. The critical path in each subsystem was determined by executing the mainframe code. Changes in system resistances were then calculated and evaluated for the noncritical paths. These resistances were used to prescribe the necessary adjustments to the system balancing devices, including the position of all balancing dampers. Once the appropriate field adjustments were made based upon the analysis, another set of data was collected and processed. The result from this second test was fed back into the system to determine if the new results were within the acceptance criteria. If not, additional adjustments were made. These final adjustments included proportional balancing techniques.

This testing sequence was repeated for each subsystem until each subsystem in the group was balanced. The groups were then combined to complete the entire system. With the network resistances established, the analysis of different operating modes and system combinations can be performed. The complete network forms a firm basis for examining all future modifications throughout the life of the plant. The impact of planned plant modifications and those emerging in the face of uncertainty can be analyzed without jeopardizing station technical specifications or plant operation.

## ADVANTAGES

The advantages of these HVAC integrated testing and system simulation methods and techniques should be apparent. The most important is system integration, which allows us to incorporate the various system and subsystems interactions into an integrated model. This provides a capability, which, to date, has not been available to the power industry, to correctly address the system and operating mode interfaces. Experience has shown that such interface has a key impact on the safe and economic operation of installations with large complex HVAC systems. Furthermore, once a model is constructed, and assuming it is maintained, it can be used for the plant's lifetime and even during its systematic decommissioning.

Additionally, since the methodology is predicated on basic principles, it is easy to visualize, and its use by all engineering disciplines is straightforward. Its modular construction also allows for the selective use of its subparts as appropriate for each selected application. The method provides excellent documentation of the problems studied. While this is desirable in general, it is especially valuable for the nuclear power industry.

Another advantage of this modeling technique is its versatility in handling different operating modes. A single model provides the ability to assess a variety of different problems. Different modes, heat loads, and flow rates can readily be assessed. Different hazards and transport mechanisms can be assessed as required to study the motion of pollutants, hazardous chemicals, smoke, dust, or radioactivity via the HVAC system.

An important issue for nuclear power plants is the maintenance of its design and licensing bases. During the plant's operation, modifications in the plant procedures and commitments occur that require reconstitution of the design and licensing bases. The existence of an integrated HVAC model facilitates the demonstration of the requisite configuration control and design basis reconstitution. The model's existence eliminates the need to re-perform design basis calculations, since field measurements provide a means of describing the actual as-built plant performance.

Lastly, since this technique can be used to simulate system performance for both design and diagnostic purposes, it has outage or modification planning advantages analogous to those of physical models. Prior to modifications, it can be used to assess the impact of the proposed changes on the entire HVAC system. It allows for a quantitative assessment of potential corrective actions in an integrated framework, which provides a systematic and reproducible means for identifying potential problems before they are realized in the plant.

## CONCLUSION

These several advantages demonstrate both the uniqueness and the significant contribution that these improved techniques provide to the design and analysis of HVAC systems. The technology developed here will be transferred to future projects providing better designed, constructed, balanced, and operated HVAC systems.

## APPENDIX

### THERMAL-HYDRAULIC COMPUTER CODE

In order to describe the transportation of system fluids and heat, solutions of mass, momentum, and energy balances are obtained by solving a computer code. Incompressible and compressible behavior is considered. A thermal-hydraulic computer code has been developed to treat the design and operation of HVAC systems. This code uses a general node-path formulation accommodating both steady-state and transient analysis.

Pressure, temperature, and fluid composition are accounted for, or are specified, at the nodes. The code offers a menu consisting of boundary, active, and hybrid node types. For a boundary node, the temperature of a solid material or the temperature, pressure, and composition of a fluid are user-specified, and the corresponding heat generation rate in the node is calculated. For an active node, the solid material temperature or fluid properties are all calculated, while the heat generation rate, if any, is user-specified. The hybrid node is a special type of fluid node for which the temperature is user-specified, while the pressure, composition, and heat generation rate are calculated. The hybrid node type is available only in the steady-state version of the code.

The code offers a menu of path types to represent the flow of fluid or heat between nodes. Available fluid flow path types include a friction loss type, a fan type, and a damper type. Heat transfer paths allow conduction, convection, and radiation to be modeled.

The duct friction loss formulation will accommodate not only turbulent flow devices (e.g., fittings) and laminar flow devices (e.g., idealized filters) but also devices operating in the region in between these limiting cases (e.g., coils). The generalized pressure loss relation used is derived from Coad and Sutherlin (1974):

$$P_u - P_d = \frac{\bar{R}W^E}{2g_c\rho_u} \tag{4}$$

where:

$P_u$ - path upstream node pressure (psfg) [Pa]

$P_d$ - path downstream node pressure (psfg) [Pa]

$\bar{R}$ - path "resistance parameter" value (a valve greater than zero is required) (The units of R depend on the value of E.)

W - path mass flow rate (lbm/h) [kg/h]

E - path mass flow rate exponent (dimensionless)
- 1.0 for laminar flow
- 2.0 for turbulent flow

$g_c$ - gravitational constant (ft/h$^2$) [m/h$^2$]

$\rho_u$ - path upstream node density (lbm/ft$^3$) [kg/m$^3$]

In this formulation, the path resistance parameter value depends upon the flow rate exponent value assigned. In the case of turbulent flow through typical segments of HVAC ductwork, R is the conventional loss coefficient divided by the square of the associated flow cross-sectional area.

To represent a fan, the recommended path type permits direct input of fan total head rise in feet of fluid flowing as a function of fan inlet volume flow rate. Since the typical fan manufacturer's curve (for fixed rpm and fixed blade angle) plots pressure rise versus fan inlet volume flow for a stated value of fan inlet density, it is necessary to convert this density-specific data to the more general form required by converting the pressure rise scale to a head rise scale using the inlet density. This curve must be examined to ensure that head rise decreases monotonically with increasing volume flow. If this does not occur, there is an unstable region in the fan curve that must be eliminated. Such a region is replaced with a connected line segment having a slope of the proper sign and sufficient magnitude for stability.

To determine the unknown resistance to which a balancing damper must be adjusted in order to give the desired flow in its leg of a system, a specified flow rate (damper) path may be utilized with the steady-state version of the code. To accommodate this path type, certain input data are arranged to guide calculation of pressure and density in the end nodes of the damper path. These calculated properties are then used in conjunction with the specified flow rate and an assigned E of 2.0 to calculate the value of R (the resistance parameter) for the damper path, using Equation 1. Since the resistance parameter for E of 2.0 is the quotient of the loss coefficient and the square of the associated path flow cross-sectional area, pressure loss data from the damper manufacturer may be used to predict the damper setting required.

To aid in the modeling of heat generation and heat transfer effects, additional node and path types are provided and a menu of heat transfer function types. Heat transfer between a pair of nodes may be accounted for by a convective or radiative type of path. This type of path may connect any selected pair of nodes and one of several heat transfer function types may be assigned to it. The heat flow rate through such a path is taken as the product of the path area, the temperature difference between the path and nodes, and the value of a heat transfer coefficient function. Available are heat transfer function types suitable for representing:

- forced convection to a body immersed in a fluid stream, or to the walls of a channel,
- natural convection to the side walls, floor, or ceiling of a room, or to a body exposed to the room's atmosphere, and
- radiation between solid surfaces, or between a surface and an adjacent atmosphere.

The menu of node and path types provided by the code allows for the proper modeling of heat sources, temperature, compositions, and densities as required for selected applications, as well as the usual devices considered in HVAC systems.

## METHODS OF SOLUTION USED BY THE THERMAL-HYDRAULIC COMPUTER CODE

The steady-state version of the code employs an iterative process to obtain a solution. First, the full set of unknowns is divided into four subsets:

- compressible fluid system loop flows,
- densities of compressible fluid system active nodes,
- specie concentrations of compressible fluid system active nodes, and
- temperatures of all active nodes.

Then, in rotation, each subset is solved via Newtonian or Gaussian iteration until successive solutions differ by no more than a user-specified tolerance. Finally, when successive solutions of all four subsets require no more than one iteration per subset (to meet the tolerance criterions), it is assumed that a solution has been found. The compressible fluid system loop flows are the set of unknowns recommended by Cross (1986) for the solution of a flow network. Modern treatment of this method refers to it as the loop balancing method (Streeter and Wylie 1975). Cross also presented a node balancing scheme that is simpler than the loop balancing method since it avoids setting up the flow loops. However, the node balancing scheme exhibited numeric difficulty in some cases. No such trouble has occurred with the loop balancing method. In some cases, a proper set of loops may be determined by inspection of the flow diagram for a network. However, for the more complicated cases, an automatic loop- generating algorithm, similar to that described by Epp and Fowler (1970), is used.

For the transient version of the code, the integration with respect to time utilizes a modification of the fourth order Runge-Kutta technique proposed by Treanor (1966). Treanor's method works well even for equations with vastly different time constants. Automatic control of the time step size is provided based on an error estimation technique described by Lubard and Schetz (1967). The Lubard and Schetz method draws a comparison of the results obtained by taking two half-size steps and a single full-size step across each proposed time interval. If the two results are not sufficiently close, the interval is rejected in favor of one half as large. Otherwise, the result for the two half-size steps is accepted. Following acceptance of an interval, the proposed size for the next interval remains unchanged, unless the one-step and two-step results are very close for that case the proposed size for the new interval is increased by 26%. This scheme has yielded a stable integration in situations where simpler methods have failed completely.

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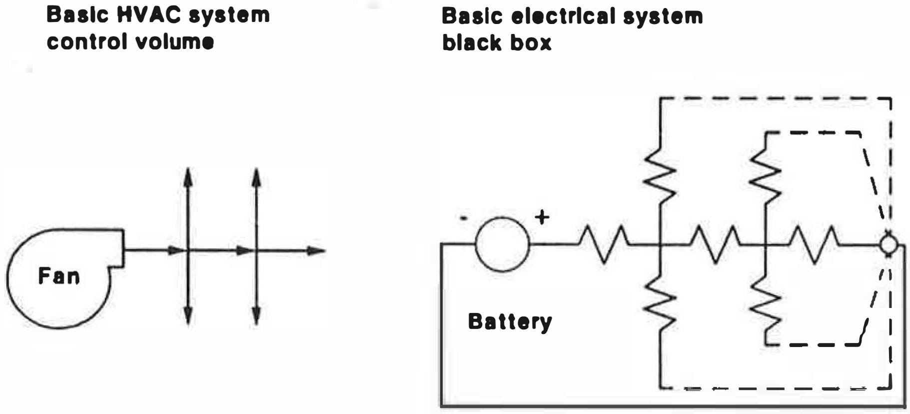

| Flow parameters | Electrical parameters |
|---|---|
| 1. Pressure | 1. Voltage |
| 2. Flow rate | 2. Current |
| 3. Duct resistances | 3. Electrical resistance |

*Figure 1. Electrical analogy to fluid systems*

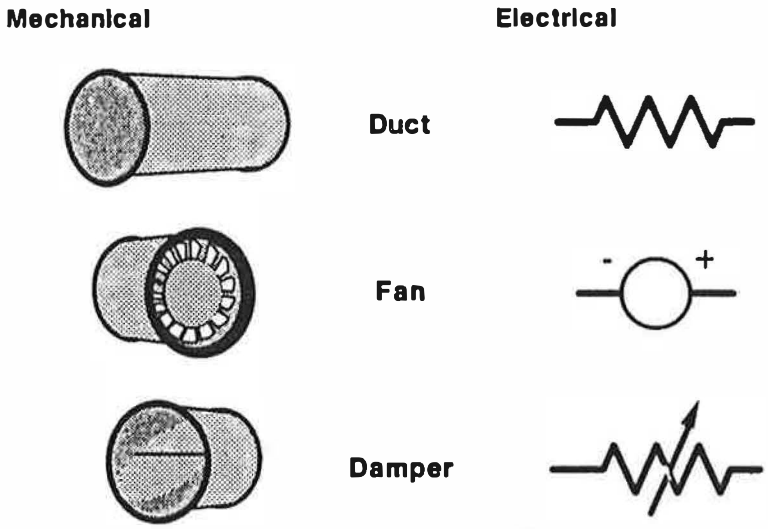

*Figure 2. Symbology*

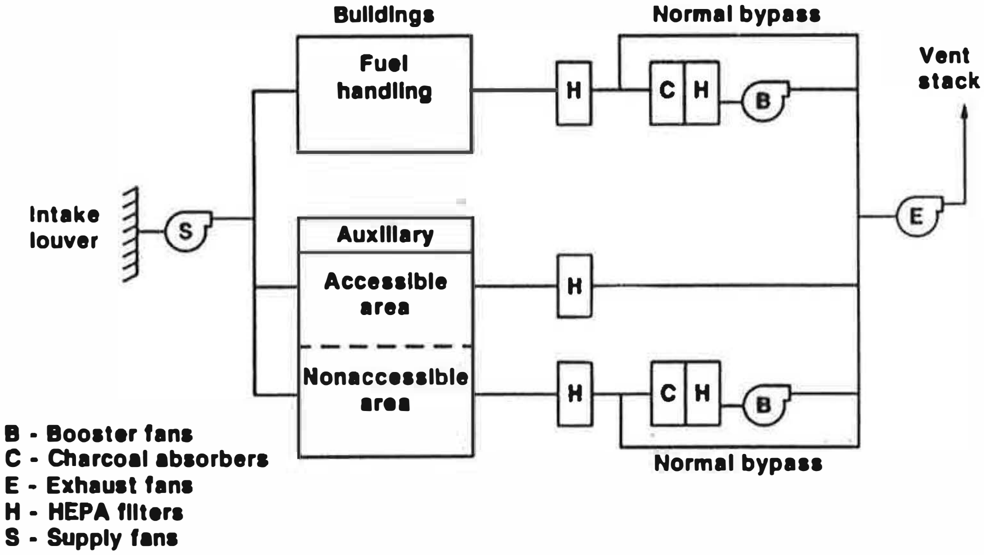

*Figure 3. Simplified auxiliary building HVAC system*

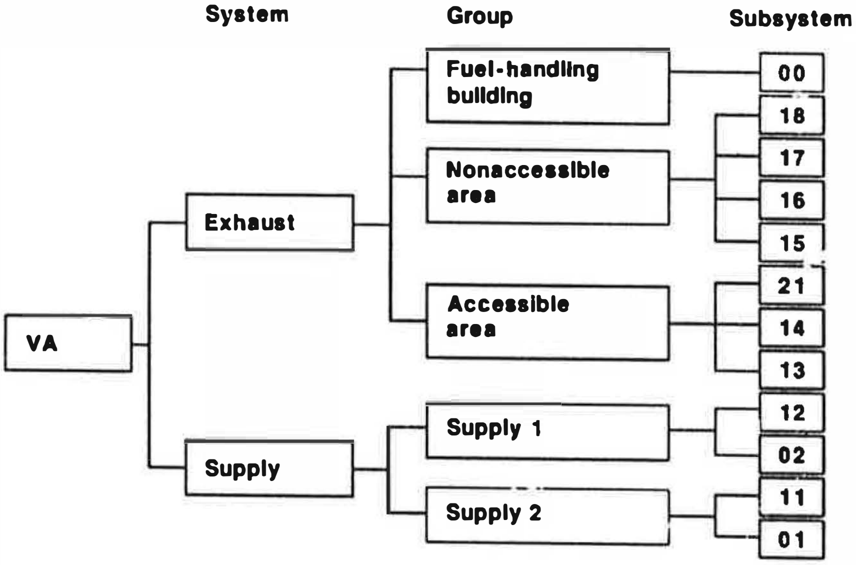

*Figure 4. Auxiliary building HVAC system (VA) breakdown*

## Discussion

**T.J. VOGAN, Florida Power and Light, Juno Beach, FL:** Will analysis handle simultaneous heat load and airflow data in order to balance habitability and environmental qualification criteria?

**PASCHAL:** Yes, the method described can analyze simultaneous mass flow rate, heat addition, and gas composition changes within a given system.