A METHOD OF SELECTING AND SIZING HVAC SYSTEMS

FOR THE ARCHITECTURAL PROFESSION

By

KEITH JULIAN YANCEY

Bachelor of Science in Architectural Studies

Oklahoma State University

Stillwater, Oklahoma

1982

Submitted to the Faculty of the Graduate College
of Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF ARCHITECTURAL ENGINEERING
December, 1984

A METHOD OF SELECTING AND SIZING HVAC SYSTEMS

FOR THE ARCHITECTURAL PROFESSION

Thesis Approved:

Lester L. Boyer
Thesis Adviser

Alan Brunken

Walter Grondzik

James F. Knight

Norman N. Durham
Dean of the Graduate College

PREFACE

This study is concerned with developing a method of selecting and sizing HVAC systems during the early phases of the architectural design process. The method is in the form of a design tool usable by architects for early design decisions. The process involves using initial design program data to arrive at possible HVAC systems that may be incorporated into an architectural project. The approximate space allocations for HVAC equipment can then be derived from such selections as well as the magnitude of the heating and cooling loads. A discussion of the architectural design process is included in order to gain an understanding of how this design tool may be applied. Two diverse architectural project types are used to exemplify the use of this tool. The tool itself is a self-supporting manuscript which is included in Appendix C of this thesis.

I wish to express my sincere appreciation to my major advisor, Dr. Lester L. Boyer, Professor of Architecture and Architectural Engineering, for his guidance and assistance throughout this study. I would also like to thank Walter T. Grondzik, Associate Professor of Architecture, for his guidance and initial inspiration in the HVAC field.

I am also thankful to Jim Knight and Alan Brunken, Professors of Architecture, for their participation and advisement.

Special thanks are due to the design professionals around the country whose input to my HVAC survey has provided invaluable information for the formulation of this study.

Finally, I would like to express special gratitude to my parents, Juliette and Jon Yancey, for their encouragement and unending support in all my pursuits.

TABLE OF CONTENTS

Chapter | Page

LIST OF TABLES

LIST OF FIGURES

Figure		Page

Figure Page

CHAPTER I

INTRODUCTION

The Architectural Design Process

Designing and constructing a building is a very involved process. The architect must be an all-encompassing professional able to tie together every facet of design. His skills must lie not only in conceptualization, but also in coordination of engineering services. Collaboration with project engineers is very important in the early design phases so that a minor misinterpretation is not extended to a major problem at the completion of the project. Incorporating a design tool into the these early design phases can assist the architect with decisions concerning the HVAC system for space allocations and total building integration. To gain a better understanding of how a method can be developed, and used, the architectural design process itself must be analyzed.

The scheduling of an architectural design project is traditionally divided into five major phases:

1. Programming (Information Gathering and Conceptual Design)
2. Schematic Design
3. Design Development
4. Construction Documents
5. Contract Administration

Each phase includes specific tasks to be performed before the next phase can commence (see Figure 1).

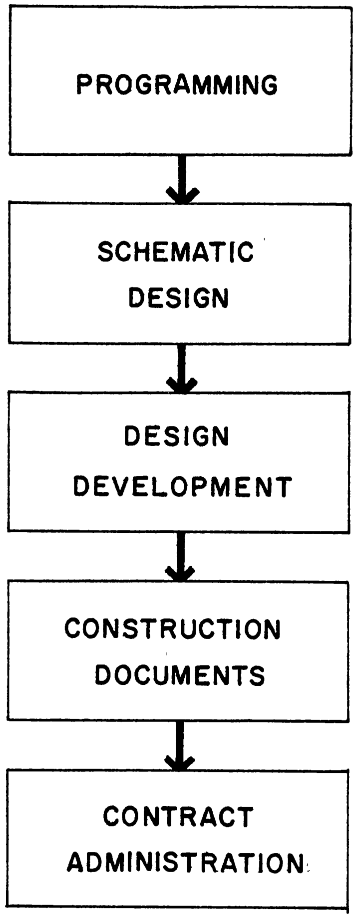


Figure 1. The Architectural Design Process

Programming Phase

The programming phase is the initial phase of an architectural design. An architect must formulate a program based on input from the client. A program committee may be appointed to assist in gathering data concerning the needs of the project.

The first variable to be identified is the building type. There are five basic types:

- Residential - single family detached; multifamily
- Commercial - offices; shopping centers

- Industrial - fabricating; manufacturing
- Institutional - schools; health care
- Special Purpose - auditoriums; libraries, etc.

After the building type is established, a project budget is usually discussed. A budget must be presented by the client. The architect will discuss the clients' wants and needs and determine if the funding is sufficient to carry out these objectives.

Once the financing is established, the site conditions must be analyzed. In most cases, the site is already selected by the client, but sometimes the architect is asked to assist in site selection. A complete site survey, topographical, and soil analysis is conducted to determine specific data about the site.

After reviewing the information given to the architect, he must perform an investigation that will determine facilities suitable for the required functions. Among other considerations is the HVAC system. Requirements such as temperature range, humidity levels, orientation factors, and outside air quantities are all identified. Locations and approximate sizes of mechanical equipment are noted. Applicable building, plumbing, mechanical, and electrical codes are reviewed for possible recommendations and/or restrictions on HVAC system types. Besides the system within the building, the availability of utilities is determined. Connection and unit costs of gas, electric, water, district steam and/or chilled water, and sewers are all investigated during the programming phase.

From all the data and information acquired, the architect should fully understand the proposed project. The program, as prepared by the architect, should be reviewed in detail and approved in writing by the owner (1).

Schematic Design Phase

The primary objectives of the schematic design phase are (1):

- to assist the client in his understanding of the program
- to illustrate possible solutions for the project within the shortest possible time and appropriate expense
- to assist the client in determining the feasibility of the project

More than one solution may be presented to the client but one is selected and developed. Preparing functional space diagrams is one way of arriving at a solution. Constructing a diagram of the information developed during programming can insure proper role relationships within the building. Sketches are then derived from the diagrams and evaluated by the client.

In addition to sketches, certain computations are made during the schematic design phase. For instance, expected usable floor area, heating and cooling loads, expected energy consumption, and approximate HVAC system size and cost.

To better explain the sketches and drawings to the client, the architect often produces quick and simple perspective sketches along with a small scale model to study mass, proportions, scale, and the relation of parts.

At the end of the schematic design phase, it is important to secure the client's written approval on the documents submitted. This will affirm authority to proceed to the next design phase.

Design Development Phase

The main objective of the design development phase is to fix and describe the size and character of the entire project and such other essentials as may be appropriate (1). All architectural and engineering questions are formulated from the approved schematic design studies and resolved in detail. The design development documents include (1):

- site plan indicating general location and nature of the improvements
- plans, elevations, sections, schedules and notes as required to fix and describe the project as to architectural, structural, mechanical, and electrical systems
- outline specifications of preliminary project manual
- further statement of probable construction cost

Before any development of these documents can proceed, it is necessary to have sufficient data concerning the HVAC system, including location and duct sizes along with other component sizes. Heating and cooling loads need to be refined based on more accurate estimates of ventilation rates, internal gains, window, wall, floor, and roof areas, and building construction. For non-residential buildings, loads should be analyzed by computer along with any applicable energy analysis. In addition, elevators and moving stairways, illumination, acoustics, and structural systems must be developed. Careful consideration of all building systems, particularly the interface of structural, electrical, and mechanical are resolved in this phase. It is here that the rather specific dimensions of the interstitial spaces and floor to floor heights are determined.

The design development phase is the heart of the architectural design process. Form and character, along with function of the project, are established and integrated into one complete, working system.

Methods of approval for the design development phase are similar to those for schematic design. A written authorization is needed in order to proceed to the next phase.

Construction Documents

The construction documents consist of both working drawings and specifications. By this time, the development of any new technical data is minimized and detailed requirements for construction are set forth.

When the client approves the construction documents, he may authorize bid taking for project construction from several contractors, or he may enter into direct negotiation with a selected contractor (1).

Contract Administration

Contract administration is the final phase of building design and construction. The various building components are actually assembled during this phase. The architect is in charge of reviewing shop drawings, issuing field reports, and submitting change notices.

General Statement

Building design and construction techniques have become increasingly complex. The architect must have education, training, and experience that will enable him to successfully integrate all the various facets of building science in order to yield the most functionally efficient and aesthetically pleasing results. Exposing the architect to the many engineering considerations early in the design process will allow him to utilize this knowledge to obtain a more optimum design solution and thus "bridge the gap" between the architect and the engineer.

CHAPTER II

PROBLEM STATEMENT

Approach

Several categories of tools are needed to provide quantitative information about HVAC system design to help facilitate the architectural design process.

First, rules-of-thumb may be applied in the programming phase. They help to give preliminary sizes and general configurations of system elements. Second are estimation methods which can be applied in the schematic design phase. These methods are used to evaluate the design's overall performance in terms of, for example, CFM per square foot or square feet per ton of refrigeration. Such methods must be simple and fast so that they can be routinely utilized to appraise various design considerations. Third are analysis tools that are used to provide detailed information about heating and cooling loads and overall HVAC system performance. This final level of analysis may be relatively expensive and time consuming. As a result, it may only be carried out once or twice at an advanced design phase such as design development to confirm earlier estimates and "fine tune" the design.

Goals and Purpose of Study

The architect has within his reach many different references and tools for sizing HVAC systems. Rules-of-thumb are very helpful, but as an architectural project develops, they become superficial; and more definitive solutions are needed.

Selecting HVAC systems often involves knowing a great deal about particular system and building characteristics and performance with which the architect should rely heavily on the systems engineer.

Given the parameters and priorities set by the architect, a system sizing and selecting process based on this initial input can be developed which incorporates rules-of-thumb, code considerations, and design estimations.

The purpose of this study is to provide a design tool for architects who are not well versed in the design of HVAC systems. Many practicing architects and engineers have their own method for the design of HVAC systems, but these methods are generally not well developed or documented. This study presents a process developed for selecting and sizing HVAC systems throughout the early phases of an architectural project.

Specific Objectives

A major objective of this study is to develop a method for providing quantitative information about HVAC system design which will assist in the architectural design process. The specific objectives are as follows:

1. establish an approach which will quantitatively group subjective and objective parameters into one matrix for evaluating and selecting HVAC systems for buildings,
2. create a viable method to arrive at system sizes and space allocations from the programming and schematic design phases of an architectural project,

3. produce a design tool to help make these mechanical system selecting and sizing methods usable by an architect.

Scope and Limitations

Developing an HVAC system selection and sizing process involves many quantitative and qualitative variables. Considering each variable individually and in a logical format can be a tedious job, especially if this process must be repeated several times due to project changes. The use of graphs, diagrams, and a computer can allow the architect to accumulate and apply available information directly and acquire quick and sufficiently accurate results.

By organizing the HVAC system selection and sizing procedure into a series of graphs, diagrams, and even a computer program, the architect can get a handle on types, sizes, and location of mechanical equipment needed for an architectural design project. Designing a method specifically intended for architects can assist with early design decisions in the programming and schematic design phases.

A method of this type cannot be used as a final computational approach for choosing correctly-sized mechanical equipment components for buildings. Many parameters unknown in detail to the architect must be sufficiently delineated with final calculations performed by the engineer. Without computing actual heating and cooling loads in an energy sensitive analysis, this method is valid only through the end of schematic design process (see Figure 2). Final results, then, may slightly vary from preliminary estimations; which may require some limited modifications to the original design.

The proposed method is limited to the selection and sizing of conventional HVAC system types. Active and passive solar systems, daylighting, nuclear power, etc., all have a major impact on a building's mechanical system but are not within the scope of this study.

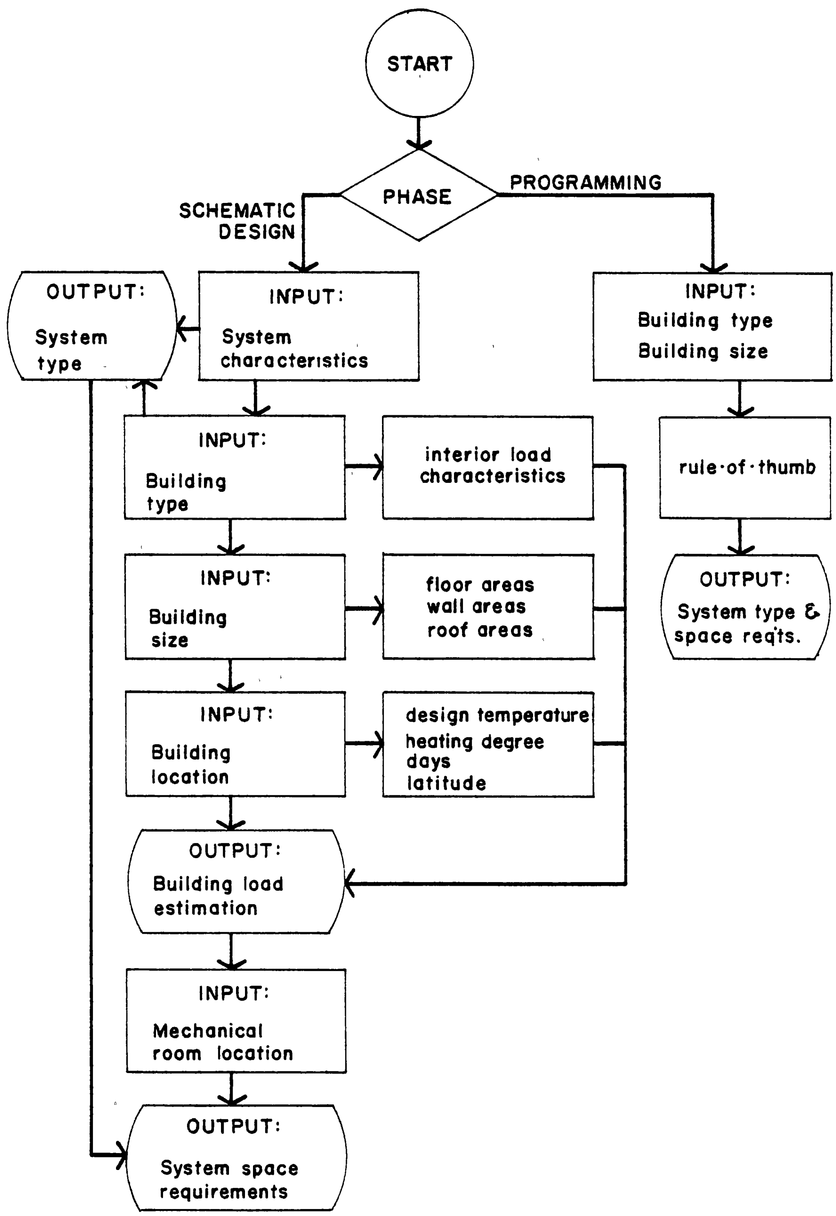


Figure 2. Applicability of Proposed Method

CHAPTER III

HVAC SYSTEM TYPES

Air-conditioning system design is constantly advancing, and combinations of various smaller system types are being integrated into larger overall systems to suit the specific needs of a particular application. Because of these variations, it is often difficult to categorize a complete system under one particular classification. Basically, all air-conditioning systems fall into four major categories:

1. all-air
2. air-water
3. all-water
4. unitary (refrigerant)

The classification refers to the energy transport medium that is delivered into the conditioned space.

All-Air Systems

An all-air system can provide complete sensible and latent cooling and sensible heating through air delivered to a space from a central location.

There are two basic types of all-air systems: single-path and dual-path (2). In a single-path system the main heating and cooling coils are in a series flow air path using a common duct with air at the same temperature to supply all the terminal outlets. In a dual-path system, the coils are in either a parallel or a series-parallel flow air path. With this system type, the warm and cool air flows can be mixed at the central unit and then travel in a single duct to the conditioned space, or they can travel in two separate parallel ducts to be mixed in a terminal outlet at the conditioned space.

These classifications can be broken down as follows (5):

Single-path systems

- single zone, constant volume
- zoned reheat, constant volume
- variable volume
- variable volume induction
- variable volume, reheat

Dual-path systems

- dual-duct, constant volume
- dual-duct, variable volume
- multizone, 2-deck
- multizone, 3-deck

Single Zone

A single temperature control zone, constant volume system is the simplest all-air system type (see Figure 3). A single zone system cannot simultaneously heat and cool, therefore it is often used in combination with other systems. The single zone unit can be installed within or remote from the space being served with or without ductwork. The unit may be self-contained or connected with a central plant that may serve other units as well. Since a single zone system can only respond to one set of space conditions, it is most often applied where the load is uniform or stable. Unless a humidifier is included in the system, it cannot control humidity independent of temperature requirements.

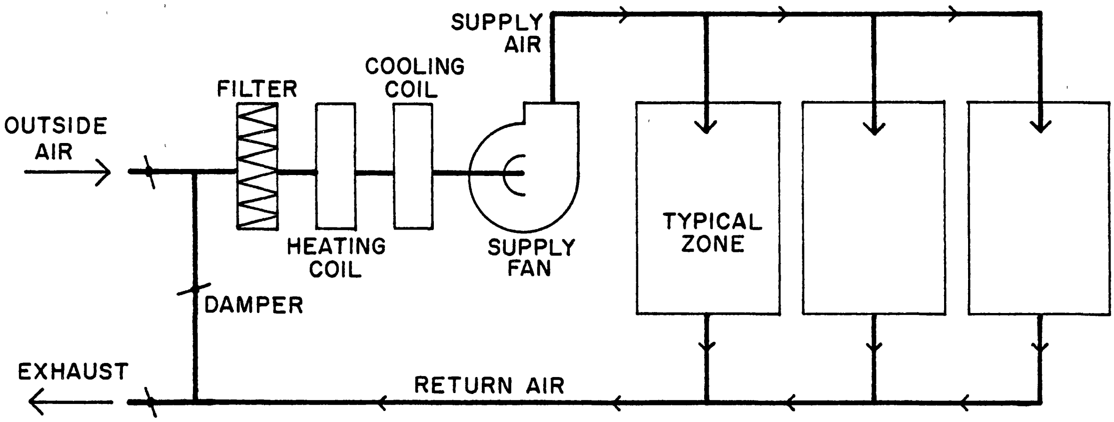


Figure 3. Single Zone System Schematic

Single Zone with Reheat

The reheat system is a single path system with the application of heat as a secondary process applied to preconditioned primary air or recirculated room air (see Figure 4). In relatively small systems, a heating coil (hot water, electric, or steam) is located in the duct at each zone. In larger, more sophisticated systems, high pressure duct design and pressure reduction devices allow system balancing at the reheat zone.

The reheat system offers a great deal of flexibility to the designer in the early design phases. It can be changed to accommodate changes in the design by simply adding a heating coil or terminal box.

Reheat systems are often very uneconomical and energy-inefficient if energy is used to reheat preconditioned air. However, if waste heat from another area of the building is used to reheat, this system can prove to be very efficient. In some applications recirculated condenser water is used for reheat which is not only beneficial for thermal comfort in a conditioned space but also improves the efficiency of the condenser. Reheat systems which utilize energy for re-conditioning should generally be avoided, especially in large projects, if not already prohibited by local codes.

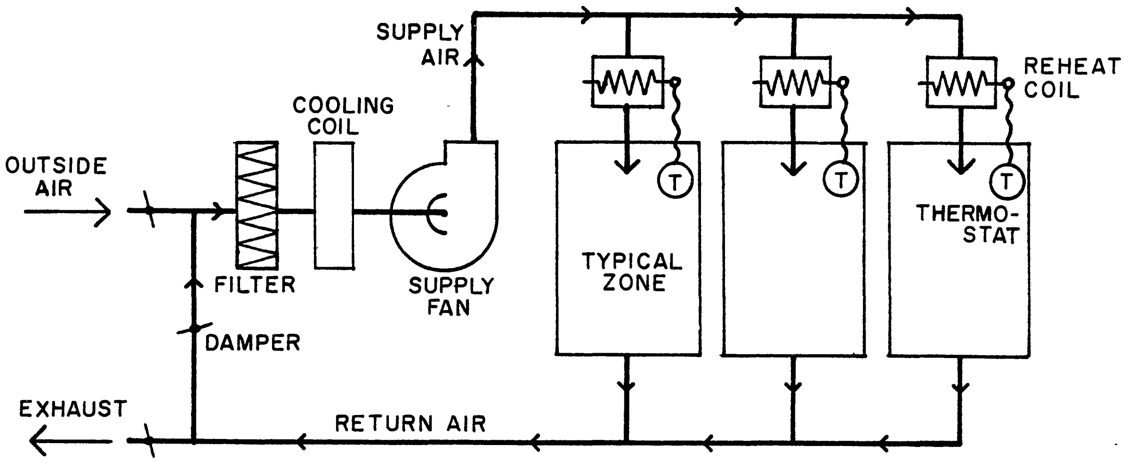


Figure 4. Single Zone with Reheat System Schematic

Single Duct Variable Volume

A single duct, variable air volume (VAV) system is a single path system which, instead of regulating the air temperature, regulates the air flow quantity (see Figure 5). Each zone has a thermostat that controls a "VAV box" which, in turn, regulates the rate of air flow to that zone. Since a typical VAV system cannot simultaneously provide heating and cooling, an independent system (usually perimeter heating) is often incorporated.

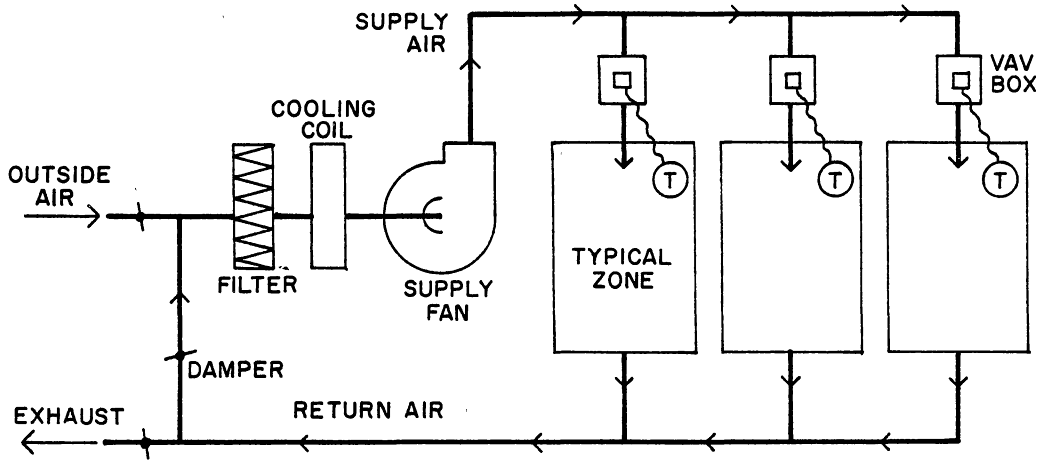


Figure 5. Single Duct VAV System Schematic

Variable Volume Induction

A variable volume induction system utilizes terminal units in which primary air is supplied at high velocity and pressure through induction nozzles, in turn inducing secondary air from the space (see Figure 6). Control is achieved through: simultaneously reducing primary air and increasing induced air to provide a constant supply to the space; reducing supply air to the space; or reheating. The primary advantage of this system is the space saved due to smaller duct work than that of a low velocity system. Because it is a high velocity system, noise and energy usage may be a major concern.

<u>Variable Volume with Reheat</u>

A single duct, variable volume system with reheat is very similar to a single duct, constant volume system with reheat, except that the reduction in air flow is the initial step in control (see Figure 7). The operating cost is much less than that of a constant volume system with reheat since the application of the heating coil can be suspended until the flow rate is at a minimum; and, also, since it is operating at minimum flow rate, not as much energy for reheat is needed.

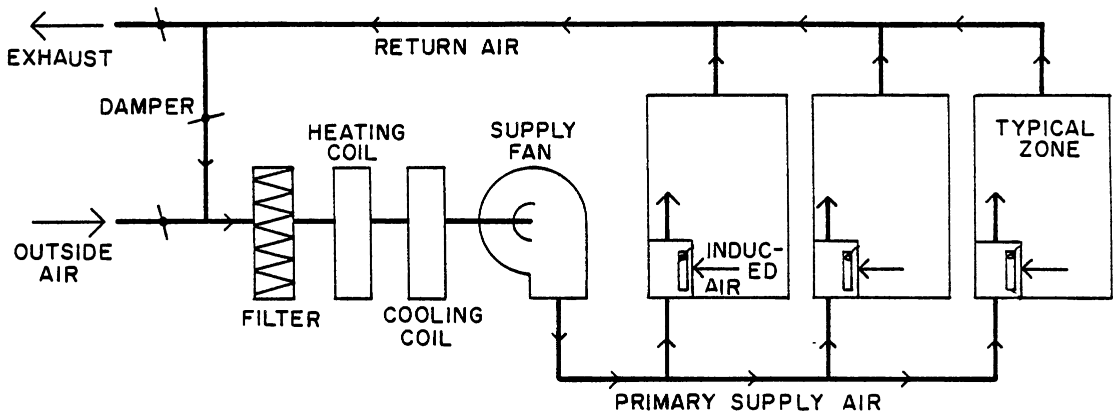


Figure 6. Variable Volume Induction System Schematic

Another type of VAV reheat is achieved by individual zone fans or fan-powered VAV boxes. It is similar to VAV induction in that air from the space is recirculated directly with the primary air and supplied to the space.

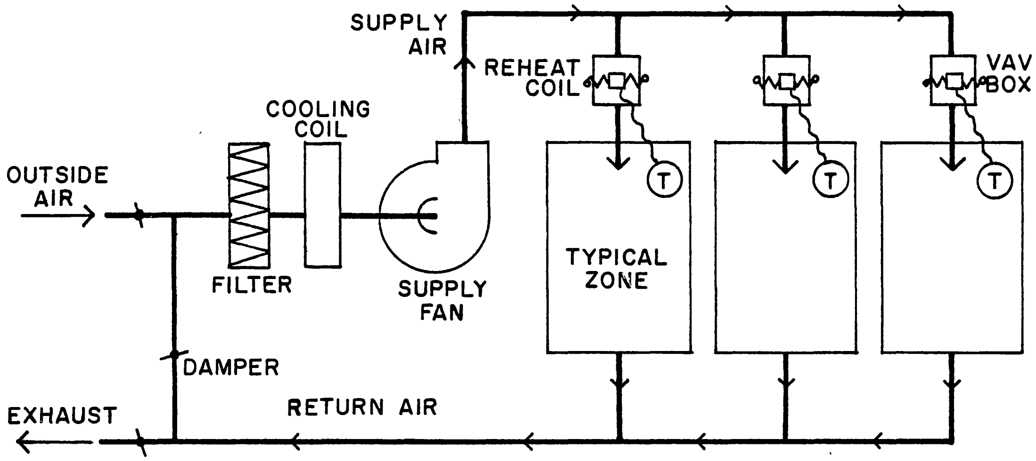


Figure 7. VAV with Reheat System Schematic

Dual Duct-Constant Volume

A dual duct system is a dual-path system with cool and warm air streams running in parallel through separate ducts as shown in Figure 8. In response to a zone thermostat, the air is mixed in proper proportions in a terminal mixing box. Although a dual duct system provides simultaneous heating and cooling along with excellent comfort controllability, it also has many disadvantages. Since a dual duct system is a form of reheat, it is uneconomical and energy inefficient. Also the space utilized for ductwork is far more than with any other system due to crossovers and twice as many ducts.

Dual Duct-Variable Volume

Unlike the dual duct-constant volume system, the dual duct-VAV system blends the cold and warm air in various volume combinations. In some systems, single duct VAV units are connected to the cold deck for cooling-only operation serving interior spaces (3). The schematic arrangement is identical to the dual duct-constant volume system.

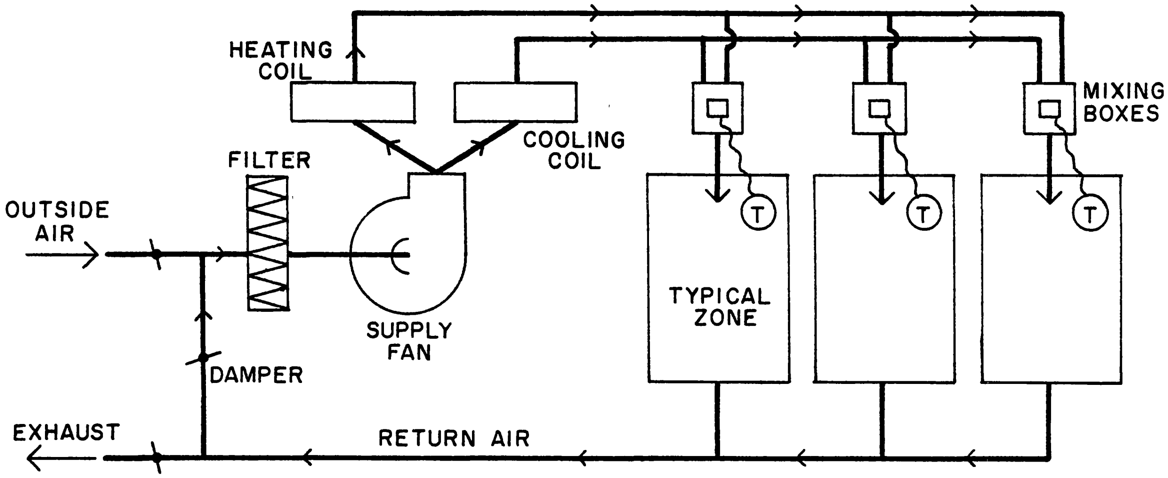


Figure 8. Dual Duct-Constant Volume System Schematic

Multizone-2-Deck

A 2-deck multizone system is a dual-path system similar to a dual duct system except that mixing of air streams occurs back at a central unit instead of occurring at the space as shown in Figure 9. It is adapted for a relatively small number of zones that can be served from a single, central air handling unit. A multizone system is also a form of reheat and is energy inefficient, but VAV may be applied to reduce total energy consumption.

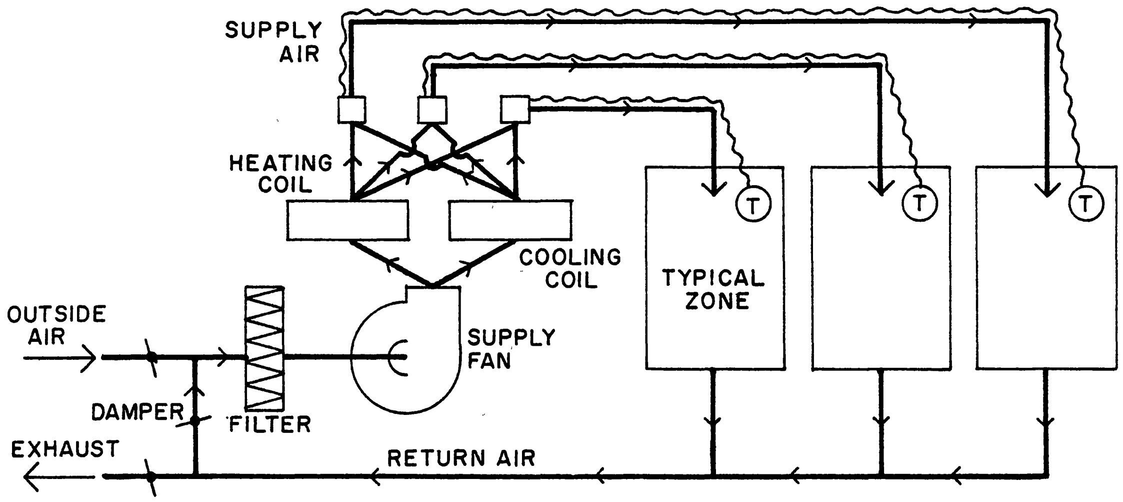


Figure 9. Multizone-2-Deck System Schematic

Multizone-3-Deck

A 3-deck multizone system is identical to a 2-deck multizone except that a third "neutral" deck is incorporated in order to save energy. The neutral deck functions similar to a bypass in which little energy is expended by mixing return air with air from the hot and cold decks. The 3-deck system schematic is identical to that of the 2-deck system with one more deck incorporated in the supply air flow path.

Air-Water Systems

In an air-water system, both air and water are delivered to the conditioned space in order to perform the air-conditioning function. In most air-water systems, the heating and cooling is achieved by changing the temperature of the air and/or water to maintain constant control of the comfort conditions throughout the year. A major advantage of an air-water system over an all-air system is that less space is required for distribution; most ductwork is replaced by piping.

Air-water systems are generally classified as two-pipe, three-pipe, and four-pipe systems. A two-pipe system employs one supply and one return circuit. In a three-pipe system, there are two supply circuits--hot and cold water--and one return circuit. A four-pipe system uses both two supply and two return circuits. The advantage of a three-pipe system over a two-pipe system is flexibility. A three-pipe system offers simultaneous heating and cooling as well as better control from one zone to another. The advantage of a four-pipe system over a three-pipe system is energy efficiency. In a three-pipe system, hot and cold circuits are mixed in the return circuit and "separated" at a central plant. In a four-pipe system the two circuits never mix, therefore cool water returns to the chiller and warm water to the boiler, thus using less energy to re-condition the water than a three-pipe layout.

<u>Air-Water Induction</u>

An air-water induction system incorporates primary air supplied at high velocity and pressure through induction nozzles which induces secondary air from the space (see Figure 10). It performs in the same way an all-air induction system performs except that a secondary water coil is incorporated into the system which heats or cools the secondary air. In most applications, these induction units are installed under a window. A distinct advantage of these systems in the wintertime is that they can function as a convection heater during off hours, supplying hot water to the coil without supplying primary air.

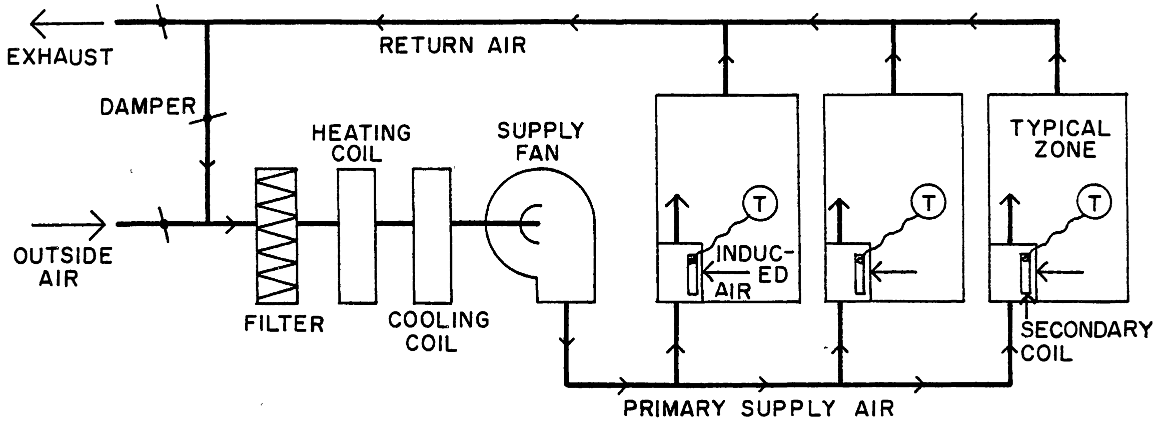


Figure 10. Air-Water Induction System Schematic

Air-Water Fan Coil

An air-water fan coil system is very similar to an air-water induction system except that a fan is utilized in each terminal box instead of relying on primary air for space circulation (see Figure 11). Since the primary air is not needed to induce the secondary air, it may connect to the fan-coil unit directly or supply the room separately.

Air-Water Radiant Panel

Air-water radiant panel systems provide radiant heating or cooling utilizing panel terminals in the ceiling, floor, or walls. A constant volume air stream is supplied for dehumidification and ventilation (see Figure 12). Radiant panel systems are similar to other air-water systems except that thermal conditions are maintained primarily by direct transfer of radiant energy, rather than by convection heating and cooling (3).

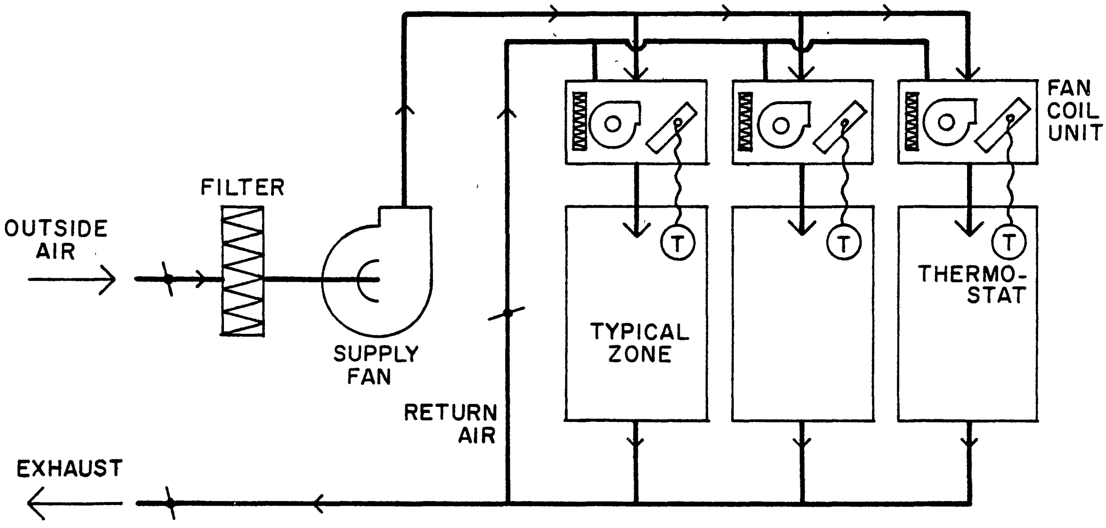


Figure 11. Air-Water Fan Coil System Schematic

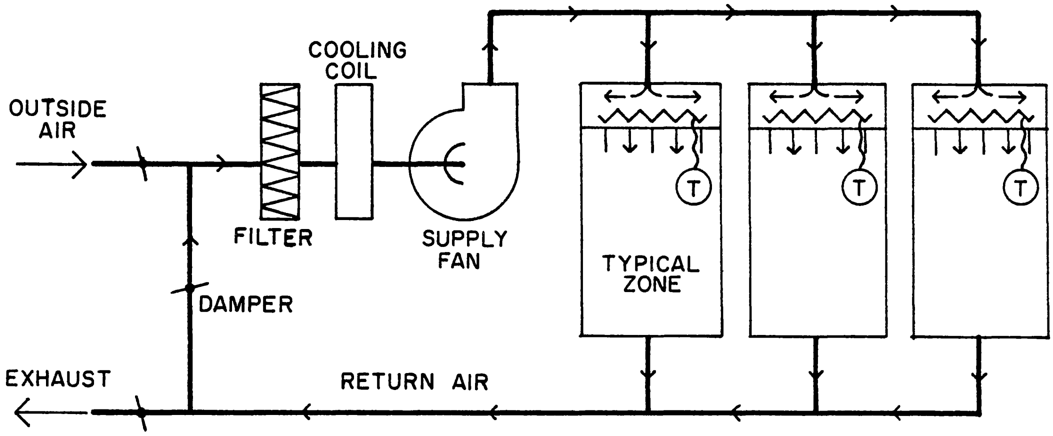


Figure 12. Air-Water Radiant Panel System Schematic

Hydronic Heat Pumps With Outside Air

Although often categorized in a class of its own, a hydronic heat pump with supplementary air can be classified as an air-water system. A heat pump extracts heat from one substance and transfers it to another substance at a higher temperature. In the case of an applied hydronic heat pump system, heat is extracted from, or added to a space by refrigerant in the cooling/heating coil. A water loop then extracts heat (when cooling) from the heat pump condenser. An applied heat pump system is most efficient when an equal number of units are cooling as are heating since the water loop is continuous and heat extracted from one zone can be used to heat another zone. Outside air is supplied to each unit for required ventilation air. The system schematic for a hydronic heat pump system with outside air is similar to that of an air-water fan coil system.

All-Water Systems

An all-water system conditions a space by circulating water from a central refrigeration or heating plant through coils or panels in terminal units located within the conditioned space. The most common all-water systems are valance units, baseboard radiation, and fan coil systems.

Valance

A valance unit is a device which cools the air in a space by natural convection without the use of a fan. A finned-tube mounted in a sheet metal enclosure allows air to pass over the coil by convection (see Figure 13). Valance units operate quietly and simply, but air distribution is minimal.

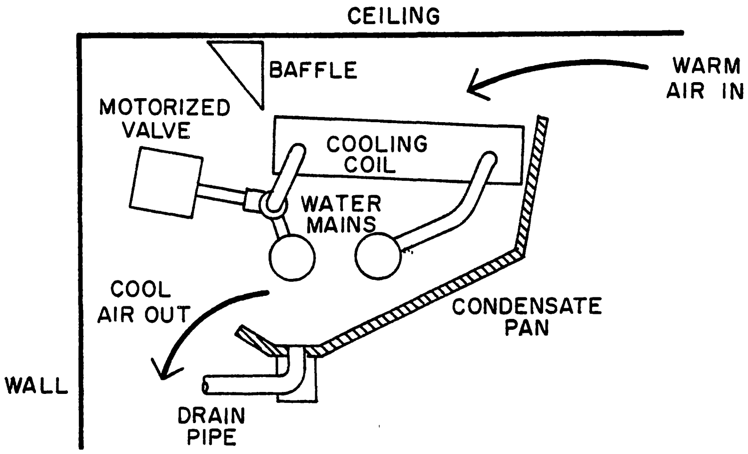


Figure 13. Section Through Valance Unit (3)

Baseboard Radiation

Baseboard radiation is identical to a valance system except that it supplies heating instead of cooling and is located near the floor to take advantage of rising convective air currents.

Fan Coil and Hydronic Heat Pumps

The operation is similar to that of the air-water fan coils and heat pumps except that supplementary air is not provided. Air is recirculated through the system from the conditioned space.

Unitary Equipment Systems

These systems, often referred to as refrigerant or multiple packaged systems, consist of factory matched refrigerant cycle components for the extraction or addition of heat. These systems are normally located within or near the conditioned space and consist of only those elements essential to the production of heating and cooling.

Air-Cooled Room Conditioner

An air-cooled room conditioner (such as a standard residential window air-conditioning unit) is designed for mounting through a wall or window (see Figure 14). Since installation must be on the perimeter of the structure, aesthetics becomes a prime concern. Many units are capable of heating and cooling and can be in full operation with only an electrical hook-up.

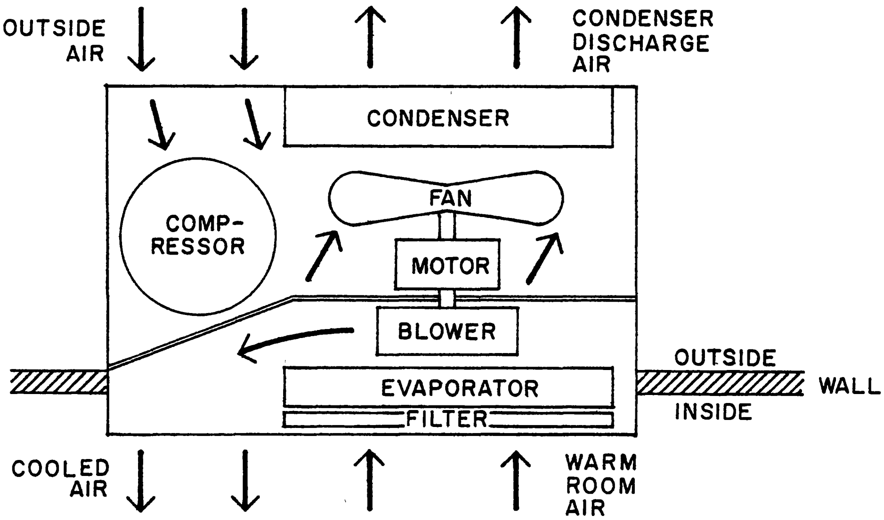


Figure 14. Section Through an Air-Conditioning Window Unit

Air-to-Air Heat Pump Systems

An air-to-air heat pump is similar to a conventional through-the-wall system except that it contains a reversing valve that allows the heat pump cycle to be used for space heating when the temperature outside does not drop below approximately 35°F. A prime advantage of a heat pump is a reduction in annual energy consumption for space heating.

Unit Heaters

Unit heaters are most often employed in areas where no air-conditioning is required (warehouses, gymnasiums). Unit heaters are often gas fired and, along with natural ventilation, are complete systems for some applications.

Basic Equipment Categories

In general, all HVAC systems, without regard to the system classification, can be categorized as built-up or packaged. "Built-up" refers to equipment in which each component is selected separately and combined to form a complete system. The term "packaged" means it is a factory matched piece of equipment which can be pretested prior to arrival at the job site.

Various applications yield a broad scope of equipment types: outdoor or indoor unitary, central station, multiple units, or split and single systems. Most outdoor applications are roof-top units, central or incremental. Indoor equipment is often located in service areas adjacent to the conditioned space. Irregardless of the system type chosen for a project, both built-up and packaged systems can be arranged to achieve similar results.

CHAPTER IV

SYSTEM SELECTION PROCESS

General Considerations

The selection of an HVAC system to meet a building's specific needs is often very difficult to understand for a novice in the field. The selection process itself is usually more heuristic rather than scientific, and ordinarily ends up being a compromise between what is ideal and what is practical.

The choice on a system is best made when all the people affected by it can provide the needed amount of input. The owner is interested in a low cost, good quality system while the people utilizing the building are interested in being comfortable. Since it is practically impossible to get feedback from all the people who should be involved at an early stage of the architectural project, the designer must have enough insight to make the proper decisions. Consequently, many unsuccessful selections are made due to the fact that factors that influence present and future decisions are not being identified and properly assessed. Some factors in an actual project may include:

- Building use type
- Building size
- Budget for the project
- Architecture of the specific building
- Owner's specific requirements (owner occupied or leased)

- Population density
- Continuity of operation
- Comfort considerations
- Quality of maintenance and serviceability
- Space availability
- Fuel availability and cost
- Code considerations
- Magnitude of the heating and cooling loads

Another issue that may not be as clear-cut but may have an impact in system selection is the engineer's fee. Besides suggesting an "optimum" system for a particular application, he may also consider a system which will yield the greatest profit. For example, the engineer may prefer to choose a system which is easy to design and trouble free. If the engineer's fee is sufficient, he should evaluate several systems for life cycle cost and total system-building integration. If the engineer's fee is meager, such a systems optimization analysis may not be possible.

Several evaluation techniques have been developed for systematically comparing HVAC system data. Most methods utilize the physical characteristics of the building and systems being analyzed and the priorities set forth by the designer. A typical example of a comparison method is shown in Table I for a municipal library (3). Flexibility in a rating system is essential, in order that results which have meaning to all parties concerned may be achieved (4). However, if the results from these "rating systems" don't correspond with what's being done in the field, then they are of no use to the designer.

TABLE I

COMPARISON OF ALTERNATIVES IN SELECTING AIR-CONDITIONING SYSTEM FOR MUNICIPAL LIBRARY

OBJECTIVES		SYSTEM A			SYSTEM B		
Musts		Remarks		Yes/No	Remarks		Yes/No
• Initial costs $< \$5.90/\text{ft}^2$		$\$5.75/\text{ft}^2$		Yes	$\$5.05/\text{ft}^2$		Yes
• Humidity control		Possible		Yes	Possible		Yes
• Removal of SO_2		Easy in future		Yes	Possibly, but costly		Yes
Wants	Wt.	Remarks	Sc.	Wt. x Sc.	Remarks	Sc.	Wt. x Sc.
• Lowest first cost	1	$\$5.75/\text{ft}^2$	4	4	$\$5.05/\text{ft}^2$	10	10
• Lowest owning cost	10	Estimate $\$5.50/\text{ft}^2$	8	80	Estimate $\$5.00/\text{ft}^2$	10	100
• Lowest operating cost	6	Estimate $\$7.00/\text{ft}^2$	7	42	Estimate $\$6.00/\text{ft}^2$	10	60
• No stationary engineer	3	Required	0	0	Required	0	0
• Aid in smoke control	1	Areas zoned	10	70	Areas unzoned	5	35
• No cooling tower	2	Evap. cond. possible	5	10	Not required	10	20
• Hot pipe in basement	6	All in basement	10	60	Covers 10% floor	7	42

TABLE I (Continued)

Wants	Wt.	Remarks	Sc.	Wt. x Sc.	Remarks	Sc.	Wt. x Sc.
• Filter 85% efficiency	5	85%	10	50	85%	10	50
• Noise level > NC 30	9	All areas > NC 30	10	90	80% areas < NC 30	8	72
• Flexible for part changes	4	Relatively easy	10	40	Ductwork changes req'd.	4	16
• Min. leakage hazards	8	No pipe in ceiling	10	80	Heat & cool pipe over-head	6	48
• No wall penetrations	4	Penthouse only	8	32	Required throughout	0	0
			Total:	558		Total:	453

Source (9)

With the many variables involved in selecting a system, it is necessary to establish a process that will subdue, rather than try to eliminate the causes of unsuccessful decisions. Therefore, a truly useful method of evaluating and selecting an HVAC system for a particular application must include all objective and subjective factors, as well as the relative importance of each based on the project in question. The method should be versatile enough to be used in the several initial phases of the building design process. Although the method itself may be somewhat idealistic, the parameters worked with should model realistic situations. By incorporating three distinct approaches, a fairly accurate method may be derived that can be utilized in the programming and schematic design phases of an architectural project. The three distinct approaches are: a historical approach; a survey approach; and a scale rating approach. In order to establish their advantages and limitations, the relative impact of each approach in the programming and schematic design phases is analyzed.

The Programming Phase

In the programming phase of an architectural design project, the two selection approaches that are of most use to the architect are the historical and survey approaches; exploring what's been done in the past, and acquiring information on what is being done in the field today.

The first building variable to be identified in this phase is the purpose for which the building is being constructed--the building type. It is often difficult to place a specific building into one particular category in order to apply a rule-of-thumb. For purposes of this study, building types are classified according to the proposed Building Energy

Performance Standards (5).

- Clinic
- Community Center
- Gymnasium
- Hospital
- Motel
- Multifamily High Rise
- Nursing Home
- Office - Large
- Office - Small
- School (Elementary/Secondary)
- Shopping Center
- Store
- Theatre/Auditorium
- Warehouse

Historical Approach

To get a better understanding for the design and application of HVAC systems for the various types of buildings, each building type is discussed separately along with an account of systems that have been used in the past in each particular application.

Clinic. Consists of inpatient and outpatient diagnostic and treatment areas. Applications of HVAC systems may be similar to those for typical office buildings (single-zone, VAV), except air quality is more of a concern. The general clinical areas should be maintained at a minimum relative humidity of 30 percent. The type of air filter used is critical and must be of high efficiency. An all air system or air-water system is mandatory for this type of application.

Community Center. Includes general assembly facilities with tables and chairs. Also includes smaller areas for gatherings or for just a few people. The HVAC system must be able to handle a great diversity in loads. Ventilation is important in the case of larger gatherings. Heating and cooling may be required simultaneously. Rooftop units are quite often used in community centers since most areas are only one story tall.

Gymnasium. Most gymnasiums are part of a school or health facility and are not normally cooled. They usually include a perimeter radiation system or unit heaters located in the ceiling areas along with a central ventilation system. For schooltime use, the space temperatures are often kept between 65 and 68° F to stimulate student activity and minimize sweating. In the evening or on weekends, conditions may change for sporting events or social affairs. The application of the gymnasium must be evaluated. If it is to be used as a multipurpose space, general auditorium conditions may apply.

Hospital. Practically every combination of systems can be and have been utilized in a hospital application. There are four major reasons why an HVAC system for a hospital must be very sophisticated: 1. the need to restrict air movement in and between the various departments, 2. the specific requirements for ventilation and filtration to dilute and remove contamination in the form of odor and airborne microorganisms, 3. the need for different temperature and humidity requirements for various areas, and 4. the need for sophistication in design to permit accurate control of environmental conditions (6). The need for an all air central system among other systems is mandatory. Local codes and federal regulations will sometimes govern systems and applications.

Motel. The guest room in a motel is usually a single room with a bathroom opposite an outside wall. The total structure is usually no more than two stories tall. For guest rooms, fan coil systems or packaged self-contained unit systems are most used. The lobby areas, restaurant, and meeting rooms are controlled by separate systems than the guest rooms, but may be supplied by the same chillers and boilers if a central plant is used.

Multi-family High Rise. Very similar to motel-hotel applications, except that kitchen facilities must be considered. Equipment for this system may be installed in a separate mechanical equipment room in the apartment or above a suspended ceiling. Greater flexibility is possible with electric furnaces since gas- or oil-fired furnaces require flues which could take up a considerable amount of space in a high rise.

Nursing Home. There are three basic types of nursing homes: 1. extended care facilities, 2. skilled nursing homes, and 3. residential care homes (6). The HVAC system should provide for dilution and control of odors and should be free from drafts. Temperature control should be provided on an individual room basis. Types of systems that meet these criteria fairly well are: VAV with reheat; constant volume reheat with heat recovery; radiant ceiling with constant volume air; under window or ceiling induction with reheat and heat recovery; fan coil or unitary heat pumps with primary air.

Office - Large. Usually includes both perimeter and interior zone spaces. Interior zones usually require a uniform cooling rate often handled by a VAV system. The perimeter zone requires both heating and cooling (sometimes simultaneously) and is most often a separate system from that of the interior zone. Cooling towers are the largest single piece of equipment required for air-conditioning in a large office building and are usually located on the roof. Areas that need special consideration are computer rooms, elevator machine rooms, mechanical equipment rooms, lobbies, and atria.

Office - Small. Included in this category are spaces for privately owned, small firms--doctor's and dentist's offices, etc. Depending on the exterior glass percentage, perimeter radiation with single duct, low velocity, packaged HVAC systems can be used. Most small offices are envelope dominated.

School (Elementary/Secondary). Energy is an important issue in schools. HVAC equipment should be capable of efficient operation at extremely low and variable loads. In smaller single-building facilities, centralized systems are often applied. In larger schools where auditoriums, computer rooms, cafeterias, etc., exist, it may be more economical to put each area on a separate system, rather than on one central system.

Shopping Center. Included in this category are large regional shopping malls. The single level and smaller malls usually incorporate unitary systems for mall and tenant air-conditioning. The larger and multilevel malls have tended to use central plant systems for mall and tenant air-conditioning. Each tenant is usually metered separately for all utilities. The main mall area itself should be designed to maintain a slightly higher pressure than each individual store.

Store. Many small stores usually have large glass areas in the front which may need special consideration. In store applications (small stores, variety stores, department stores, and supermarkets), single-package rooftop equipment is the most common. With the use of multiple units to condition the store, a minimal amount of ductwork is needed. In larger stores, the system must be able to handle fluctuating loads.

Theatre/Auditorium. One of the main concerns with this application is noise control. A quiet system should be selected and located away from the seating areas. Outside ventilation air is the major contributor to the total cooling load, along with heat gain from the people. Most assembly buildings are served by all-air systems, usually of single zone or variable volume type. Cooling is the major objective except in ancillary areas where some heating may be needed.

Warehouse. Most warehouses are only heated and ventilated. Shipping, receiving, and inventory control offices associated with warehouses are the only areas generally air-conditioned. Large forced-flow unit heaters are typically used in order to keep temperatures from dropping below 40° F to protect sprinkler piping or stored materials from freezing.

Listed in Tables II and III are those systems which were typically used in each different building category in the past. These lists of systems are compiled from manuals used for cost estimations at that particular time (7, 8).

Survey Approach

Experience is a major influence when deciding on the type of system to employ in a certain application. To get a view of this experience an HVAC survey was sent to architectural and mechanical engineering firms throughout the U.S. Contacts were made through the ASHRAE Energy Management Committee and the American Consulting Engineers Council Directory (9). Over 400 surveys were mailed with an approximate return of 30 percent.

TABLE II

TYPICAL HVAC SYSTEM SELECTIONS (1966)

BUILDING TYPE	SYSTEM TYPE(S)
Clinic	Hot, chilled water fan coil units.
Community Center	Gas packaged A/C units; hot, chilled water fan coil units.
Gymnasium	Gas packaged A/C & forced air units.
Hospital	Hot, chilled water fan coil units.
Motel	Hot, chilled water fan coil units.
Multifamily High Rise	Hot, chilled water fan coil units; packaged heat pumps.
Nursing Home	Hot, chilled water fan coil units.
Office - Large	Hot, chilled water, dual duct.
Office - Small	Heat pumps; Hot water, DX, multizone.
School (Elementary/ Secondary)	Gas packaged A/C units; hot, chilled water fan coil units.
Shopping Center	Gas packaged A/C and forced air units.
Store	Heat pumps; unit heaters; hot, chilled water fan coil units.
Theatre/Auditorium	Gas multizone, DX, dual duct.
Warehouse	Gas fired unit heaters.

TABLE III

TYPICAL HVAC SYSTEM SELECTIONS (1976)

BUILDING TYPES	SYSTEM TYPE(S)
Clinic	Single zone w/reheat; four pipe fan coil units.
Community Center	Single zone w/reheat; radiation.
Gymnasium	Heating & ventilation.
Hospital	Dual duct; induction; four pipe fan coil units.
Motel	Two-pipe fan coil units and radiation.
Multifamily High Rise	Two-pipe fan coil units and radiation.
Nursing Home	Single zone w/reheat; incremental units.
Office - Large	Single zone w/terminal reheat; fin-tube radiation.
Office - Small	Single zone w/reheat coils; fin-tube radiation and convectors.
School (Elementary/ Secondary)	Single zone w/reheat; four pipe fan coil units.
Shopping Center	Single zone w/reheat.
Store	Single zone; four pipe fan coil units.
Theatre/Auditorium	Single zone w/reheat; radiation.
Warehouse	Heating and ventilation.

The survey developed for use in this thesis contains a list of the 14 general building types discussed in the previous section. Accompanying each building type are three budget categories (tight budget, medium budget, and no budget). From an attached list of system types, respondents were asked to place a letter and/or number corresponding to those systems which they would most likely select for that particular building type in their specific climatic region under each of the three budget categories.

The survey was flexible enough that a respondent could form a combination of various system types to create one overall integrated system. The basic systems included in the survey are:

- Single zone
- Single zone with reheat
- Two deck multizone
- Three deck multizone
- Single duct variable air volume
- Dual duct
- Induction
- Fan coil units
- Hydronic heat pumps
- Unitary units

The general application parameters for each system include:

- Central system
- Roof-top system
- Packaged system
- Split system
- Economizer cycle

The results from the surveys are presented in Appendix B in bar graph form, along with a list of the respondents' comments. Each building type shows two graphs--one for the basic system type and one for the general application. Table IV presents the specific survey results according to building and budget types. This table was derived from statistical analysis of the combination of system types reported in the survey responses. The respondents' comments and discussion, along with reasons for selection, helped to clarify these combinations. The survey form itself is included in Appendix A.

TABLE IV

SYSTEM SELECTION SURVEY RESULTS

BUILDING TYPE	TYPICAL HVAC SYSTEM SELECTIONS
Clinic	• Tight Budget--Single zone; electric baseboard radiation; rooftop. • Medium Budget--Single duct VAV; hot water baseboard radiation; rooftop. • No Budget--Single duct VAV; fan powered induction boxes; central.
Community Center	• Tight Budget--Single zone; electric baseboard radiation; rooftop. • Medium Budget--Single zone; hot water baseboard radiation; rooftop. • No Budget--Single duct VAV; hot water baseboard radiation; rooftop.
Gymnasium	• Tight Budget--Single zone; heating and ventilating; rooftop. • Medium Budget--Single zone; electric baseboard radiation; rooftop. • No Budget--Single zone; hot water baseboard radiation; rooftop.

TABLE IV (Continued)

BUILDING TYPE	TYPICAL HVAC SYSTEM SELECTIONS
Hospital	• Tight Budget--Fan coil units; single zone with reheat; central. • Medium Budget--Fan coil units; single duct VAV; hot water baseboard radiation; central. • No Budget--Fan coil units; dual duct; VAV w/ reheat; hot water baseboard radiation; heat recovery; central.
Motel	• Tight Budget--Packaged, through the wall unitary units. • Medium Budget--Packaged fan coil units. • No Budget--Four-pipe fan coil units; packaged heat pumps; central.
Multifamily High Rise	• Tight Budget--Packaged, through the wall unitary units; electric baseboard radiation. • Medium Budget--Fan coil units; heat pumps; hot water baseboard radiation. • No Budget--Four-pipe fan coil units; hot water baseboard radiation.
Nursing Home	• Tight Budget--Packaged, through the wall unitary units; electric baseboard radiation. • Medium Budget--Fan coil units; hot water baseboard radiation; central. • No Budget--Four-pipe fan coil units; hot water baseboard radiation; central.
Office - Large	• Tight Budget--Single duct VAV; electric baseboard radiation; central. • Medium Budget--Single duct VAV; hot water baseboard radiation; central. • No Budget--Single duct VAV; fan powered VAV boxes on perimeter; central.
Office - Small	• Tight Budget--Single zone; air-to-air heat pumps; electric baseboard radiation; rooftop. • Medium Budget--Single duct VAV; fan powered induction units; rooftop. • No Budget--Single duct VAV; hot water baseboard radiation; fan powered induction units; central.

TABLE IV (Continued)

BUILDING TYPE	TYPICAL HVAC SYSTEM SELECTIONS
School (Elementary/ Secondary)	• Tight Budget--Packaged, rooftop, single zone, unitary units; unit ventilators. • Medium Budget--Single zone; single duct VAV; hot water baseboard radiation; rooftop. • No Budget--Single duct VAV; hot water baseboard radiation; central.
Shopping Center	• Tight Budget--Single zone; rooftop. • Medium Budget--Single zone; rooftop. • No Budget--Single duct VAV; central.
Store	• Tight Budget--Single zone; rooftop. • Medium Budget--Single zone; rooftop. • No Budget--Single zone; single duct VAV with reheat; central.
Theatre/Auditorium	• Tight Budget--Single zone; multiple single zone units; rooftop. • Medium Budget--Single zone; rooftop. • No Budget--Single zone; multiple single zone units; hot water baseboard radiation; central.
Warehouse	• Tight Budget--Single zone; gas fired unit heaters. • Medium Budget--Single zone; heating and ventilating; rooftop. • No Budget--Single zone; heating and ventilating; rooftop.

Comparing both the historical data and that collected through the use of the survey shows a difference in system applications over time. In 1966 a fair amount of dual duct and multizone systems were employed in architectural projects. By 1976 energy was much more of a concern than in 1966 but reheat systems, which were popular, still wasted a lot of energy. Today a single duct all-air system is the most common with energy conservation as an important issue. By employing a contributary perimeter system, comfort conditions can be met with minimal expenditures of energy.

A certain pattern can be detected in the survey results from "tight budget" to "no budget." Most tight budget systems include a single zone rooftop system with electric baseboard radiation. Those with no budget most often include a VAV central system with hot water baseboard radiation. In some applications, such as a hospital, budget has no major influences.

The Schematic Design Phase

A major objective of the schematic design phase is to secure the best solutions to the design problems presented in the programming phase. A common method of arriving at a solution is to prepare an array of specific design parameters which would limit the scope of alternatives. By the schematic design phase, the architect should know more about the project in order to answer specific questions, resulting in a system selection best suited to fit that project.

There are many factors that influence the decision of which HVAC system to employ in an architectural project. Some of these factors are very difficult, if not impossible, to evaluate in such an early design phase. In this study, only those factors which can be predicted with some reasonable accuracy are considered. To have a better perception of the factors' influence in the selection process, each one will be categorized and discussed separately.

OBJECTIVE	SUBJECTIVE
• Initial cost	• Appearance
• System capacity	• Maintainability
• Building size	• System reliability
• System space requirements	• Flexibility
• Annual cost	• Comfort results
• Number of zones	
• Code considerations	

Objective Factors

The objective factors involved with the system selection process are those which are measurable on a common scale, such as monetary units. These types of factors are the easiest to incorporate into a rating method for system selection and evaluation.

Initial Cost. Usually, in the field, the cost is of such importance that it is separately identified in any comparative analysis. Initial costs include: construction costs of the system, additional building costs that are attributed to the system, costs to design, and costs to administer construction. For purposes of this study, actual system costs will not be addressed, but rather only weighted in accordance with the project application.

Capacity. The system selected for a particular application must be able to handle the heating and cooling loads. For instance, a 150 ton chiller would not be used in a building with a cooling load of 175 tons. Although systems are sometimes oversized due to equipment availability, load uncertainty, and safety factors, the system with the closest capacity to the building loads should be selected.

Building Size. The size of the building, as opposed to the magnitude of the loads, is a major influence on the selection of a system. Some systems operate more efficiently in larger applications than others and vice versa.

Space Requirements. In most cases, the space needed for the HVAC system is a critical consideration. The more space taken up by the system, the less space able to be utilized or leased by the owner; thus the reason for many rooftop applications. The type and size of the project will usually influence the importance of available space.

Annual Cost. Included in this category are both the owning and operating costs. Owning costs occur even if the system is not active. They include initial costs, salvage value, property taxes, rents, and insurance. Operating costs refer to money spent on energy, wages, supplies, water, material, maintenance, parts, and services (10).

Number of Zones. Another physical characteristic of a system is the number of zones it can serve simultaneously; heating and/or cooling. The importance of flexibility and future expansion must be evaluated with respect to the project. If open planning is involved, then zone flexibility is necessary. If future expansion is foreseen, the initial system may need to be oversized.

Code Considerations. In certain parts of the country, building codes will influence what can and cannot be used in terms of HVAC systems, however, almost never directly. The stringency of code requirements will depend on the type of project. This, in turn, narrows the scope of the system possibilities.

Subjective Factors

Subjective characteristics (10) cannot be measured objectively on a common scale. What may be important to one person may not be a concern with another person. An array of characteristics and system alternatives should be established and compared against the objectives of those affected by the system selection. In order to incorporate these factors into a rating system, they can be evaluated subjectively on an "excellent" to "bad" basis and be transferred to an arbitrary scale expressed as one through ten.

Appearance. An HVAC system can greatly affect the aesthetic qualities of an architectural design. Some systems may be completely eliminated due to architectural design restraints. For instance, a rooftop unit may be ruled out if it is clearly visible and unattractive to the building.

Maintainability. The ability to maintain a system's performance may become a major issue, depending on its specific application. For instance, in an office application, fan coil units may be rejected due to maintenance having to occur in the office work area. Systems installed in very limited spaces may also hinder maintainability.

System Reliability. The reliability of each component is more easily measured than the reliability of an entire system. Each component of a system must be evaluated from a failure point of view, and its effects due to the failure. For instance, in an office, if a central air handler breaks down, a large portion of the office is affected. If a fan coil system is used and one breaks down, only a small area is affected. In turn, a central chiller may fail, in which case the entire building would be affected.

Flexibility. Rearrangement and functional changes of a system are often required. Open offices may change or be converted into a different type of space, therefore a system must be evaluated with respect to its ability to cope with such changes.

Comfort Results. Comfort can be classified as both objective and subjective. ASHRAE Standard 55 sets parameters for thermal comfort on which heating and cooling load calculations are based, but not everyone will be comfortable in this range. The factors that most greatly affect overall comfort are: air temperature, relative humidity, air motion, mean radiant temperature, noise level, and air quality. The importance of these factors is based on the specific application. For example, the noise level in a theatre is more important than that in a shopping center, unless, of course, the noise level in a shopping center is unbearable.

Matrix Approach

Most HVAC system rating methods that have been developed in the past are based on a comparative format. The designer decides the relative importance of each project characteristic as well as each system's proficiency in a particular application. Joseph Olivieri (11) presented an air-conditioning rating system at the ASHRAE 1971 semi-annual meeting in Philadelphia, Pennsylvania. His method consists of the following comfort equation:

$$CC = \frac{XM^2 + XR^2 + XT^2 + XH^2 + XC^2 + XV^2 + XS^2 + XQ^2}{10}$$

where: CC = comfort coefficient

M = air motion rating

R = MRT rating

T = air temperature rating

H = relative humidity rating

C = temperature control rating

V = ventilation rating

S = sound rating

Q = reliability rating

X = 1 or 2; but can only be 2 for 2 items

Each factor is rated from 0 to 10.

One year later, another air-conditioning rating scale was developed by Alfred Greenberg (4). His approach is based on Olivieri's equation; however, the factors include many more parameters such as operating and maintenance costs, flexibility, appearance, etc.

Several other system selection methods have been developed, all of which are quite efficient for systematically comparing data, however, none of these cater specifically to the architect.

The key to a successful project is matching a building's demands with what a system can offer--system and building compatibility. A way of achieving this is through the scrutiny of all the parameters involved. By incorporating building characteristics, system characteristics, subjective and objective factors, and results from the programming phase into a system selection matrix, the architect can examine a vast array of system possibilities without having to be proficient in HVAC design.

The selection method proposed in this study involves the use of a "system selection matrix" (see Figure 15). The x-axis (read horizontally) contains the system types. The y-axis (read vertically) contains the subjective and objective factors for each system type. This arrangement allows the architect to gain relative information about each system type in order to conduct a comparative analysis of HVAC systems.

C	ALL AIR																																																							AIR-WATER							ALL WATER						UNI-TARY		
T	SINGLE ZONE																				MULTI				SINGLE DUCT VAV																				DUAL DUCT						INDUCTION						IND		F COIL				HHPOA	F. COIL				HHP	VAL	TTW	UH	AHP
L	CENTRAL										ROOFTOP										C		R		CENTRAL										ROOFTOP										CENT			ROOF			CENT			ROOF																		
R	YES					NO					YES					NO									YES					NO					YES					NO					Y	NO		Y	NO		Y	NO		Y	NO																	
P	N	BB		TB		N	BB		TB		N	BB		TB		N	BB		TB		2	3	2	3	N	BB		TB		N	BB		TB		N	BB		TB		N	BB		TB		C	C	V	C	C	V	E	C	V	E	C	V	C	R	2	3	4	E		2	3	4	E					
M		W	E	W	E		W	E	W	E		W	E	W	E		W	E	W	E						W	E	W	E		W	E	W	E		W	E	W	E		W	E	W	E																												
#																																																																									
a																																																																										
b																																																																									
c																																																																									
d																																																																									
e																																																																										
f																																																																									
g																																																																									
h																																																																									
i																																																																									
j																																																																									

Figure 15. System Selection Matrix

A unique characteristic of this method is an array of values already assigned in the matrix. In most methods, both the building and system characteristics must be input by the architect. Using this method, the architect only has to rate the importance of each factor characteristic of his own project. Since these numbers are relative ratings, skepticism may develop as to the validity of each assigned value, therefore, each row, column, and element must be discussed individually.

<u>X-axis</u>. The organization of the various systems along the x-axis is critical. Because overall performance varies with combinations of system types, each system integration must be considered separately.

Because there are virtually thousands of system combinations, only those which may have a strong impact on the architectural design are considered.

The x-axis is comprised of six levels for system categorization. The first level is the general system classification (denoted "C" on the matrix). There are four major classifications--all-air, air-water, all water, and unitary. The all air systems are assumed to have full economizer cycles. The "unitary" classification includes that equipment which is not considered a total system by itself, but rather self contained, factory packaged incremental units.

The second level is made up of system types (T). Included in this level are: single zone, multizone, single duct VAV, dual duct, induction, fan coil, heat pump, valance, through the wall units, and unit heaters. At this level some overlapping occurs between general classifications but each system type is segregated according to its distinct characteristics. For instance, a fan coil unit can be considered a factory packaged unitary unit, but since it is part of a central system, fan coil units are categorized as air-water or all-water systems for purposes of this matrix.

The third level considers the location of the mechanical equipment (L). The term "central" is taken in this matrix to mean located inside. "Rooftop" includes chillers, boilers, and/or air handling units located on the building's roof.

The fourth level is reheat (R). This only pertains to all-air systems. Although using energy to reheat air distributed to a space violates most building codes, these systems are still being used today, for example, where waste heat is used or on a special project such as a hospital. The specific type of reheat system is not delineated in the matrix.

Level five and level six deal with a separate system for the perimeter zone (P) and the medium used (M). These levels are specifically intended for use with all-air systems that don't have the capability of heating and cooling simultaneously. The three choices under the "P" category are none (N), baseboard (BB), and terminal boxes (TB). Baseboard and terminal box categories are further divided by the medium being used--water (W) or electric (E). Included under the baseboard category are finned tube radiators, circulating condenser water loop, geothermal or solar assisted, or electric radiant. Each specific type is not discussed separately as it is not within the scope of this study. Terminal boxes, for purposes of this study, refer to any factory-made device for air-distribution. Unlike baseboard radiation, terminal boxes have moving parts inside them--fans, dampers, etc. Included under this category are fan powered VAV boxes and fan powered induction boxes (typical induction is under a separate category).

Using the six levels comprising the x-axis, 21 unique, basic system types are considered in the matrix:

--All-air

- single zone
- single zone with reheat
- 2-deck multizone
- 3-deck multizone
- single duct variable air volume
- single duct variable air volume with reheat
- dual duct - constant volume

- dual duct - variable volume
- dual duct with reheat
- induction - constant volume - perimeter installation
- induction - variable volume - perimeter installation
- induction with reheat-perimeter installation

--Air-water

- induction (with coil in induction unit)
- fan coil with outside air (2-pipe, 3-pipe, 4-pipe, or 2-pipe with electric heating coil) - perimeter or ceiling installation
- hydronic heat pumps with outside air - perimeter or ceiling installation

--All-water

- fan coil (2-pipe, 3-pipe, 4-pipe, or 2-pipe with electric heating coil) - perimeter or ceiling installation
- hydronic heat pumps - perimeter or ceiling installation
- valance system

--Unitary

- through-the-wall vapor compression air conditioners
- unit heaters
- air to air heat pumps - perimeter installation

Y-axis. Factors that are considered when selecting an HVAC system make up the y-axis. The factors under consideration in this matrix are stated as follows:

a. low initial cost

b. energy conservation (low operating cost)

c. building appearance (limiting architectural design restraints)

d. system maintainability (layout efficiency of mechanical equipment)

e. minimal space requirements (limiting the amount of rentable space for mechanical equipment)

f. flexibility (feasibility of system changes)

g. acoustical comfort (low noise)

h. minimal plenum depth

i. durability (system service life)

j. thermal comfort (controllability)

To acquire results from this process, the designer must rate each of these 10 objective and subjective factors on a scale from 0-100, so long as the total of all ratings adds up to 100. The equation that is used to evaluate a system rating is:

$$R = s+x(a)+x(b)+x(c)+x(d)+x(e)+x(f)+x(g)+x(h)+x(i)+x(j)$$

where: R is the rating of a system and

X is the value assigned by the designer.

Within each element of the matrix, a relative value is assigned according to a particular system's proficiency in carrying out a specific task. The value itself is an arbitrary number between one and ten, but the parameters from which it is derived are fixed. To further illustrate the way in which each value is determined in the system selection matrix, factors "a" through "j" are discussed individually.

The "a" factor is for determining a system's initial cost relative to costs of other systems. Exact costs are not of concern to the architect in the schematic design phase but estimations are available and can be used for comparative purposes. Through the utilization of estimating manuals (7, 12), a rating scale can be established to rate various systems according to first costs. The matrix rating is a relative function of the highest and lowest initial costs, designating 10 the lowest first cost. The value is calculated by:

$$M_R = 10 \left[1 - \frac{(P_X - P_L)}{(P_H - P_L)} \right]$$

where: M_R is the matrix rating

P_X is the unit cost of the system in question

P_L is the unit cost of the lowest priced system

P_H is the unit cost of the highest priced system

Values for systems not included below are interpolated for use in the matrix.

• Packaged through the wall unit	\$785/ton	10 pts.
• Packaged air-to-air heat pump	\$1065/ton	9 pts.
• Single zone rooftop packaged unit	\$1270/ton	8 pts.
• Incremental hydronic heat pump	\$1485/ton	7 pts.
• Multizone rooftop unit	\$1535/ton	7 pts.
• Multizone four pipe system	\$1645/ton	6 pts.
• Low pressure VAV with electric baseboard	\$1930/ton	5 pts.
• High pressure VAV with hot water reheat	\$2275/ton	4 pts.
• High pressure VAV induction	\$2290/ton	4 pts.
• 2-pipe fan coil with outside air	\$2305/ton	4 pts.
• High pressure VAV dual duct	\$2350/ton	3 pts.

• High pressure dual duct	$2410/ton	3 pts.
• 4-pipe fan coil with outside air	$2575/ton	2 pts.
• High pressure induction	$2860/ton	1 pt.

The "b" factor is used for recognizing energy conscious systems. Many system selections in the HVAC field are based on a life cycle cost analysis. Included in this analysis are energy conservation considerations--i.e., the cost of system operation. But even with extensive informatjion about utility rates, system components, and efficiencies, any calculation of future costs is still only an estimation on the engineer's part. Accurate energy savings calculations can only be made if total system interaction is fully understood. For instance a "reheat" system may refer to that which uses additional energy to reheat preconditioned air, or it may refer to a system which utilizes waste energy in the form of recirculated condenser water from the chillers. A VAV system in one application may not use the same amount of energy as a similar system in another application. Since the system types in this selection matrix are quite general, the values assigned for each type are based not on absolute energy performance of a system, but rather the general potential of a system to conserve energy. For example, a VAV system with baseboard radiation has the ability to incorporate a heat recovery or solar assisted heating system whereas an incremental through the wall unit has very limited possibilities and hence receives a lower rating in this category.

The considerations and parameters for the energy conservation rating are:

• Unitary units	1 pt.

- Valance - no fans or moving parts but not much flexibility for incorporating energy efficient design 2 pts.
- Fan coil units - with outside air - 2- & 3-pipe 3 pts.
- Induction - high velocity uses more energy than low velocity 3 pts.
- Multizone and dual duct - mostly energy inefficient since warm and cool air flows eventually mix 3 pts.
- Fan coil units - all-water - no outside air to condition - 2- & 3-pipe (Note: split boxes in matrix refer to fan coil unit in ceiling-top value, or fan coil unit in wall-bottom value) 4 pts.
- Hydronic heat pumps - if equal amount of zone with heating and cooling 6 pts.
- Single zone and VAV with electric perimeter heating - full economizer 8 pts.
- Single zone and VAV with terminal boxes - full economizer; power needed for fan in boxes but may use heat from the lights for perimeter zone 9 pts.
- Single zone and VAV with hot water baseboard - full economizer and possible recirculated condenser loop or solar heated water loop 10 pts.

Note: for purposes of this matrix, a system with reheat is considered to utilize more energy than a system without reheat.

The "c" factor concerns the building appearance. The location of mechanical equipment has a major influence on the aesthetic qualities of a building. This is an important consideration since the value of a building is often closely related to its finished appearance. The types of systems most susceptible to architectural criticism are incremental through the wall units and rooftop systems. In many cases, rooftop units can be "hidden" in order not to destroy the building's appearance. The matrix ratings for appearance are derived from the parameters established below.

- Repetitious wall penetrations where vents, louvers and/or equipment is visible on the building exterior — 1 pt.
- Large rooftop systems on small low rise buildings — 3 pts.
- Medium size equipment (terminal boxes) inside the work space — 6 pts.
- Small size equipment (baseboard radiation) inside the work space — 8 pts.
- No visible mechanical equipment — 10 pts.

Note: this particular rating does not take into account those systems whose equipment is used for architectural effect (i.e., exposed ductwork).

The "d" factor is used to determine system maintainability. Maintainability for purposes of this study refers to serviceability and accessability of HVAC components. Routine maintenance is usually done by an operating engineer who must gain accessibility to the equipment. In some cases of routine maintenance or equipment failure an outside service firm must handle the job. Therefore, the matrix rating given to a system for maintainability is directly related to the efficient layout of the equipment.

- All equipment in one generously sized central apparatus room — 10 pts.

- All equipment in multiple apparatus rooms 5 pts.
- Most all equipment in tenant offices 1 pt.

The "e" factor is a value directly related to the amount of usable floor space taken up by mechanical equipment. A major influence on this rating is whether the equipment is inside or outside of the building. Air-water, all-water, and unitary systems in general require less space than all-air systems due to smaller (or no) fan room requirements and less (or no) space requirements for duct shafts. The following baseline criteria are used for calibrating the matrix rating values:

- Unitary systems 10 pts.
- All-water systems 9 pts.
- All-air rooftop systems 8 pts.
- Air-water central systems 5 pts.
- All-air central systems with perimeter terminal boxes 1 pt.

For rating system flexibility, the factor "f" is used. The flexibility of a system is based on its ability to cope with zonal or space usage changes. Most of the time, small, incremental systems can be rearranged to adjust to zonal changes, whereas large, more complex systems are not so easily adapted. The relative matrix values are based on the following criteria:

- Unitary equipment 10 pts.
- All-water systems - piping and terminal box rearrangement required 7 pts.
- Air-water systems - piping and terminal box rearrangement plus possible ductwork changes required 5 pts.

- All-air VAV system - from VAV boxes to air diffusion device offers some flexibility. For extensive changes, major ductwork changes are required 4 pts.
- All-air dual duct and multizone - extensive ductwork changes are required 1 pt.
- Reheat on any system offers added flexibility +1 pt.

The "g" factor is based on the relative magnitude of noise produced by a system. The assigned value of "g" is based only on the conditions which exist in the occupied areas of the building. The numerical rating for "g" then is based on the assumption that all the equipment has been installed to achieve good acoustical comfort output--low noise in occupied areas. For instance, assuming the main mechanical room is not adjacent to the work space or that rooftop equipment is properly isolated, etc. The matrix ratings are based on the following assumptions:

- Unitary equipment - compressors and fans directly in occupied spaces (equipment NC > 40) 1 pt.
- Induction units - high pressure, high velocity air (terminal NC $\cong$ 40) 2 pts.
- Fan coil units - fans located near or directly in work space (equipment NC $\cong$ 37) 4 pts.
- VAV system with terminal boxes - low powered fans located directly in occupied spaces plus intermittent air flow may be noticeable (terminal box NC $\cong$ 35) 5 pts.
- Single zone system - assuming fan room is remotely located (diffuser NC $\cong$ 30) 8 pts.
- Baseboard or valance - no moving parts 10 pts.

The depth of a ceiling plenum (h), is typically directly related to the HVAC distribution system. Equipment such as fan coil units, hydronic heat pumps, or VAV boxes located in the ceiling plenum will influence the space needed below the structure. The matrix ratings are based on the following system characteristics:

- Dual duct - extensive ductwork and possible crossovers — 1 pt.
- Multizone - extensive ductwork — 2 pts.
- Single duct VAV - VAV boxes not more than 16" deep above suspended ceiling — 3 pts.
- Fan coil units and hydronic heat pumps - not more than 14" deep; since units are approximately 50" x 30", coordination with lights and structure may need to be considered when located in ceiling plenum — 3 pts.
- Air-water systems - units located on perimeter with smaller ductwork — 8 pts.
- Unitary - located on perimeter — 10 pts.

The durability of a system (i), refers to its expected service life. In most cases if the building is designed to last a long time, so should the HVAC system, as it is usually more expensive to replace than it is to initially install. By examining the components that make up each system, an average service life of a system can be derived (see Table V).

TABLE V

EQUIPMENT SERVICE LIFE

EQUIPMENT ITEM	MEDIAN YEARS
Through-the-wall units	15

TABLE V (Continued)

EQUIPMENT ITEM	MEDIAN YEARS
Hydronic heat pumps	19
Rooftop single zone and multizone	15
Steel fire-tube boilers	25
Electric radiant heaters	10
Hot water radiant heaters	20
Centrifugal fans	25
Unit gas heaters	13
DX or water coils	20
Packaged centrifugal chillers	23
Wood cooling towers	20
Air-cooled condensers	20
Induction and fan coil units	20
Ductwork	30
VAV and dual duct boxes	20

Source (9)

Evaluating each system based on its primary components and their corresponding service life, the following rating values are derived:

- Unitary systems 1 pt.
- Gas unit heaters 1 pt.
- Rooftop systems - assuming some equipment (ductwork, diffusers, etc.) inside 3 pts.
- Hydronic heat pumps 5 pts.
- Fan coil and induction units 6 pts.
- VAV system with electric baseboard radiation--central air handler, cooling tower 7 pts.
- Single zone with hot water baseboard - central air handler, cooling tower 10 pts.

The "j" factor evaluates a system's ability to provide thermal comfort. Each system is rated based on its proficiency in the following areas:

- temperature control 2 pts.
- air motion 2 pts.
- outside air requirements 2 pts.
- humidity control 2 pts.
- air quality 2 pts.

Having derived all of the ratings for each system type, they are all incorporated into the system selection matrix for use by the architect (see Figure 16). Because the evaluation of each individual system would be long and tedious, a variation of the system selection matrix is used to show the results from the HVAC survey (see Figure 17) which could limit the comparative analyses of systems to a selected few. In this particular matrix, A through N (on the y-axis), refer to building type:

A. Clinic

B. Community Center

C. Gymnasium

D. Hospital

E. Motel

F. Multifamily High Rise

G. Nursing Home

H. Office - Large

I. Office - Small

J. School (Elementary/Secondary)

K. Shopping Center

L. Store

M. Theatre/Auditorium

N. Warehouse

The black squares in the matrix designate the upper 60 percentile of systems selected for that particular application according to the survey. Single zone and single duct VAV take up the most space in the selection matrix because these systems are the most common and lend themselves easily to various combinations with other systems. The grey (hatched) boxes indicate contributary systems in the upper 50 percentile that are commonly associated with the single zone and single duct VAV systems.

	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
C	ALL AIR																							
T	SINGLE ZONE																				MULTI			
L	CENTRAL										ROOFTOP										C		R	
R	YES					NO					YES					NO								
P	N	BB		TB		N	BB		TB		N	BB		TB		N	BB		TB		2	3	2	3
M		W	E	W	E		W	E	W	E		W	E	W	E		W	E	W	E				
a	7	6	7	6	7	8	6	7	6	7	7	6	7	6	7	8	6	7	6	7	6	5	7	6
b	8	8	6	7	6	10	10	8	9	8	8	8	6	7	6	10	10	8	9	8	3	3	3	3
c	10	8	8	6	6	10	8	8	6	6	3	3	3	3	3	3	3	3	3	3	10	10	3	3
d	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	10	10	10
e	2	2	2	1	1	2	2	2	1	1	8	8	8	7	7	8	8	8	7	7	3	3	7	7
f	5	3	3	3	3	3	2	2	2	2	5	3	3	3	3	3	2	2	2	2	1	1	1	1
g	8	8	8	6	6	8	8	8	6	6	8	8	8	6	6	8	8	8	6	6	8	8	8	8
h	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2	2
i	10	9	8	9	8	10	9	8	7	8	3	3	3	3	3	3	3	3	3	3	10	10	3	3
j	8	10	10	10	10	6	10	10	10	10	8	10	10	10	10	6	10	10	10	10	10	10	10	10

	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
C	ALL AIR																									
T	SINGLE DUCT VAV																				DUAL DUCT					
L	CENTRAL										ROOFTOP										CENT			ROOF		
R	YES					NO					YES					NO					Y	NO		Y	NO	
P	N	BB		TB		N	BB		TB		N	BB		TB		N	BB		TB		C	C	V	C	C	V
M		W	E	W	E		W	E	W	E		W	E	W	E		W	E	W	E						
a	5	4	5	4	5	6	4	5	4	5	5	4	5	4	5	6	4	5	4	5	3	3	3	3	3	3
b	8	8	6	7	6	10	10	8	9	8	8	8	6	7	6	10	10	8	9	8	2	3	3	2	3	3
c	10	8	8	6	6	10	8	8	6	6	3	3	3	3	3	3	3	3	3	3	10	10	10	3	3	3
d	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	10	10	10	10	10
e	2	2	2	1	1	2	2	2	1	1	8	8	8	7	7	8	8	8	7	7	3	3	3	7	7	7
f	7	5	5	5	5	5	4	4	4	4	7	5	5	5	5	5	4	4	4	4	2	1	1	2	1	1
g	7	7	7	5	5	7	7	7	5	5	7	7	7	5	5	7	7	7	5	5	8	8	7	8	8	7
h	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1	1
i	9	8	7	8	7	9	8	7	8	7	3	3	3	3	3	3	3	3	3	3	10	10	10	3	3	3
j	8	10	10	10	10	6	10	10	10	10	8	10	10	10	10	6	10	10	10	10	10	10	10	10	10	10

	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
C	ALL AIR						AIR-WATER							ALL WATER						UNITARY		
T	INDUCTION						IND.		F. COIL				HHPOA	F. COIL				HHP	VAL	TTW	UH	AHP
L	CENT			ROOF																		
R	Y	NO		Y	NO																	
P	E	C	V	E	C	V	C	R	2	3	4	E		2	3	4	E					
a	5	4	4	5	4	4	1	1	4	3	2	4	3	5	4	3	5	7	7	10	10	9
b	2	3	3	2	3	3	3	3	3	3	4	2	6	4	4	5	3	6	2	1	1	1
c	6	6	6	3	3	3	6	3	10/1	10/1	10/1	10/1	10/1	10/1	10/1	10/1	10/1	10/1	6	1	1	1
d	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	1	1	1
e	6	6	6	8	8	8	6	8	9/6	9/6	9/6	9/6	9/6	9/7	9/7	9/7	9/7	9/7	9	10	10	10
f	4	3	3	4	3	3	5	5	5	5	5	5	5	7	7	7	7	7	10	10	10	10
g	2	2	2	2	2	2	2	2	4	4	4	4	3	4	4	4	4	3	10	1	1	1
h	7	7	7	7	7	7	8	8	3/8	3/8	3/8	3/8	3/8	3/10	3/10	3/10	3/10	3/10	10	10	10	10
i	6	6	6	3	3	3	6	3	6	6	6	5	6	5	6	6	5	5	10	1	1	1
j	10	10	10	10	10	10	10	10	2	4	5	4	4	2	4	5	4	4	2	4	4	4

Figure 16. System Selection Matrix - Weighting Factors

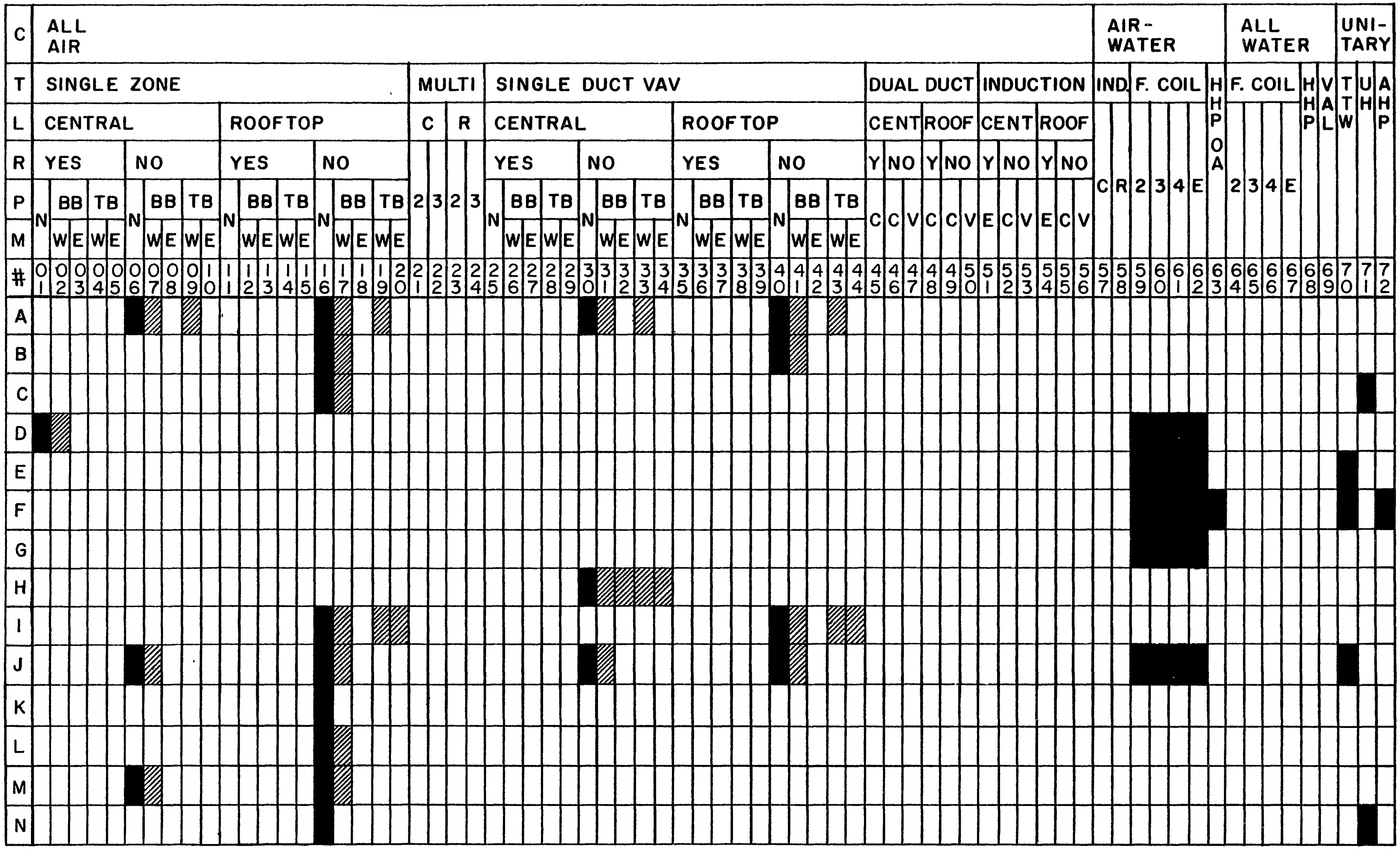


Figure 17. System Selection Matrix - Survey Results

Schematic Design Conclusions

By the end of schematic design, the architect should have a fairly good idea of the system type that best suits his project's needs. It cannot be emphasized enough that the results gathered from the use of this method are not definitive. There are many variables which may influence the selection of an HVAC system for each specific project--owner, cost, energy incentives, local codes, etc. Once the designer becomes familiar with the method, he should input his own relative values based on experience and familiarity with the project. The purpose for a method of this type is to expose the architect to various solutions early in the design phase. State of the art HVAC designs and analysis of any phase beyond schematic design requires the attention of a systems engineer.

CHAPTER V

SYSTEM SIZING PROCESS

General Considerations

Providing adequate space for mechanical equipment is an issue that must be considered early in the design process. Before an accurate estimate can be made as to the required size of equipment rooms, a basic understanding of the equipment involved is required.

There are obviously many "environmental control" systems employed in a building. Each system incorporates its own equipment and components. The electrical system includes transformers, switchgear, emergency generators, and electrical distribution components. The main plumbing system utilizes gas and water meters, domestic hot water heaters, ejector pumps, fire protection system pumps and piping. The HVAC system as well employs its own equipment and components. This study deals with just the equipment pertaining to the HVAC system. In most cases, the HVAC system will have the largest space requirements of all the environmental systems.

Equipment

The types of equipment comprising the HVAC system can be divided into three major sections: refrigeration equipment, heating equipment, and air handling equipment. Only those components which have major influences on the architecture and space requirements of a design are discussed in the following pages.

Refrigeration Equipment. There are three basic refrigeration methods:

1. Vapor Compression
2. Absorption
3. Thermoelectric.

Vapor compression and absorption are the most common methods employed for air-conditioning applications.

The vapor compression refrigeration cycle consists of four major components: compressor, condenser, evaporator, and expansion device (see Figure 18). In smaller air-conditioning applications, air is blown directly across the cooling coil (usually a DX coil) and supplied into the conditioned space. These systems are mostly incorporated in unitary equipment (through the wall units and fan coil systems). Although some central DX type systems are used for general air-conditioning, long refrigerant pipe runs are not recommended due to line pressure drop and heat gain.

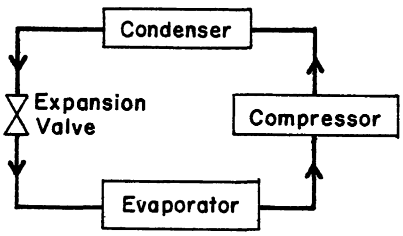


Figure 18. Simple Vapor Compression Refrigeration Cycle

In most large air-conditioning applications, a liquid chilling system is utilized. A liquid chiller refrigerates a liquid (usually water since it has the highest specific heat per unit cost) which in turn is supplied to the cooling coils in air handling units throughout the building. The name given to the chiller is based on the compressor type used. There are three major refrigeration compressor types used in large systems:

- Reciprocating
- Helical rotary
- Centrifugal

Reciprocating compressors are simply piston driven crankshafts used to compress refrigerant vapor. Reciprocating chillers are mostly used for smaller cooling loads; up to approximately 100 tons. They are well suited for air-cooled condenser applications and low temperature chilled water refrigeration.

Helical rotary or screw type compressors reduce volume directly with two helically grooved rotors in motion compressing the refrigerant vapor. Unlike the reciprocating compressor, the helical rotor has nearly constant flow performance which makes control easier.

Centrifugal chillers are the most common and most versatile for air-conditioning applications. They offer a wide range of capacities by altering built-in design items. Centrifugal chillers can deal with variations in load conditions with nearly proportionate changes in power consumption. This makes it possible to achieve closer temperature control and better energy conservation.

Absorption is another major refrigeration type (see Figure 19). It is mostly used instead of vapor compression in industrial applications using waste heat. The overall efficiency is poor and, therefore, it is only used when a significant amount of waste heat or solar energy is available.

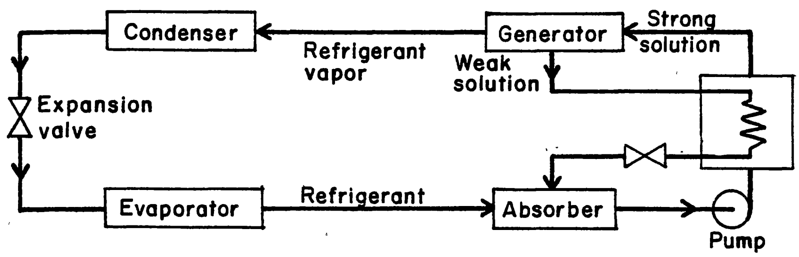


Figure 19. Absorption Refrigeration Cycle

Heat rejection in the refrigeration process is achieved through a condenser. A condenser may be water-cooled, air-cooled, or evaporative, and is usually the largest piece of refrigeration equipment. A condenser must always be exposed directly or indirectly to the atmosphere to that heat may be removed.

Water cooled condensors use water to remove heat from the condensing coil. In most cases, this water is then cooled by contact with the atmosphere through the use of a cooling tower.

Air-cooled condensers come in many different shapes and sizes. They are classified as: condenser remote from the compressor, or condenser as part of a condensing unit, and are either cooled with forced air flow or natural convection air flow.

Evaporative condensers use both water and air to condense refrigerant inside the coil. Water is sprayed onto the condenser coil while a fan blows air across it, thus heat is removed by the water evaporating off the coil.

The other general components of the refrigeration equipment are pumps, piping, and instrumentation.

There are generally two pump sets, one for condenser water (if a cooling tower is used) and one for chilled water. One set typically consists of two pumps connected in parallel for operational continuity in case one pump fails.

The piping systems can be divided into two categories: the piping contained within the mechanical room, and the piping that serves the air handling units throughout the building. The piping in the main mechanical room consists mostly of fuel lines, steam, refrigerant, and water connections; whereas the piping to the air handling units usually just contains water.

The instrumentation includes thermostats, flow controls, gauges, valves, and sometimes a central computer control to monitor and balance the refrigeration system.

Heating Equipment. The heating system is substantially less complex than the refrigeration system. The major component in a central heating system is the boiler.

Boilers are either steam or hot water type manufactured for high or low pressure. Fuel for the boiler is usually coal, oil, gas, or electricity. When a boiler utilizing combustible fuels is operated indoors, combustion air must be supplied to the boiler room and proper exhaust from the boiler must be ducted directly outside.

Depending on the project in question, district steam and chilled water may be available from a central plant. Many downtown areas of large cities are served by such a system. In this case, the central mechanical room in the building may only consist primarily of pumps, piping, heat exchangers, and instrumentation; no chillers or boilers.

Air Handling Equipment. The air handling system can be divided into three major parts: the air handling unit, the air distribution system, and the air diffusion devices.

The major components of an air handling unit are: heating and/or cooling coils, fan, and filter. The two basic air handling unit types are prefabricated units and built-up units. Prefabricated types include the coils, filters and fans that are all selected as a package and frequently shipped subassembled to be erected in the field (3). With built-up units, each component is selected separately and integrated by the engineer into one complete system. Depending on the function and physical characteristics of the space to be conditioned, proper additional components can be selected and arranged: outdoor air intakes, return air fans, bypass sections, mixing plenums, preheat coils, and controls.

The air distribution system consists primarily of ductwork and dampers. The ductwork should deliver conditioned air to an area as directly, quietly and economically as possible (3). In most applications where the ductwork is concealed, it is rectangular to achieve a shallow depth. By using a high velocity system, the size of the ductwork can be further reduced from that of a low velocity system but at some energy cost. Where ductwork is exposed, it is usually round for aesthetic reasons, and should always be coordinated with the structure. The primary function of the dampers is to mix and balance the air flow in the distribution system. They are analagous to valves in a piping system.

The air diffusion devices include diffusers, registers and grilles. The function of these devices is to introduce air into a conditioned space to obtain specific environmental conditions. Special attention must be paid to the air diffusion system's performance so as not to cause drafts that could hinder comfort conditions. These devices are usually incorporated in the ceiling; however, depending on the diffuser type, they may be installed in a wall or a sill.

The Programming Phase

Rules-of-thumb for system space planning used in the very early design phases are often postulated as a function of a building's total floor area. Although very few buildings are exactly identical in concept and design, these rules-of-thumb provide a reasonable approximation of the final space requirements.

The system to be used, building configuration, and many other variables will often dictate the space and arrangement required for the HVAC system. In most cases, two major areas are considered when allocating space for the mechanical equipment: fan rooms and central mechanical rooms.

A fan room contains air handling equipment and, depending on system arrangement, vertical shafts for air distribution. Large ducts originating from a fan room are somewhat difficult to maneuver. Therefore, a fan room's location should follow the expected geometry of the main distribution system. The location should also permit connection to outside air intakes and exhaust outlets. The number of fan rooms is often up to architect. A packaged air handling unit has a maximum capacity of approximately 25,000 cfm, whereas a built-up unit usually has the capacity of approximately 60,000 cfm (13). Therefore, depending on the design of the building, one fan room may serve 10-20 floors or one or several fan rooms may be incorporated on each floor. However, smoke control requirements for life safety purposes may dictate fan room locations.

The central mechanical room consists primarily of refrigeration and/or heating equipment: chillers, boilers, condenser and chilled water pumps, piping, and controls. Space requirements for a central mechanical room depend on equipment types being utilized, equipment configurations, and necessary provisions for maintenance and expansion. The central mechanical room location should not be too remote from that of the fan rooms. An intermediate floor, top floor, or roof is usually the most economical due to shorter condenser and chilled water piping runs, but possibilities of structural vibration need special attention. A boiler using combustible fuels, if located on the roof, has a special advantage in that enough combustion air is readily available and the need for a chimney through the building is eliminated.

The air distribution system should successfully coordinate and complete the total HVAC system in any particular application. Two basic schemes for distribution are vertical and horizontal (14).

Vertical distribution utilizes small, local risers to serve designated spaces with no, or very little, horizontal distribution. From an engineering standpoint, it is desirable to have vertical duct distribution systems with a minimum of horizontal branch ductwork because they are usually less costly, easier to balance, create less conflict with pipes, beams, and lights, and enable the architect to consider using lower floor-to-floor heights than with a horizontal distribution scheme (3).

Horizontal distribution is usually incorporated in the ceiling plenum originating from few but large vertical risers. This scheme is more common than the vertical distribution scheme because it offers good air diffusion performance in open plan areas, rather than having to be integrated with elements of fixed planning such as columns or fixed partitions. There are also more buildings with a horizontal configuration than with a vertical configuration.

Guidelines and Rules-of-Thumb for the Programming Phase

Fan Rooms. Assuming that the central mechanical room is located remotely from the fan rooms, areas for fan rooms require 2 to 7 percent of the gross building area. An optimum clear height is about 15 feet (2).

Central Mechanical Rooms. An allowance of 2 percent of the total gross building area will assure adequate flexibility in design (14).

Distribution. Vertical shafts are needed to accommodate return and exhaust air, supply air, chilled, hot, and condenser water piping. In general, a cross section of a shaft having a ratio of 2:1 to 4:1 is easier to develop than large square shafts (3). Vertical shafts take up about 0.3 to 0.4 percent of the total gross building area. The ceiling sandwich size depends on the largest duct and/or crossover. Separate supply and exhaust duct shafts minimize duct crossovers. Ten to fifteen percent additional shaft space should be allowed for future expansion and modifications (3).

The Schematic Design Phase

In the programming phase, basic rules-of-thumb are used to size mechanical rooms without knowing mechanical equipment sizes. In the schematic design phase, enough information is usually known to estimate on the approximate HVAC equipment sizes. Two major factors influence the size of HVAC equipment--type and capacity. The equipment capacity is, in turn, governed by the magnitude of the building loads. By estimating the building heating and cooling loads and necessary air requirements, a fairly accurate judgment can be made as to the equipment capacity and, as a result, its ultimate size.

Two variables that are helpful in sizing the central mechanical room and the fan room are square feet per ton of refrigeration (ft^2/ton), and cubic feet per minute of air flow per square foot (CFM/ft^2), respectively. Total refrigeration and air quantities can then be found knowing the building's floor area.

To estimate air-conditioning equipment sizes, cooling load estimating figures have been established and published in several estimating manuals (2, 7, 15). An average of all these figures for each building type discussed in this study is found in Table VI.

Early in the schematic design phase when most building parameters are still not known, these cooling load check figures yield fairly accurate results for sizing the air-conditioning equipment. As more information on the project becomes available, more precise load estimations can be calculated by dividing the loads into envelope and interior loads.

TABLE VI

TOTAL COOLING LOAD CHECK FIGURES

BUILDING TYPE	FT^2/TON	CFM/FT^2
Clinic	240	1.1
Community Center	300	1.5
Gymnasium	250	1.5
Hospital	240	1.1
Motel	300	1.2
Multifamily High Rise	300	1.2
Nursing Home	260	1.1
Office - Large	290	1.0
Office - Small	250	1.0
School (Elementary/Secondary)	250	1.3
Shopping Center	300	1.8
Store	275	1.0
Theatre/Auditorium	250	2.0
Warehouse	N/A	N/A

Envelope Loads

Envelope loads refer to heat loss and heat gain through the building skin. The energy needed to compensate for heat loss depends on three factors: the temperature inside the building, the temperature outside the building, and the U-value of the skin. The energy needed to compensate for heat gain includes all these plus the effects from solar radiation. Most building codes dictate the interior temperature. Exterior design temperatures can be found in climatological data for various cities. The building skin U-value is a function of the materials used. However, most building codes have adopted ASHRAE Standard 90--"Energy Conservation in New Building Design," (16) which sets a maximum value for heat transfer per unit area across the building's skin. By employing the appropriate value into a load estimating method, a realistic picture of the heating and cooling loads due to climatic effect can be gained.

Heating Loads. ASHRAE Standard 90 uses a value called "U_o" meaning 'U' overall. It is analagous to a regular U-value of a wall or roof, but the U_o value takes into consideration all the components in a wall or roof construction (for example, doors, windows, skylights) and combines them into one value. The suggested U_o value for a particular application is based on heating degree days (HDD). Figures 20 through 23 show the recommended U_o values for non-residential and residential buildings, for both walls and roof.

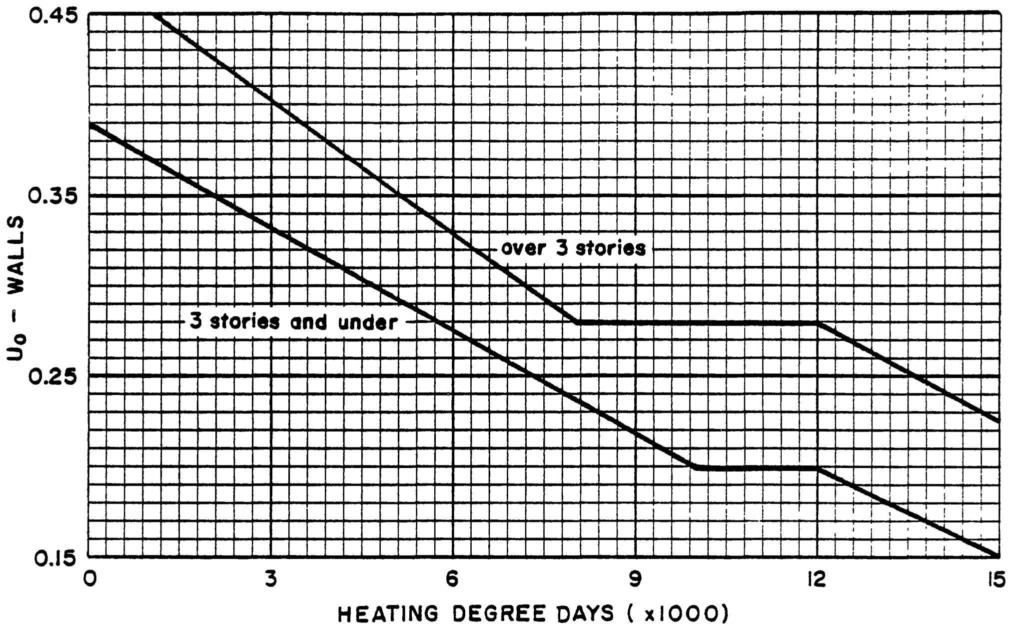


Figure 20. U_o for Walls - Commercial (16)

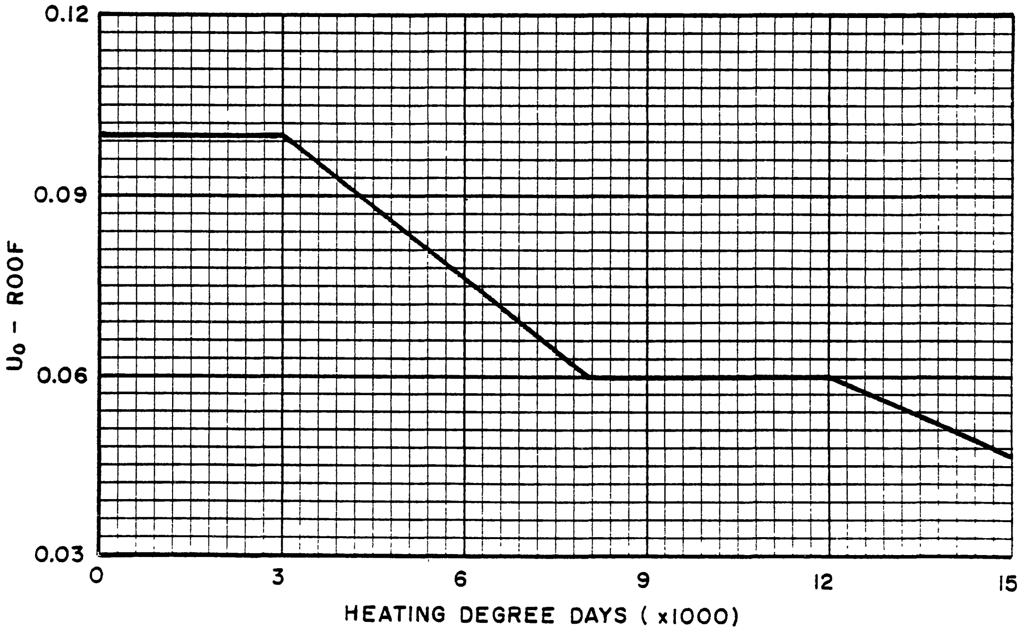


Figure 21. U_o for Roof - Commercial (16)

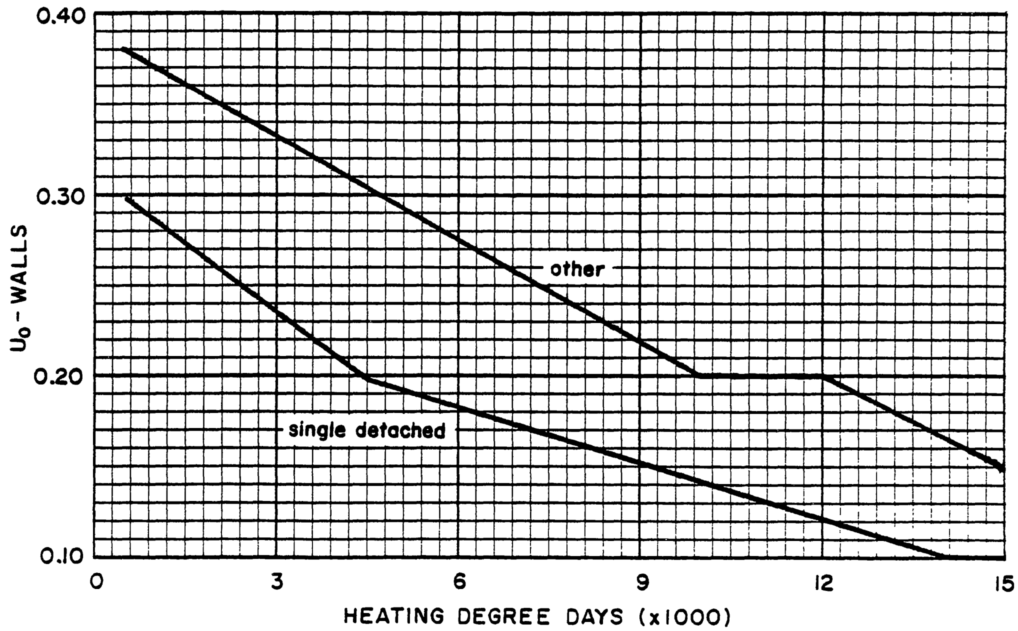


Figure 22. U_o for Walls - Residential (16)

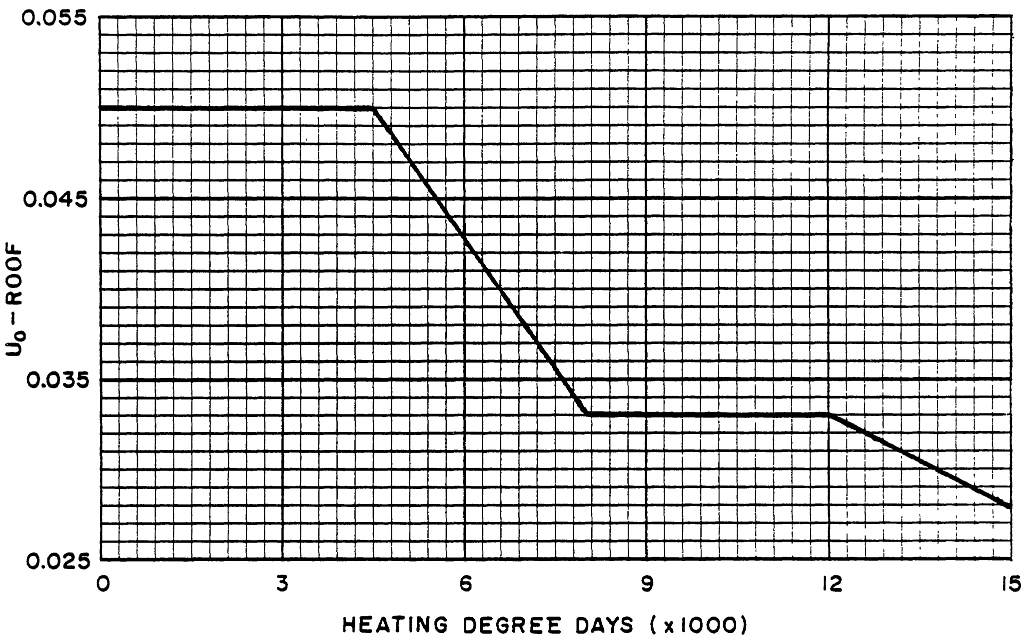


Figure 23. U_o for Roof - Residential (16)

In addition to heat loss through the walls and roof is that through the slab edge. A U-value of 0.5 Btuh/°F per linear foot is a good estimation for this heat loss. This value is based on a recommended 2 inch edge insulation (17).

Infiltration and recommended outside air quantities (although not often considered an envelope load) have a substantial impact on the heating load in addition to the heat transfer through the skin of the building. These loads may be beneficial for offsetting the interior zone's heat gains but should still be considered in heat loss calculations for a conservative estimation. Because the load due to infiltration must be met in the room where it occurs and since in the preliminary stages of design exact room arrangements may not yet be known, it is often difficult to accurately determine. For easier heat loss estimations, both the infiltration load and the load due to recommended outside air quantities according to ASHRAE Standard 62 (20), can be combined into a CFM per square foot value based on a recommended CFM per person quantity and an infiltration rate of 0.5 air changes per hour. If these values are in turn multiplied by 1.08 $\text{Btuh}\cdot\text{min/ft}^3\cdot{}^\circ\text{F}$, then a coefficient in units of $\text{Btuh}/{}^\circ\text{F}\cdot\text{ft}^2$ can be used to estimate the heat loss knowing Δt and building area. These values appear in Table VII.

The total design heating load equals:

$$\Delta t\ [U_o\ (\text{walls}) \times \text{Area (walls)} + U_o\ (\text{roof}) \times \text{Area (roof)} + 0.5 \times \text{Length (slab edge)} + \text{Infiltration coefficient} \times \text{Area (floor)}]$$

The only heat loss in a typical building is that due to climatic effects. Therefore, unless some type of heat recovery system is used, boilers or other heating equipment used can be sized to handle this design heating load.

Cooling Loads. The cooling load is more complex than the heating load in that envelope and internal heat gains must both be considered. An overall thermal transfer value (OTTV) is used in ASHRAE Standard 90 for heat gain through the skin of the building for summer conditions. It incorporates both heat transfer and solar radiation gains. The suggested OTTV for a particular application is based on latitude. Figure 24 shows the recommended OTTV for walls. For all latitudes, the roof OTTV = 8.5 $Btuh/ft^2$.

Infiltration is not usually a consideration in cooling loads but recommended quantities of outside air will be a major influence. For simplification in calculating the estimated cooling load, this is included under "Internal Loads."

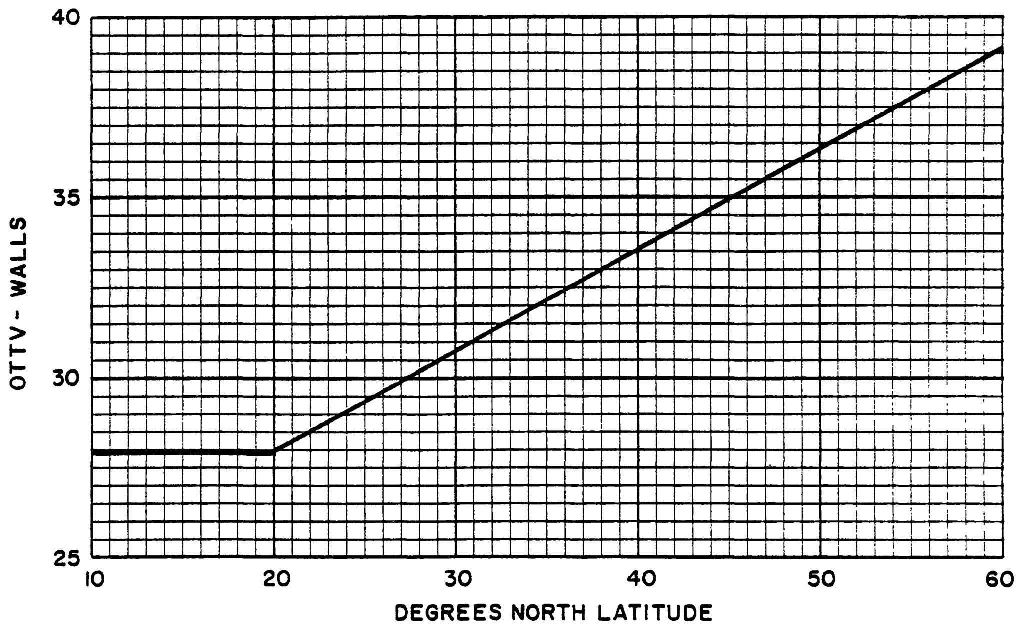


Figure 24. OTTV for Walls (16)

TABLE VII

OUTSIDE AIR AND INFILTRATION COEFFICIENTS
FOR VARIOUS BUILDING TYPES

BUILDING TYPE	$BTUH/FT^2 \cdot °F$
Clinic	0.13
Community Center	0.59
Gymnasium	1.66
Hospital (Average)	0.36
Motel	0.16
Multifamily High Rise	0.38
Nursing Home	0.16
Office - Large	0.14
Office - Small	0.14
School	0.28
Shopping Center	0.32
Store	0.22
Theatre/Auditorium	1.30
Warehouse	0.46

Internal Loads

In an actual design project the calculations for sizing the mechanical system take place before the building is actually built. The numbers in the calculation are based on information submitted by the client and governed by the project. Many times these numbers are based indirectly on code requirements. For instance, codes regulate the occupancy loads--people per square foot--and depending on the peoples' activities, values of Btuh per person are available. From these two values, a cooling load due to people is established--Btuh per square foot. Lighting and equipment loads are estimated in the manner--watts per square foot, and outdoor ventilation loads--CFM per person.

By analyzing each building type and utilizing the BOCA Basic Building Code (18), the National Electric Code (19), and ASHRAE Standard 62 (20), a fairly precise estimate of internal and ventilation heat gains can be achieved. Listed in Table VIII are such figures for each building type by which to determine cooling load estimates. (Total interior gain value is based on a summer Δt of 20°F.)

Depending on the building total gross floor area and the design temperature and the location's design temperature an accurate heating and cooling load estimate can be determined.

TABLE VIII

RECOMMENDED LOAD ALLOWANCES AND OUTSIDE AIR REQUIREMENTS FOR VARIOUS BUILDING TYPES

Clinic:

People . . . . 170 ft^2/person (420 Btuh/person)

TABLE VIII (Continued)

Lighting	2.0 watts/ft^2
Equipment	1.5 watts/ft^2
Outside Air	7.0 CFM/person
Total Interior Gain	15.3 Btuh/ft^2
Community Center:	
People	15 ft^2/person (510 Btuh/person)
Lighting	2.0 watts/ft^2
Equipment	1.0 watt/ft^2
Outside Air	7.0 CFM/person
Total Interior Gain	54.50 Btuh/ft^2
Gymnasium:	
People	15 ft^2/person (960 Btuh/spectator; 1800 Btuh/player)
Lighting	3.0 watts/ft^2
Equipment	0.5 watts/ft^2
Outside Air	20 CFM/person
Total Interior Gain	113.67 Btuh/ft^2
Hospital:	
People	100 ft^2/person (420 Btuh/person)
Lighting	2.0 watts/ft^2
Equipment	2.0 watts/ft^2
Outside Air - Patient Rooms	7.0 CFM/person
- Operating Rooms	40 CFM/person
- Intensive Care	15 CFM/person
- Autopsy Rooms	100 CFM/person
Total Interior Gain	21.14 Btuh/ft^2

TABLE VIII (Continued)

Motel:	
People	200 ft^2/person (640 Btuh/person)
Lighting	2.0 watts/ft^2
Equipment	1.0 watt/ft^2
Outside Air	15 CFM/person
Total Interior Gain	15.08 Btuh/ft^2
Multifamily High Rise:	
People	200 ft^2/person (640 Btuh/person)
Lighting	2.0 watts/ft^2
Equipment	1.0 watt/ft^2
Outside Air - General Living Areas	10 CFM/room
- Kitchens	100 CFM/room
- Bathrooms	50 CFM/room
Total Interior Gain	16.82 Btuh/ft^2
Nursing Home:	
People	100 ft^2/person (420 Btuh/person)
Lighting	2.0 watts/ft^2
Equipment	1.5 watts/ft^2
Outside Air	7.0 CFM/person
Total Interior Gain	17.68 Btuh/ft^2
Office - Large:	
People	100 ft^2/person (510 Btuh/person)
Lighting	3.5 watts/ft^2
Equipment	1.0 watt/ft^2

TABLE VIII (Continued)

Outside Air	5.0 CFM/person
Total Interior Gain	21.55 Btuh/ft^2
<u>Office - Small</u>:	
People	100 ft^2/person (510 Btuh/person)
Lighting	3.5 watts/ft^2
Equipment	1.0 watt/ft^2
Outside Air	5.0 CFM/person
Total Interior Gain	21.55 Btuh/ft^2
<u>School</u>:	
People	40 ft^2/person (640 Btuh/person)
Lighting	3.0 watts/ft^2
Equipment	1.0 watt/ft^2
Outside Air	7.0 CFM/person
Total Interior Gain	33.49 Btuh/ft^2
<u>Shopping Center</u>:	
People	50 ft^2/person (640 Btuh/person)
Lighting	3.0 watts/ft^2
Equipment	1.0 watt/ft^2
Outside Air	5.0 CFM/person
Total Interior Gain	28.64 Btuh/ft^2
<u>Store</u>:	
People	40 ft^2/person (640 Btuh/person)
Lighting	3.0 watts/ft^2
Equipment	1.0 watt/ft^2

TABLE VIII (Continued)

Outside Air	5.0 CFM/person
Total Interior Gain	32.39 Btuh/ft^2
Theatre/Auditorium:	
People	7 ft^2/person (350 Btuh/person)
Lighting	1.0 watt/ft^2
Equipment	1.0 watt/ft^2
Outside Air	7.0 CFM/person
Total Interior Gain	78.82 Btuh/ft^2
Warehouse:	
People	300 ft^2/person (640 Btuh/person)
Lighting	0.25 watts/ft^2
Equipment	0.25 watts/ft^2
Outside Air	5.0 CFM/person
Total Interior Gain	4.21 Btuh/ft^2

Space Allocations

Having an estimate of the building's heating and cooling loads is useful, but not as important to the architect as having an estimate of the space requirements for the HVAC equipment. Knowing the capacity and type of equipment needed, the physical dimensions can be determined. In turn, a mechanical equipment room can be sized to properly accommodate this equipment.

A suggested refrigeration equipment room configuration is set up as shown in Figure 25. Each refrigeration machine should be sized to handle 50 percent of the design cooling load, and one pair of pumps is needed for each machine. This arrangement is a conservative approach and allows for future expansion. The pad size for the chiller is obtained from the manufacturer (22, 23, 24). Table IX gives chiller dimensions based on packaged hermetic type.

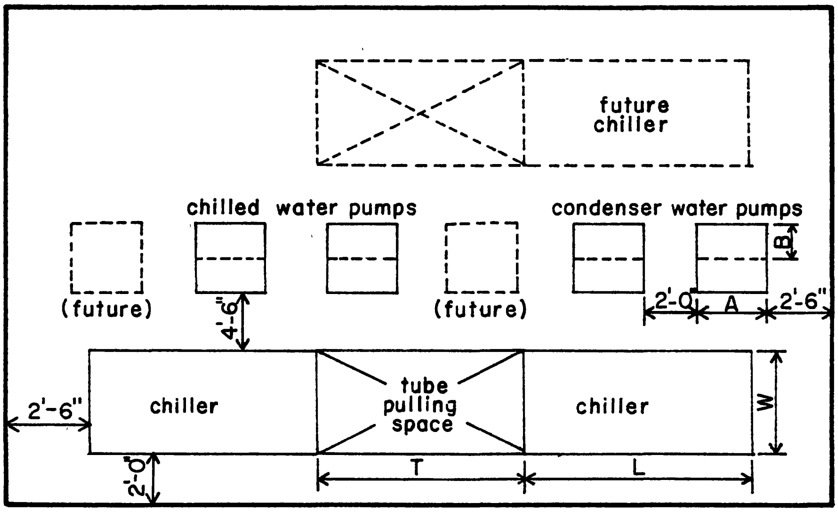


Figure 25. Typical Refrigeration Equipment Room Layout (21)

Using an optimum aspect ratio of approximately 2:3, a refrigeration equipment room size can be derived as a function of the equipment dimensions. Figures 26 and 27 show a typical refrigeration equipment room size with respect to tons of refrigeration (based on 2 or 3 chillers).

TABLE IX

REFRIGERATION EQUIPMENT SIZES

EQUIPMENT TYPE (TONS)	DIMENSIONS FOR EQUIPMENT LAYOUT L	W	HEIGHT	T	A	B
Reciprocating:						
15-30	9'-6"	3'-0"	3'-6"	7'-0"	4'-0"	3'-0"
40-60	9'-6"	3'-0"	5'-0"	9'-0"	4'-0"	3'-0"
70-150	11'-0"	3'-0"	7'-0"	9'-6"	4'-0"	3'-6"
Centrifugal:						
100-400	14'-6"	5'-0"	9'-0"	12'-0"	5'-0"	5'-0"
400-1000	14'-6"	8'-6"	10'-0"	12'-6"	7'-0'	6'-0"
1000-1600	19'-0"	8'-6"	10'-0"	12'-6"	7'-6"	6'-0"
1600-2000	19'-0"	14'-6"	10'-0"	15'-6"	8'-0"	6'-6"
Absorption:						
100-400	17'-0"	6'-6"	10'-0"	14'-6"	4'-6"	4'-0"
400-800	22'-0"	7'-6"	13'-6"	19'-6"	6'-0"	5'-6"
800-1000	27'-0"	8'-6"	15'-0"	24'-6"	7'-0"	6'-0"

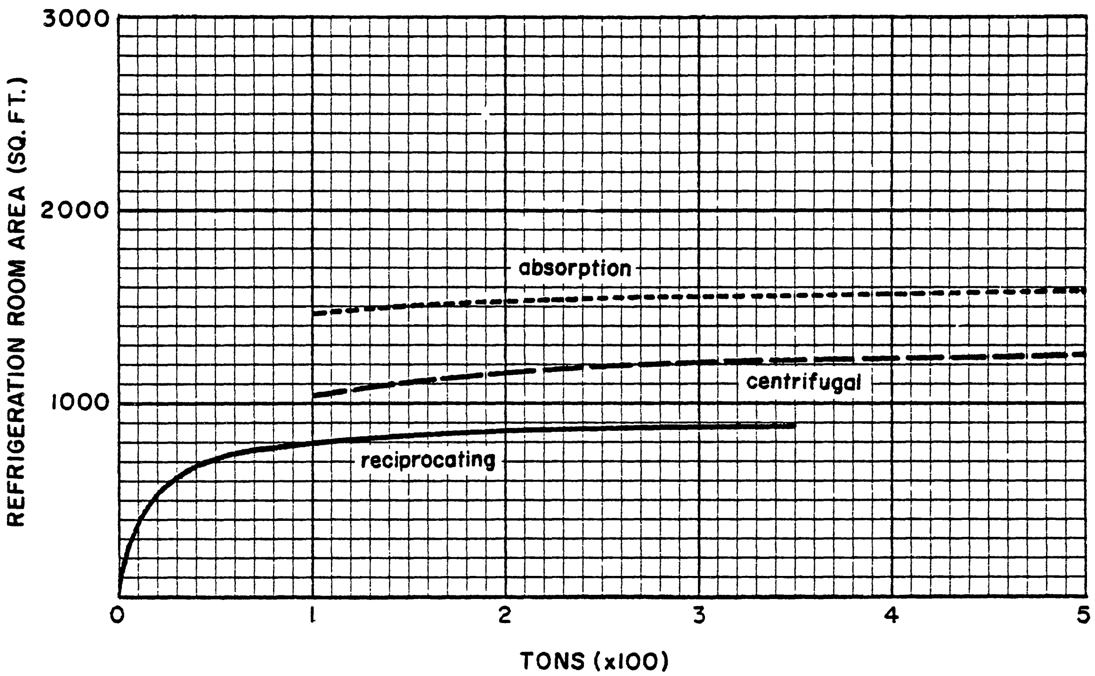


Figure 26. Refrigeration Equipment Room Area as a Function of Cooling Load (0-500 tons)

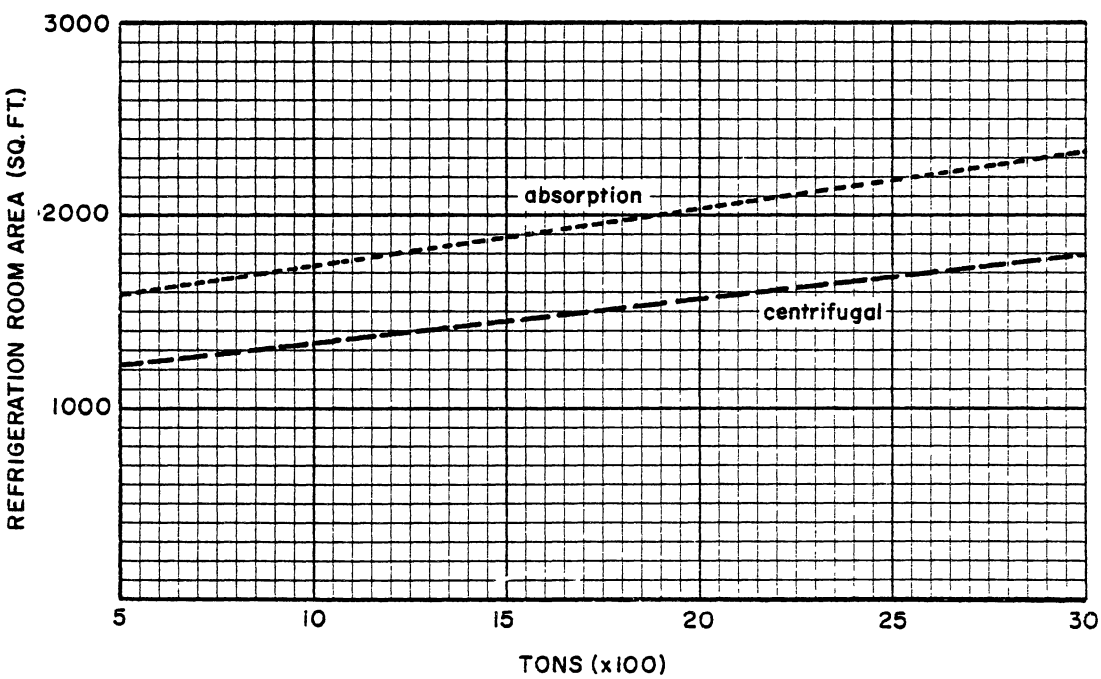


Figure 27. Refrigeration Equipment Room Area as a Function of Cooling Load (500-3000 tons)

The boiler room size can be derived in the same fashion as the refrigeration room. Figure 28 shows a typical boiler room layout, Table X gives boiler dimensions based on gas-fired, high pressure, packaged type boilers (22), and Figure 29 shows the boiler room area as a function of heating load (based on 2 boilers). If the boiler and refrigeration rooms are combined into one main mechanical room, the areas are not directly additive since tube pulling spaces may be overlapped. By multiplying the area of the boiler room by 0.25 and adding it to the area required for the refrigeration equipment will provide adequate space for all the equipment.

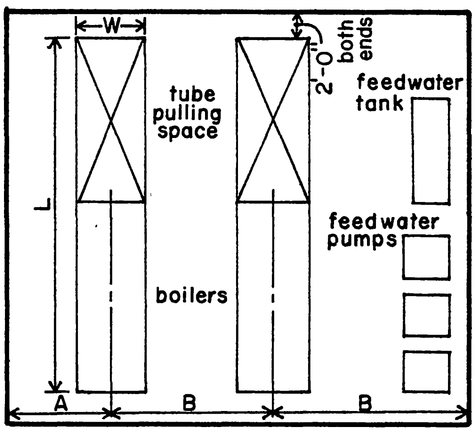


Figure 28. Typical Boiler Room Layout (21)

The fan rooms are most likely to be located remotely from the central mechanical room, throughout the building. The air flow rate, fan inlet width, and coil length will determine the overall air handling unit size and, in turn, the fan room size. Figure 30 shows a typical fan room layout utilizing a built-up air handling unit, and Table XI gives overall dimensions of built-up air handling units. Figures 31 and 32 show the fan room size as a function of CFM. The dimensions and curves include a 50 percent increase in the air handling unit length to account for a mixing plenum or for vertical ductwork, depending on the location of the fan room with respect to an outside wall. A typical shape for the fan should be approximately square.

TABLE X

BOILER SIZES

BOILER	DIMENSIONS FOR EQUIPMENT LAYOUT				
(HP)	L	W	HEIGHT	A	B
60-100	20'-0"	5'-0"	6'-6"	6'-6"	9'-0"
100-200	23'-6"	6'-0"	8'-0"	7'-0"	10'-0"
200-400	30'-6"	7'-6"	9'-6"	8'-0"	12'-0"
400-800	37'-6"	8'-6"	11'-0"	8'-6"	14'-6"

A ceiling sandwich size estimation can be made assuming some typical air distribution characteristics:

1. Maximum rectangular duct aspect ratio = 3:1
2. Design friction loss per 100 feet of duct = 0.07 in.
3. The largest duct originating from the fan room will influence the sandwich size (based on low velocity)

Figures 33 and 34 show a graph of air flow rate and its effects on the ceiling sandwich size. These values assume a return air plenum is used. It does not consider return air ducts or cross-overs that may occur with a dual duct system.

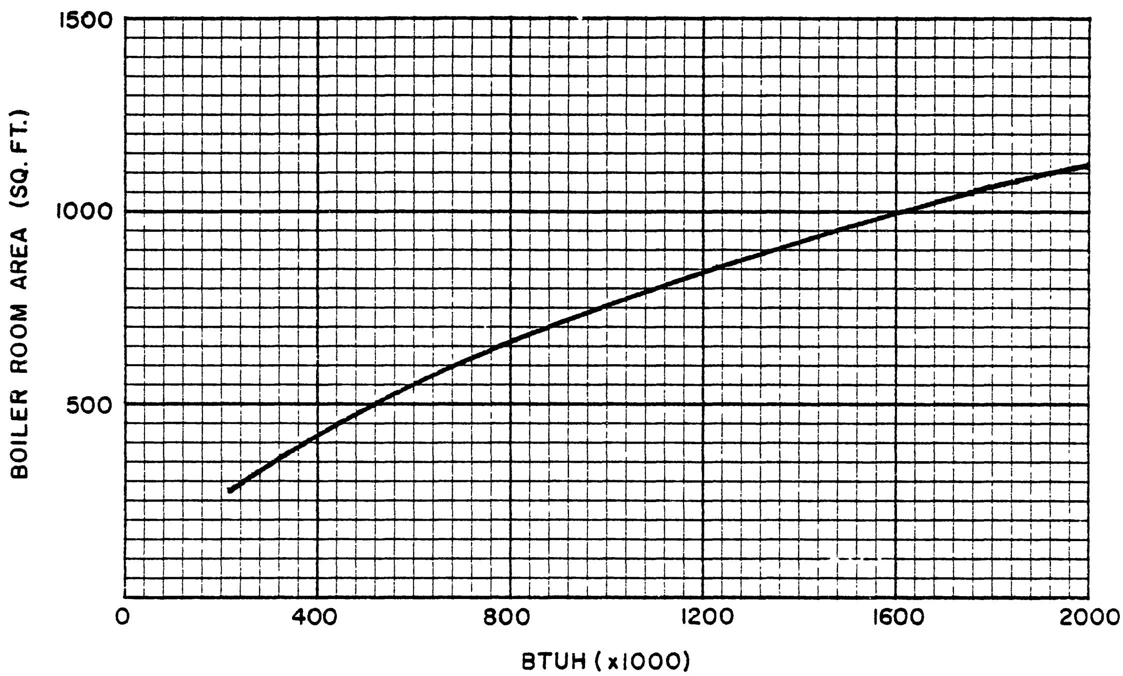


Figure 29. Boiler Room Area as a Function of Heating Load

If fan coil or heat pump units are incorporated in the ceiling plenum, the need for fan rooms may be totally eliminated, but the sandwich size may increase as much as 75 percent in order to house the equipment. If the central mechanical equipment and/or the air handling units are located on the roof, much space can be saved inside the building replacing these equipment rooms with vertical shafts for distribution, which take up less floor space.

There are many system and equipment combinations for any given application. By utilizing the information from the system selection process, fairly accurate space requirements can be obtained.

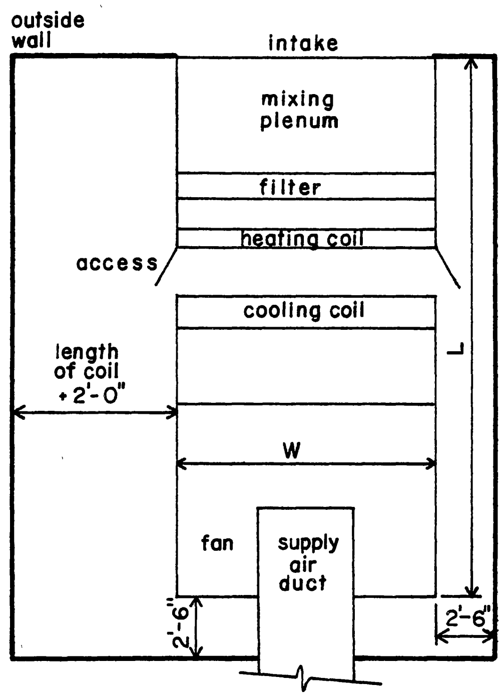


Figure 30. Typical Fan Room Layout (3)

TABLE XI

AIR HANDLING UNIT SIZES

AIR QUANTITY CFM	DIMENSIONS FOR EQUIPMENT LAYOUT W	L	HEIGHT
1,000-2,000	2'-10"	5'-3"	2'-0"
2,000-3,000	4'-6"	5'-6"	2'-2"
3,000-4,000	4'-10"	6'-9"	3'-0"
4,000-6,000	5'-0"	7'-3"	3'-0"
6,000-10,000	7'-2"	7'-6"	3'-6"
10,000-15,000	8'-7"	8'-0"	4'-2"
15,000-20,000	9'-0"	9'-3"	4'-5"
20,000-25,000	9'-0"	9'-9"	4'-8"
25,000-30,000	9'-1"	10'-6"	5'-6"
30,000-40,000	9'-7"	13'-3"	6'-4"
40,000-50,000	10'-10"	16'-6"	7'-6"
50,000-65,000	11'-0"	17'-0"	8'-6"
65,000-85,000	13'-3"	17'-6"	8'-10"

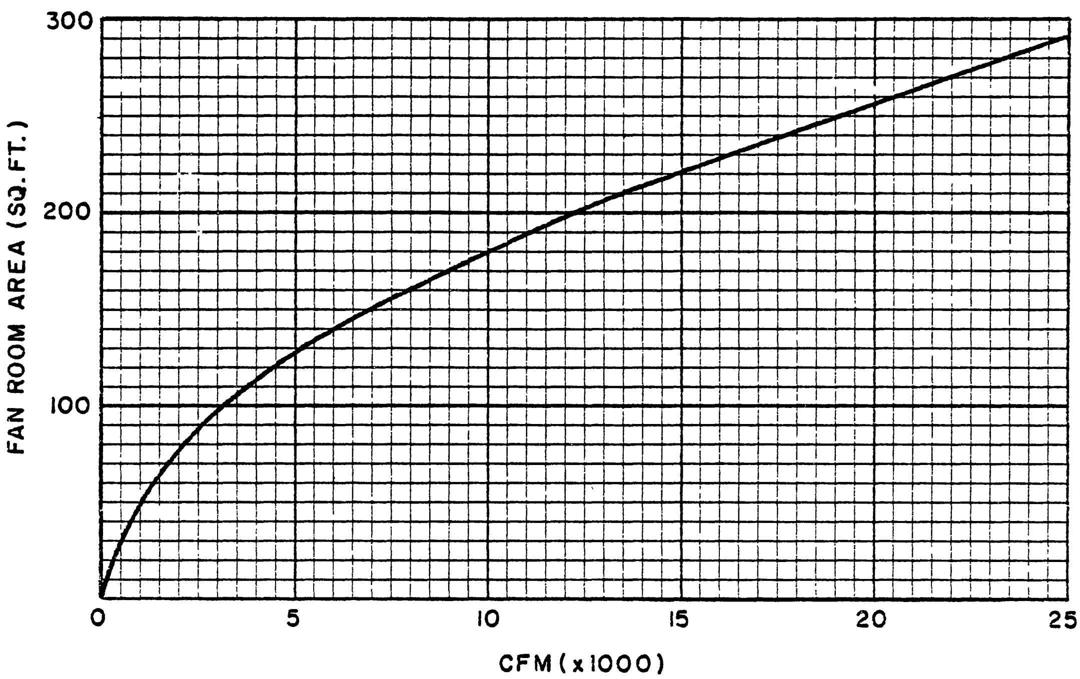


Figure 31. Fan Room Area as a Function of Air Flow Rate (0-25,000 CFM)

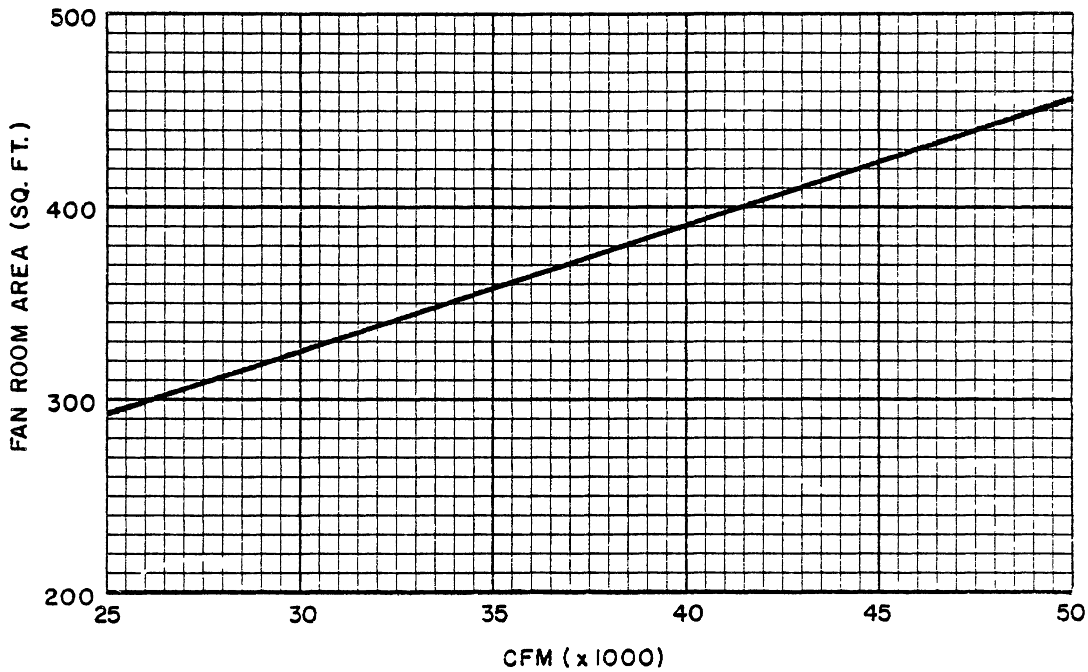


Figure 32. Fan Room Area as a Function of Air Flow Rate (25,000-50,000 CFM)

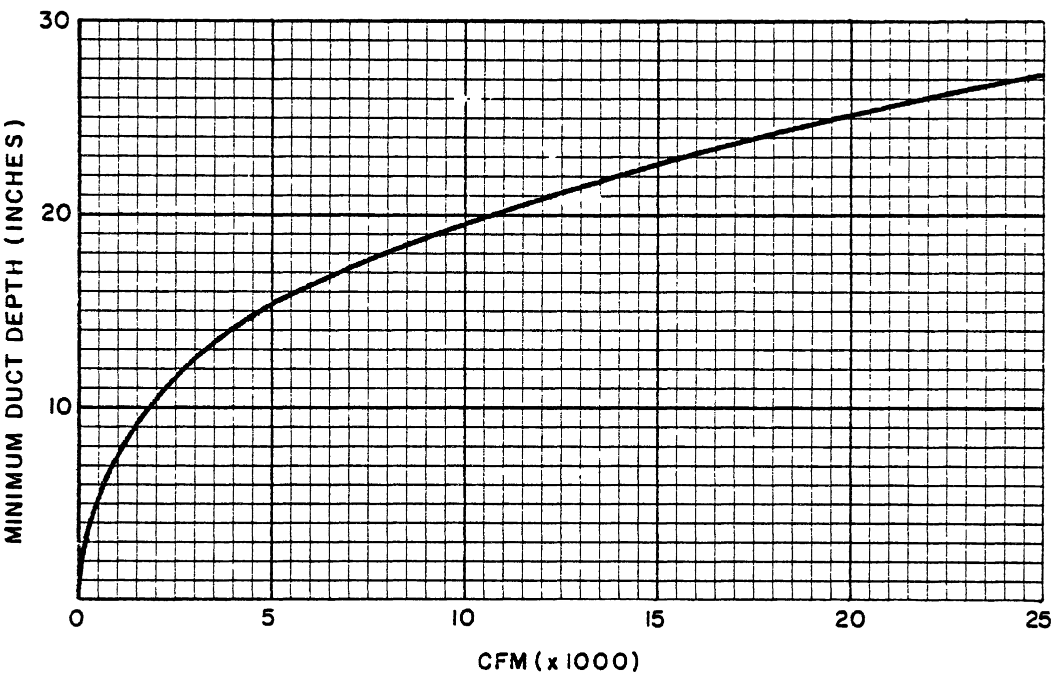


Figure 33. Minimum Duct Depth as a Function of Air Flow Rate (0-25,000 CFM)

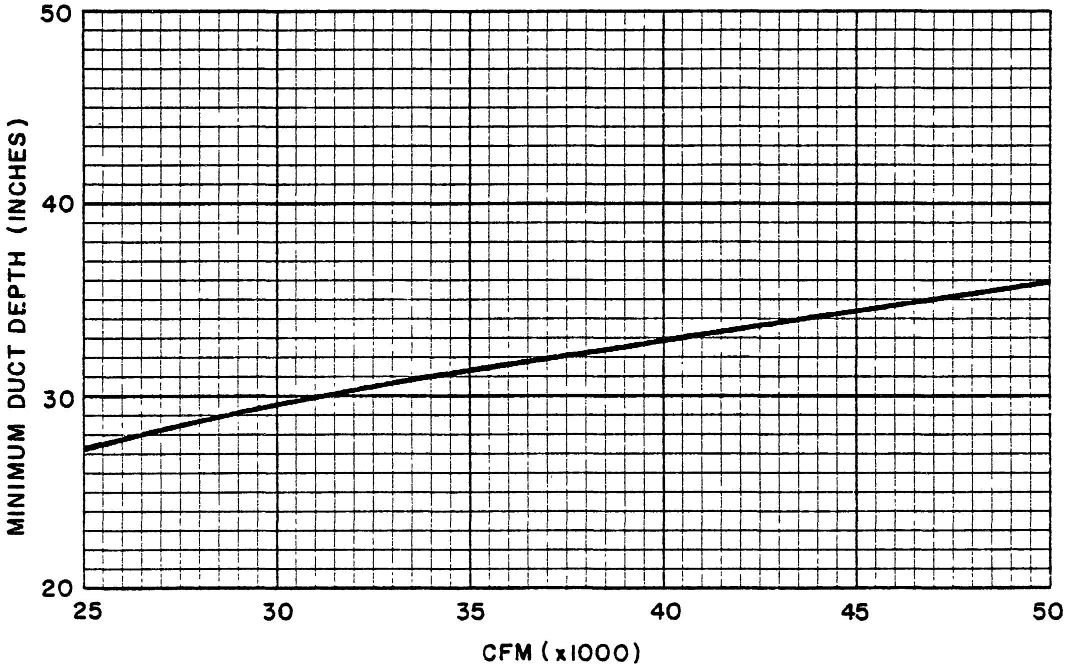


Figure 34. Minimum Duct Depth as a Function of Air Flow Rate (25,000-50,000 CFM)

CHAPTER VI

EXAMPLE PROJECT

In the two preceding chapters, a method for system selection and sizing was derived. In this chapter, the method is applied to two example projects in order to gain an understanding of its practical application in the design process. By using two diverse projects in different climatic areas, the effectiveness of the method can be analyzed.

School Project

As a first example, an elementary school in Chicago will be investigated. It is two stories high with dimensions: 200 ft. x 100 ft.; 20,000 sq. ft. per floor.

During the programming phase, a quick rule-of-thumb is appropriate for estimating mechanical room sizes. Therefore, the area of the main mechanical room is estimated to be:

40,000 sq. ft. x 0.02 = 800 sq. ft.

The total area for the fan room(s) is:

40,000 sq. x (0.02 to 0.07) = 800 to 2,800 sq. ft.

(approximately 1,800 sq. ft.)

The area for vertical shafts:

40,000 sq. ft. x (0.003 to 0.004) = 120 to 160 sq. ft.

(approximately 140 sq. ft.)

In the schematic design phase, more information about the project is generally known than in the programming phase and from this information, more accurate estimates can be made.

The first major concern is the type of system to be employed in the project. In the field, an engineer would evaluate several system choices from various points of view (life cycle cost, architectural integration, comfort considerations, etc.) and then select the system which best satisfied all the criteria. For the architect or achitecture student who may not be familiar with each system's characteristics, the scope of possibilities should be narrowed, and the pertinent information for these possibilities should be given in order that the architect may make a preliminary decision of what HVAC system type to employ. Knowing the general HVAC system type in an early design phase can help with architectural integration and determining space requirements for the required equipment. Figure 35 shows typical systems most used in a school application according to the HVAC system selection survey discussed in Chapter IV. The system types are listed along the top of the chart according to classification: all-air, air-water, all-water, and unitary. The letters along the left side of the chart indicate building types (a detailed list of system and building types is included in Chapter IV).

Any of the systems in the selection matrix may be considered in a comparative analysis, but those with the black squares can be used to limit the number of comparative trials. An overriding question to the architect should be, "Does the system concept fit the architectural concept?" Figure 36 helps to clarify four basic system concepts and should be used to decide if the architectural and system concepts are compatible.

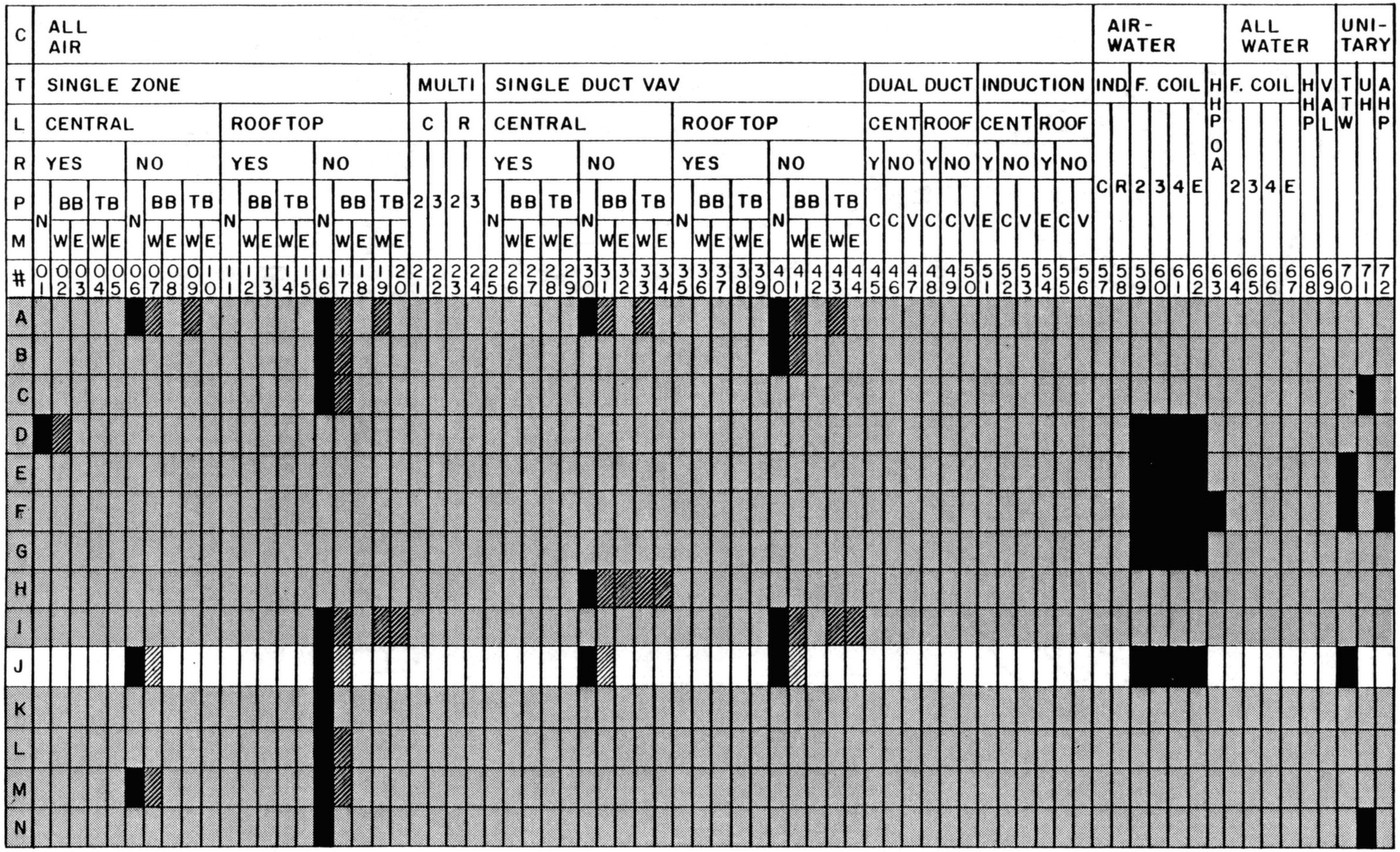


Figure 35. System Selection Matrix - Survey Results - School Example

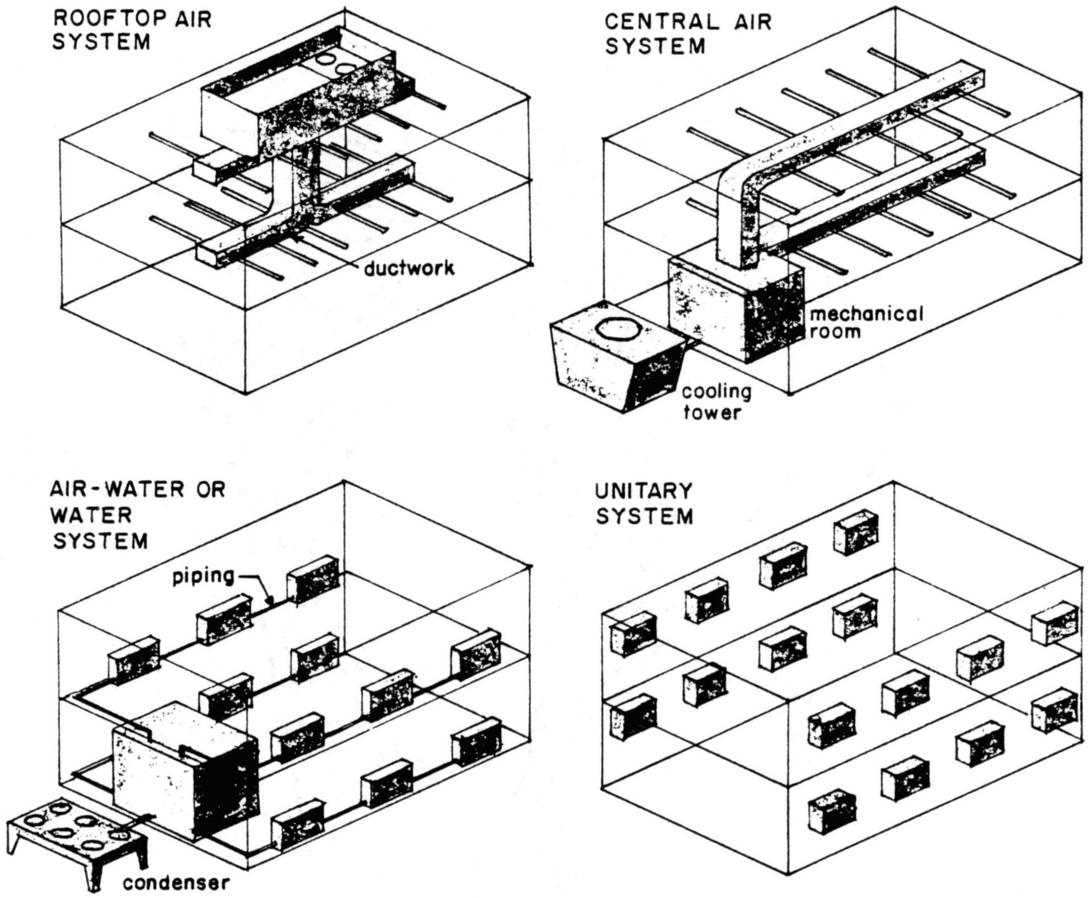


Figure 36. Conceptual HVAC System Types

For this example project, those systems which are most commonly used will be analyzed; No. 7 - single zone central with hot water baseboard; No. 17 - single zone rooftop with hot water baseboard; No. 40 - VAV rooftop; No. 41 - single duct VAV rooftop with hot water baseboard radiation; and No. 70 - incremental through the wall units. The parameters a-j (listed below) are then rated with relative importance values as they pertain to the project, based on 1-100 so long as the total adds up to 100. Figure 37 lists the relative proficiency of each system based on 1-10, 10 being the best. Although these ratings are not definite values, they can be used when one is unfamiliar with the characteristics of a particular system. The values in Figure 27 are based on the criteria identified in Chapter IV. When an architect or architecture student becomes more familiar with the method and the HVAC characteristics, he may input his own values. For the example project, each parameter is analyzed individually.

a.	low initial cost: very important in school a project	15
b.	energy conserving: also very important	15
c.	building appearance: fairly important	8
d.	system maintainability: fairly important	8
e.	minimal space requirements: very important	15
f.	flexibility: don't anticipate many changes	3
g.	acoustical (low noise): important for classroom activities	10
h.	minimal plenum depth: not much of a consideration	3
i.	durability: must last a long time; very important	15
j.	thermal comfort: students and teachers should be fairly comfortable	8
		100

The ratings for each category are then multiplied by the corresponding system's category ratings and summed.

	PARAMETER RATING		SYSTEM RATING				
			No. 7	No. 17	No. 40	No. 41	No. 70
a.)	15	x	6	6	6	4	10
b.)	15	x	10	10	10	10	1
c.)	8	x	8	3	3	3	1
d.)	8	x	8	8	10	8	1
e.)	15	x	2	8	8	8	10

f.)	3	x	2	2	5	4	10
g.)	10	x	8	8	7	7	1
h.)	3	x	4	4	3	3	10
i.)	15	x	9	3	3	3	1
j.)	8	x	10	10	6	10	4
			711	671	651	634	448

From the comparative analysis, a single zone central system with hot water baseboard radiation rates the highest. By knowing the system type that may be employed, certain spatial characteristics can be determined. For instance, with a central system, a main mechanical room must be sized, along with the fan room(s). With a rooftop system, a main mechanical room may be sized, but the area for fan rooms would not be a consideration since the air handling unit(s) may be located on the roof. By analyzing the approximate space allocations for the refrigeration and heating equipment, the architect can decide if it is desirable (from an aesthetic point of view) to include all the HVAC equipment on the roof.

The next major step in determining the space requirements is estimating the loads. For the effect of climate, three items must be known in this method: latitude, winter design temperature, and heating degree days. Chicago is at a latitude of 42°, has a winter design temperature of -4°F, and 6639 annual heating degree days (base 65°F).

C	ALL AIR																							
T	SINGLE ZONE																				MULTI			
L	CENTRAL										ROOFTOP										C		R	
R	YES					NO					YES					NO								
P	N	BB		TB		N	BB		TB		N	BB		TB		N	BB		TB		2	3	2	3
M		W	E	W	E		W	E	W	E		W	E	W	E		W	E	W	E				
#	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
a	7	6	7	6	7	8	6	7	6	7	7	6	7	6	7	8	6	7	6	7	6	5	7	6
b	8	8	6	7	6	10	10	8	9	8	8	8	6	7	6	10	10	8	9	8	3	3	3	3
c	10	8	8	6	6	10	8	8	6	6	3	3	3	3	3	3	3	3	3	3	10	10	3	3
d	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	10	10	10
e	2	2	2	1	1	2	2	2	1	1	8	8	8	7	7	8	8	8	7	7	3	3	7	7
f	5	3	3	3	3	3	2	2	2	2	5	3	3	3	3	3	2	2	2	2	1	1	1	1
g	8	8	8	6	6	8	8	8	6	6	8	8	8	6	6	8	8	8	6	6	8	8	8	8
h	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2	2
i	10	9	8	9	8	10	9	8	7	8	3	3	3	3	3	3	3	3	3	3	10	10	3	3
j	8	10	10	10	10	6	10	10	10	10	8	10	10	10	10	6	10	10	10	10	10	10	10	10

C																										
T	SINGLE DUCT VAV																				DUAL DUCT					
L	CENTRAL										ROOFTOP										CENT			ROOF		
R	YES					NO					YES					NO					Y	NO		Y	NO	
P	N	BB		TB		N	BB		TB		N	BB		TB		N	BB		TB		C	C	V	C	C	V
M		W	E	W	E		W	E	W	E		W	E	W	E		W	E	W	E						
#	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
a	5	4	5	4	5	6	4	5	4	5	5	4	5	4	5	6	4	5	4	5	3	3	3	3	3	3
b	8	8	6	7	6	10	10	8	9	8	8	8	6	7	6	10	10	8	9	8	2	3	3	2	3	3
c	10	8	8	6	6	10	8	8	6	6	3	3	3	3	3	3	3	3	3	3	10	10	10	3	3	3
d	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	10	10	10	10	10
e	2	2	2	1	1	2	2	2	1	1	8	8	8	7	7	8	8	8	7	7	3	3	3	7	7	7
f	7	5	5	5	5	5	4	4	4	4	7	5	5	5	5	5	4	4	4	4	2	1	1	2	1	1
g	7	7	7	5	5	7	7	7	5	5	7	7	7	5	5	7	7	7	5	5	8	8	7	8	8	7
h	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1	1
i	9	8	7	8	7	9	8	7	8	7	3	3	3	3	3	3	3	3	3	3	10	10	10	3	3	3
j	8	10	10	10	10	6	10	10	10	10	8	10	10	10	10	6	10	10	10	10	10	10	10	10	10	10

C							AIR-WATER							ALL WATER						UNITARY		
T	INDUCTION						IND		F. COIL				HHPOA	F. COIL				HHP	VAL	TTW	UHH	AHP
L	CENT			ROOF																		
R	Y	NO		Y	NO																	
P	E	C	V	E	C	V	C	R	2	3	4	E		2	3	4	E					
M																						
#	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
a	5	4	4	5	4	4	1	1	4	3	2	4	3	5	4	3	5	7	7	10	10	9
b	2	3	3	2	3	3	3	3	3	3	4	2	6	4	4	5	3	6	2	1	1	1
c	6	6	6	3	3	3	6	3	10/1	10/1	10/1	10/1	10/1	10/1	10/1	10/1	10/1	10/1	6	1	1	1
d	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	1	1	1
e	6	6	6	8	8	8	6	8	9/6	9/6	9/6	9/6	9/6	9/7	9/7	9/7	9/7	9/7	9	10	10	10
f	4	3	3	4	3	3	5	5	5	5	5	5	5	7	7	7	7	7	10	10	10	10
g	2	2	2	2	2	2	2	2	4	4	4	4	3	4	4	4	4	3	10	1	1	1
h	7	7	7	7	7	7	8	8	3/8	3/8	3/8	3/8	3/8	3/10	3/10	3/10	3/10	3/10	10	10	10	10
i	6	6	6	3	3	3	6	3	6	6	6	5	6	5	6	6	5	5	10	1	1	1
j	10	10	10	10	10	10	10	10	2	4	5	4	4	2	4	5	4	4	2	4	4	4

Figure 37. System Selection Matrix - Weighting Factors - School Example

The total heating load is estimated by analyzing four major heat losses: walls, roof, and slab edge, and infiltration. The standard heat transfer equation reads:

$$Q = U_o A \Delta t$$

where:

Δt = indoor design temperature - outdoor design temperature

= 70°F - (-4°F)

= 74°F

A (walls) = the perimeter x the total height

= 600 ft. x 25 ft.

= 15,000 sq. ft.

A (roof) = 20,000 sq. ft.

U_o (walls) is based on heating degree days from Figure 38.

U_o (roof) is based on heating degree days from Figure 39.

The total estimated heat loss for the walls is:

$$Q = 0.26 \times 15{,}000 \times 74$$

$$= 288{,}600 \text{ Btuh}$$

The total estimated heat loss for the roof is:

$$Q = 0.07 \times 20{,}000 \times 74$$

$$= 103{,}600 \text{ Btuh}$$

The total heat loss for the slab edge is calculated a little differently, using an average U_o value of 0.5 Btuh/°F per linear foot of perimeter. Therefore:

$$Q = 0.5 \times 600 \times 74$$

$$= 22{,}200 \text{ Btuh}$$

The total estimated heat loss due to infiltration and outside air is the gross building area multiplied by the corresponding coefficient (from

Table VII, Chapter V) which equals:

40,000 sq. ft. x 0.28 = 11,200 Btuh

The total estimated building heating load equals:

288,600 + 103,600 + 22,200 + 11,200 = 425,600 Btuh.

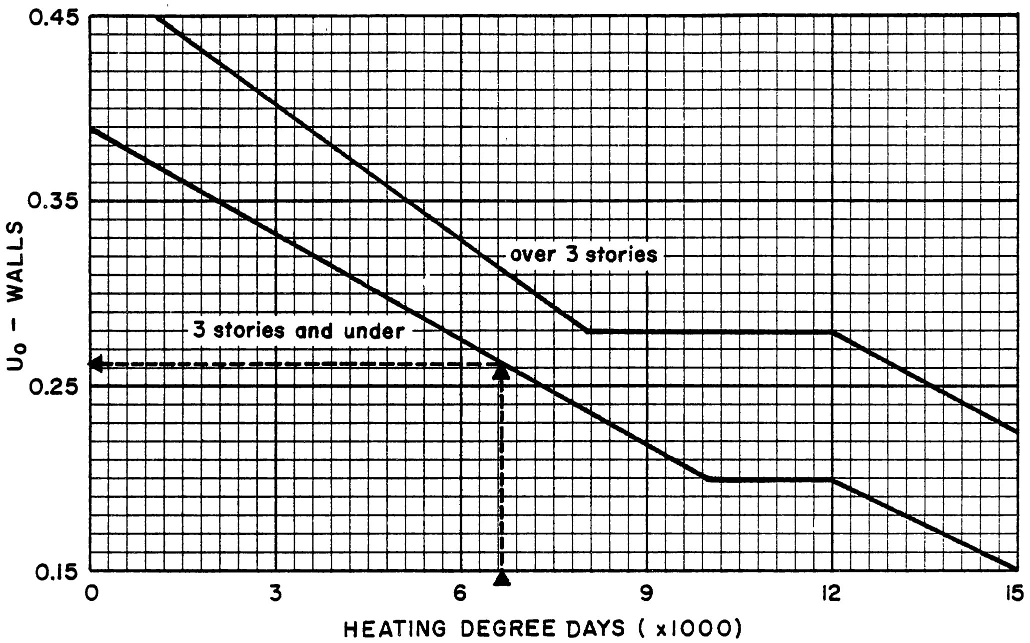


Figure 38. U_o for Walls - School Example (16)

The cooling load is divided into two major factors: internal and external gains. For external gains, the walls and the roof are considered. In Figure 40, an overall thermal transfer value (OTTV) can be obtained from knowing the latitude.

Therefore, the estimated cooling load due to the walls equals:

34 x 15,000 = 510,000 Btuh.

For the roof an OTTV of 8.5 is used irregardless of latitude.

Therefore, the estimated cooling load due to the roof equals:

8.5 x 20,000 = 170,000 Btuh.

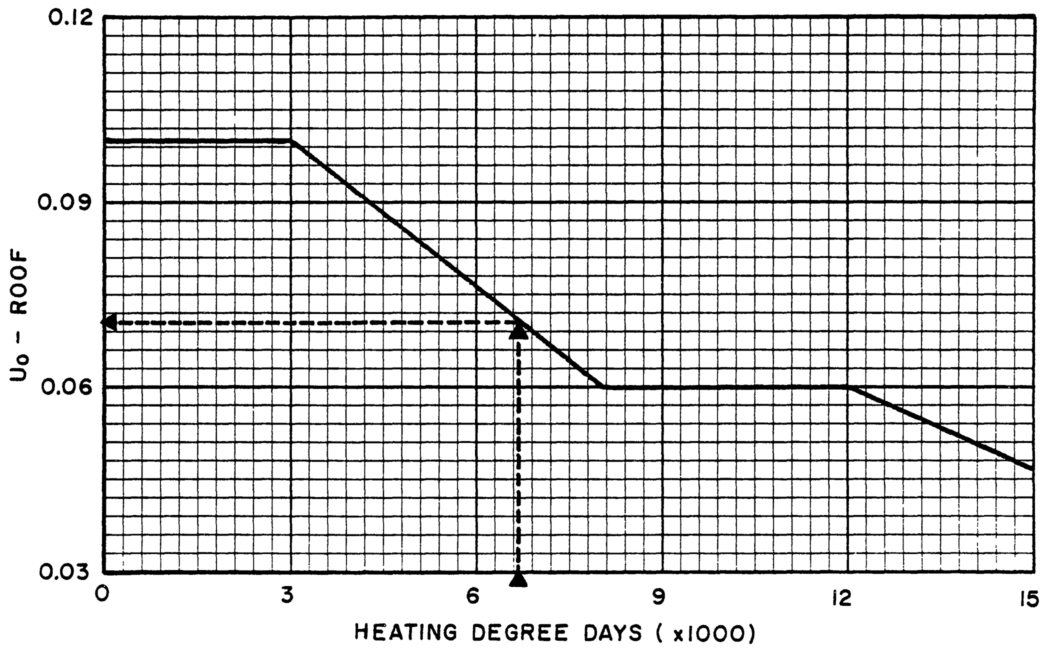


Figure 39. U_o for Roof - School Example (16)

The internal heat gains are from people, equipment, and lights. A recommended amount of outside air also adds to the heat gain. For schools, a typical internal gain per sq. ft. (from Table VIII) equals 33.49, therefore the total cooling load due to internal gains equals:

33.49 x 40,000 = 1,339,600 Btuh.

The total building cooling load equals:

510,000 + 170,000 + 1,339,600 = 2,019,600 Btuh.

Solving for total cooling tons:

2,019,600 ÷ 12,000 = 168 tons.

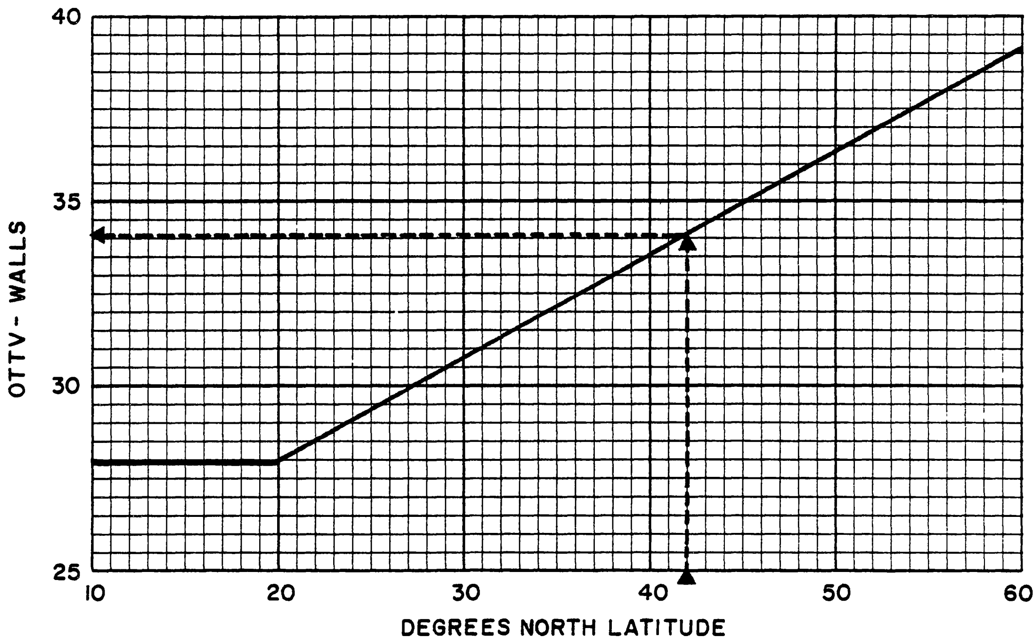


Figure 40. OTTV for Walls - School Example (16)

The last step in determining space requirements is estimating the total air quantities. Based on a Δt between room temperature and supply air temperature an air flow rate can be determined, but most building types have suggested values for air flow rates to insure comfort. Table VI (Chapter V) gives these suggested values. Choosing a value of 1.3 CFM/sq. ft., the total air quantity equals:

$$1.3 \times 40{,}000 = 52{,}000 \text{ CFM}.$$

Knowing the heating and cooling load, and total air quantity, the space requirements can finally be determined. Figure 41 gives the refrigeration room size as a function of cooling tons. Figure 42 gives the boiler room size as a function of heating load. The total main mechanical room area equals approximately 850 sq. ft. (utilizing reciprocating equipment) plus 25 percent of 425 sq. ft. for the boiler room which is 960 sq. ft. total. This value includes area for future expansion as well as space for two refrigeration machines so each can handle half the total load. The length to width ratio of the main mechanical room should be approximately 2:3.

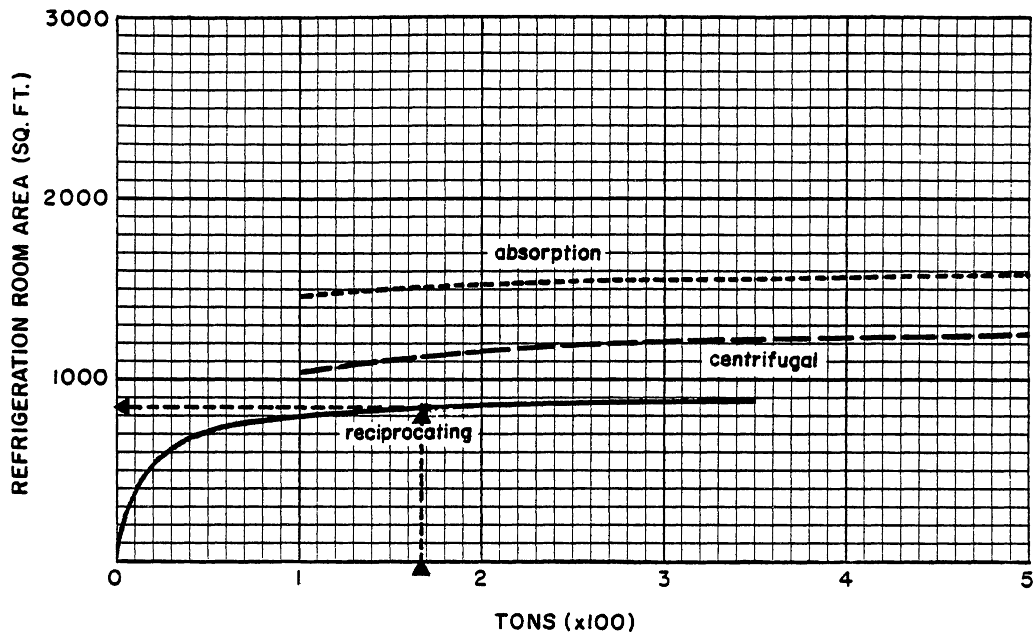


Figure 41. Refrigeration Room Area as a Function of Cooling Load - School Example

The number and location of fan rooms is primarily a design decision so long as each room is sufficiently sized to incorporate the required air-handling equipment. There are several different concepts concerning the placement of fan rooms. Figure 43 shows various arrangements for the mechanical and fan rooms. Each arrangement is equally valid but the architect should decide which is optimum for his design. If more than one fan room is used, the total CFM should be divided by the number of fan rooms and each one sized separately.

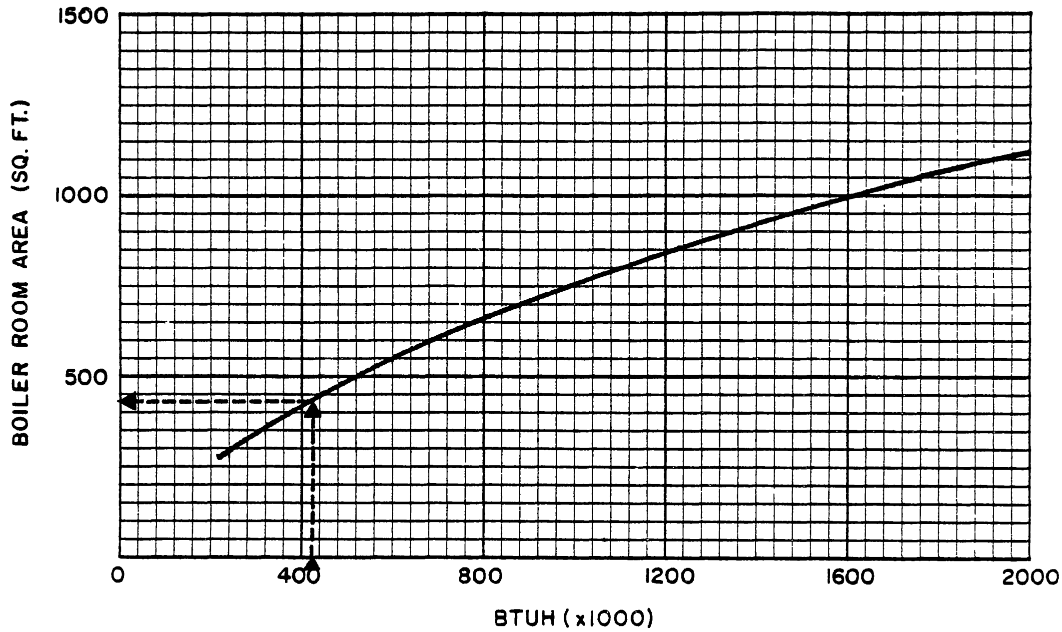


Figure 42. Boiler Room Area as a Function of Heating Load - School Example

For this example project, one fan room for each floor is selected, therefore:

52,000 CFM ÷ 2 = 26,000 CFM

which yields a fan room size of approximately 300 sq. ft. for each floor according to Figure 44. The optimum length to width ratio for a fan room is approximately 1:1. Assuming that the fan room is fairly centrally located, two main ducts can be used leaving the fan room, each transporting 26,000 CFM ÷ 2 or 13,000 CFM. Figure 45 shows a minimum duct depth of 21" based on 13,000 CFM.

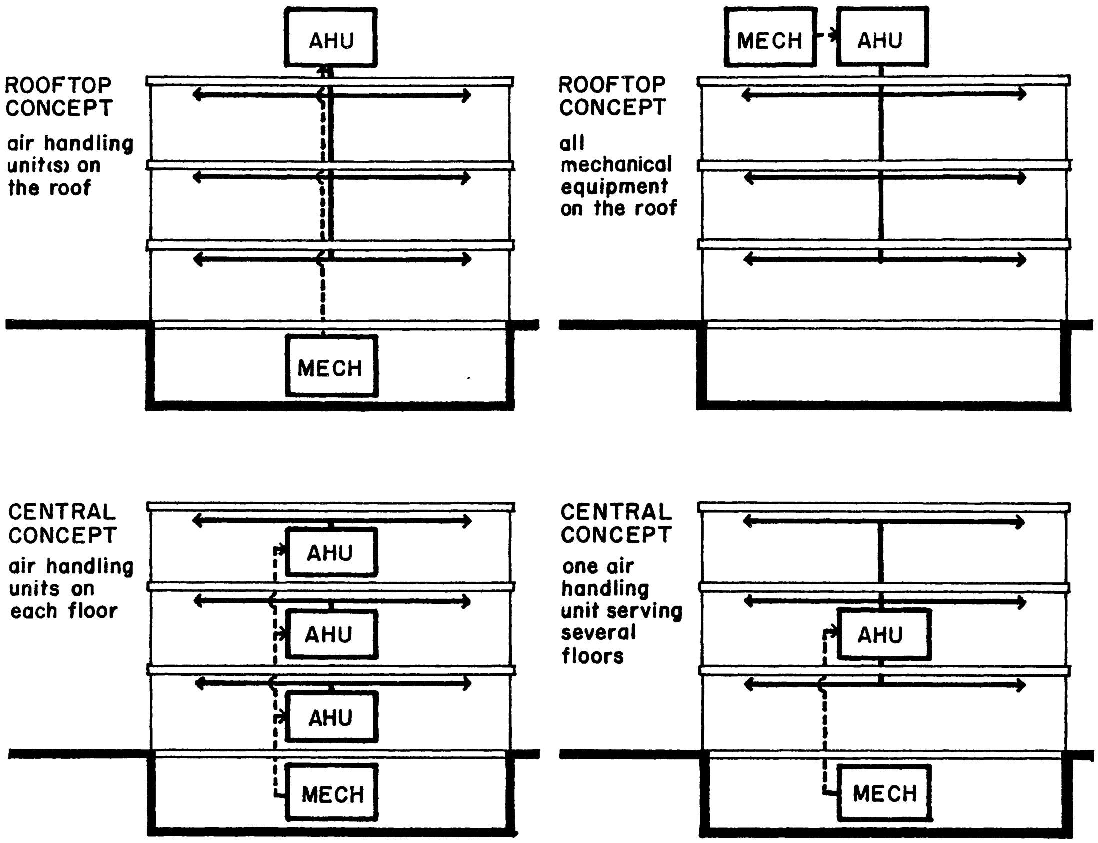


Figure 43. Conceptual Arrangements of Mechanical and Fan Rooms

The implications of each fan room arrangement become evident when using these graphs. If several fan rooms or shafts are used, the ceiling sandwich can be decreased along with the size of each fan room or shaft but total floor area devoted to fan rooms and vertical shafts increases. If less than one fan room per floor is used, then vertical shafts become a more important consideration. (For sizing a vertical shaft, the area of a fan room is found and multiplied by 5 percent.) If a total rooftop system is usual for a one story building, then virtually no interior floor space need be allocated for HVAC equipment.

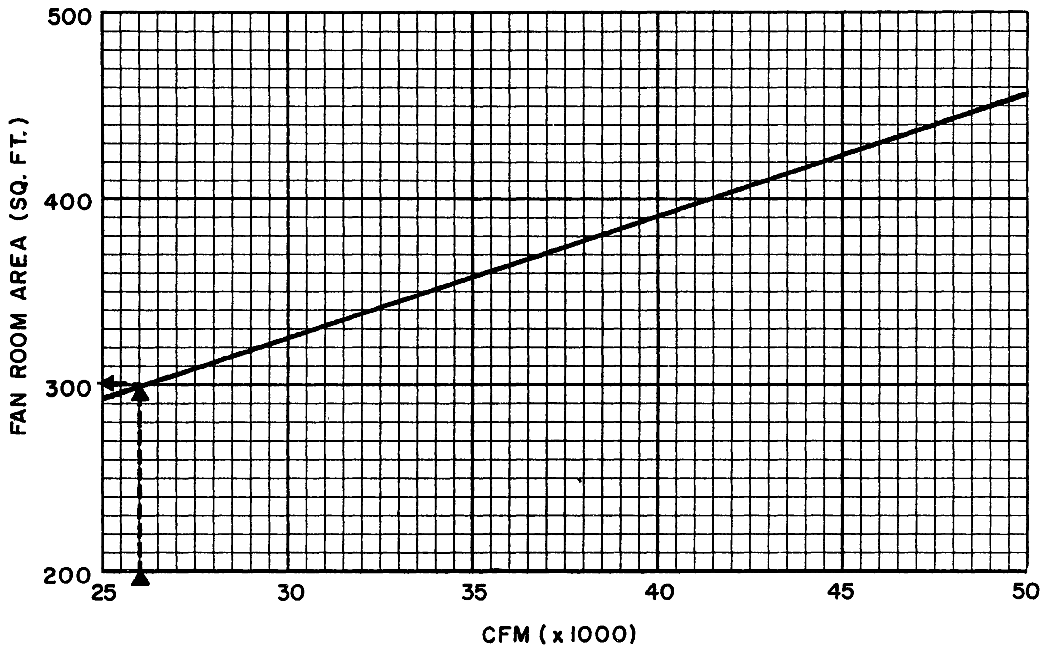


Figure 44. Fan Room Area as a Function of Air Flow Rate (25,000-50,000 CFM) - School Example

School Example Conclusions

- System type used: single zone, rooftop system, with hot water baseboard radiation.
- Total heating load: 425,600 Btuh
- Total cooling load: 168 tons.
- Total air flow rate: 52,000 CFM.
- Total mechanical room area: 960 sq. ft.
- Total fan room area: 600 sq. ft.
- Minimum duct depth in ceiling: 21".

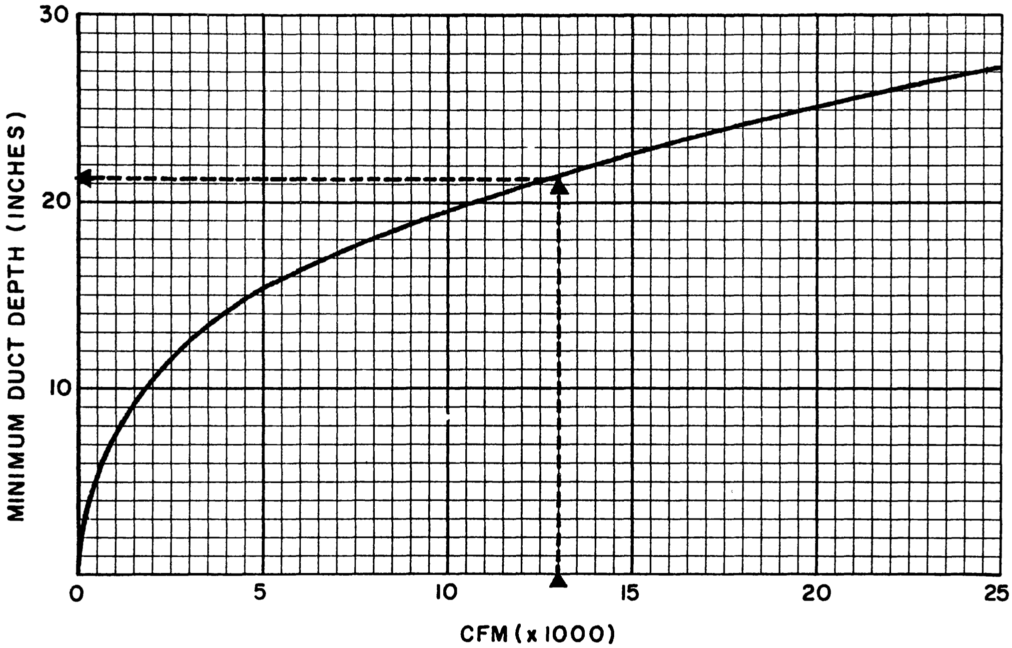


Figure 45. Minimum Duct Depth as a Function of Air Flow Rate (0-25,000 CFM) - School Example

Office Project

As a second example, a five story office building in Miami, Florida is used. It is a simple square building 120 ft. x 120 ft., 14,400 sq. ft. per floor. The procedure is the same as that for the school project. Using rules-of-thumb available for the programming phase, the space requirements are as follows:

main mechanical room = 1,400 sq. ft.

area for fan rooms = 3,240 sq. ft.

area for vertical shafts = 252 sq. ft.

From comparative analysis, a VAV central system with electric baseboard radiation will be incorporated.

Miami has a latitude of 26°, a winter design Δt of 23°F, and a total of 214 annual heating degree days. From this information, the effects of climate are calculated, yielding the following results:

total heating load = 211,968 Btuh (note that this is at extreme conditions and may occur only at night when the building is unoccupied, therefore an expensive heating system for such a building in a warm climate does not usually pay off).

total cooling load from climatic effects = 948,800 Btuh

The internal heat gains in an office building are usually fairly high, mostly because of the density of people and the high lighting loads (although not as high as for a school). Using 21.55 Btuh/sq. ft., the total internal heat gain comes out to 1,551,600 Btuh. The total cooling load then is 208 tons.

Based on these loads, a main mechanical room is sized at 850 sq. ft. Using 0.9 CFM/sq. ft., a fan room on each floor is sized at 210 sq. ft. with a minimum duct depth of 18".

Office Building Example Conclusions

- System type used: VAV, central system with electric baseboard radiation.
- Total heating load: 211,970 Btuh.
- Total cooling load: 208 tons.
- Total air flow rate: 64,800 CFM.
- Total mechanical room area = 850 sq. ft.
- Total fan room area = 1,050 sq. ft.
- Minimum duct depth in ceiling = 18".

Comparing both example projects, very little difference is detected. The total area of the school building is 40,000 sq. ft. The total area of the office building is 72,000 sq. ft., which equates to 238 sq. ft. per ton and 346 sq. ft. per ton, respectively. The reason for the difference is the much higher interior loads in the school. The main mechanical room for the school project comes out slightly larger than that for the office building primarily because a boiler is utilized in the school project and electric baseboard is used in the office building. The floor area allocated for air handling equipment in the office building example is larger than that for the school simply because there are five fan rooms in the office building as opposed to two fan rooms in the school--a design decision.

Working through the method, quite a bit of flexibility is detected; the architect could almost make the answers come out the way he wants. The same is true in the field. An engineer's estimations are dependent upon his initial assumptions.

This method is not intended to provide a definitive solution to all design problems, but it can aid in arriving at various alternatives: "What if incremental units are used?" or "What if two fan rooms are used instead of one?" These questions can be analyzed by working through the method. After familiarity is gained with the method, more logical approaches may be detected. For instance, in a gymnasium the minimum duct depth probably won't be a major concern and so it may not even be considered in the analysis.

With the information available in this method, the architect has the ability to analyze building-system compatibility early in the design phase in order to arrive at a successfully integrated solution.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary of Procedure

The method developed in this study provides the architect with a design tool which facilitates the preliminary selection and sizing of an HVAC system for an architectural project. First, an analysis of the architectural design process was outlined to give some insight as to where a method of this type might fit in. Then, a discussion of system types was necessary in order to gain a better understanding of how each system performs and operates. For selecting a system, it is important to identify and describe the building types in which various HVAC systems will be installed. Many times the architect is unfamiliar with what system performs best in a particular application, thus the reason for "historical" system selection data as well as survey data for what's being done today in the HVAC field. For sizing mechanical rooms, two basic parameters were needed: the type of equipment involved with each particular system; and the size of this equipment. The type of equipment was based primarily on the system selected. The size of the equipment was a function of the loads. All the data was then compiled to form a step by step methodology which could be used for preliminary HVAC selection and sizing decisions.

As with any preliminary calculation, the results are just estimates, but by modeling conditions of a project which are known early in the design process, fairly accurate results are attainable. Although the results gained from the method are based on conservative estimates, they still offer more flexibility than basic rules-of-thumb.

Recommendations for Further Study

In a state-of-the-art architectural design project using new or different mechanical systems, the engineer must work with the architect from the very beginning of the project. The method in this study does not take into account any state-of-the-art systems. It is very difficult to analyze all the possibilities for HVAC system design with such a method since the architect is most likely to be unfamiliar with basic system design.

A recommendation for further application of this approach is to incorporate it into a computer program and possibly a computer aided drafting program. The architect could then see the possibilities of mechanical room placements with the use of isometrics, plans, and sections. Since HVAC design and systems are constantly changing, a computer program can be designed to easily facilitate new input on sizes, shapes, and types of equipment. The selection process itself can be improved so that a computer would allow the architect to explore more possibilities in less time.

Exposure to the many engineering considerations early in the design process will allow the architect to more successfully integrate HVAC systems into the fabric of the building and hopefully "bridge the gap" between architects and engineers.

SELECTED BIBLIOGRAPHY

(1) American Institute of Architects Handbook of Professional Practice. Washington, D.C.: AIA, 1969.

(2) The ABC's of Air-Conditioning, A Primer of Air-Conditioning Types and Methods for the Architectural Profession. Carrier Air-Conditioning Co., Syracuse, New York, 1980.

(3) ASHRAE Handbook--Systems. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1984.

(4) Greenberg, A. "Introductory Approach to the Rating of Air-Conditioning Systems." ASHRAE Journal, Vol. 17, No. 6 (August 1972), p. 35.

(5) Climate Classification Analysis. Washington, D.C.: U.S. Department of Energy, DOE/CS.0016, 1979.

(6) ASHRAE Handbook--Applications. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1982.

(7) Khashab, A. M. Heating, Ventilating, and Air-Conditioning Systems Estimating Manual. New York, New York: McGraw-Hill, Inc., 1977.

(8) Andrews, F. T. The Architect's Guide to Mechanical Systems. New York: Reinhold Publishing Corporation, 1966.

(9) American Consulting Engineers Council 1983-84 Directory. American Consulting Engineers Council, Washington, D.C., 1983.

(10) ASHRAE Handbook and Product Directory--Systems. New York: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1980.

(11) Olivieri, J. B. "A Proposed Air-Conditioning Rating System." ASHRAE Journal, Vol. 15, No. 9 (January, 1971), p. 80.

(12) Means Mechanical Cost Data, 7th ed. Kingston: Robert Snows-Means Co. Inc., 1983.

(13) Carrier Air-Conditioning Company. Series 39 Air Handling Units, Catalog No. 593-914. Syracuse, New York, May, 1982.

(14) Daryanani, S. "Space Planning for HVAC Systems," Progressive Architecture, Vol. 52, No. 5, (May, 1971), p. 120.

(15) Rizzi, E. A. Design and Estimating for Heating, Ventilating, and Air-Conditioning. New York, New York: Van Nostrand Reinhold Co., 1980.

(16) ASHRAE Standard 90. Energy Conservation in New Building Design. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1980.

(17) McGuinness, W., B. Stein and J. Reynolds. Mechanical and Electrical Equipment for Buildings. 6th Ed., New York, New York: John Wiley and Sons, Inc., 1980.

(18) BOCA. Basic Building Code. Homewood, Illinois: Building Officials and Code Administrators International, Inc., 1981.

(19) NFPA. National Electric Code. Boston, Mass.: National Fire Protection Association, 1978.

(20) ASHRAE Standard 62. Ventilation for Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1981.

(21) Ramsey, C. Y. and H. Sleeper. Architectural Graphic Standards. 7th Ed. New York, New York: John Wiley and Sons, Inc., 1981.

(22) Carrier Air-Conditioning Company. Packaged Hermetic Reciprocating Liquid Chillers, Form 30H-3P. Syracuse, New York, 1981.

(23) Carrier Air-Conditioning Company. Packaged Hermetic Centrifugal Liquid Chillers, Form 19-2P. Syracuse, New York, 1979.

(24) Carrier Air-Conditioning Company. Hermetic Absorption Liquid Chillers, Form 16JB-3P. Syracuse, New York, 1975.

(22) Kewanee Boiler Corporation. Classic 111B Scotch Package Boilers, Bulletin KBC-1. Chesterfield, Missouri, 1978.

APPENDICES

APPENDIX A

SAMPLE SURVEY FORM

The HVAC selection survey was mailed to architectural and mechanical engineering firms throughout the U.S. Contacts were made through the ASHRAE Energy Management Committee and the American Consulting Engineers Council Directory. The cover letter and the survey form are included in this appendix. These documents were the only sources of information sent to the engineers, therefore their answers should have been based on past experience and dependent on their particular climatic region.

Responses from each state:

- Alabama: 4
- Alaska: 0
- Arizona: 4
- Arkansas: 3
- California: 8
- Colorado: 0
- Connecticut: 0
- Delaware: 0
- District of Columbia: 0
- Florida: 5
- Georgia: 26
- Hawaii: 0
- Idaho: 0
- Illinois: 0
- Indiana: 0
- Iowa: 0
- Kansas: 3
- Kentucky: 8
- Louisiana: 6
- Maine: 0
- Maryland: 0
- Massachusetts: 0
- Michigan: 10
- Minnesota: 2
- Mississippi: 1
- Missouri: 7
- Montana: 1
- Nebraska: 1
- Nevada: 0
- New Hampshire: 0
- New Jersey: 2
- New Mexico: 1
- New York: 9
- North Carolina: 0
- North Dakota: 1
- Ohio: 0

- Oklahoma: 6
- Oregon: 7
- Pennsylvania: 0
- Rhode Island: 0
- South Carolina: 0
- Tennessee: 4
- Texas: 6
- Utah: 0
- Vermont: 0
- Virginia: 0
- Washington: 0
- West Virginia: 0
- Wisconsin: 0
- Wyoming: 0

OKLAHOMA STATE UNIVERSITY
SCHOOL OF ARCHITECTURE

Keith J. Yancey
101 Architecture Building
Stillwater, Oklahoma 74078
16 April 1984

Dear :

I am a graduate student at Oklahoma State University currently working on my Master's degree in Architectural Engineering (Environmental Control). My thesis topic deals with the process of sizing and selecting HVAC systems, with an emphasis on architecture students and practicing architects. I realize that many factors come into play when trying to decide on an optimum system for a particular application: cost, size, types of loads, etc. I hope, however, to get a handle on these factors with your help.

I got your name from Mr. William Dillard (ASHRAE Region XII, Orlando) in the hope that you would be able to help me. Enclosed is a list of building types and system types. I would greatly appreciate it if you could take a few minutes to complete the sheet of questions and return it to me as soon as possible. With your assistance I hope to get a grasp on the types of systems that have traditionally been used in particular applications. This would help immensely in forming the framework for the actual selection process which I am trying to develop.

I've been an ASHRAE student member now for several years and have contacted ASHRAE members for assistance first, considering they would be the most help to me.

I do hope this isn't an inconvenience, but with your expertise in this field and your cooperation with this survey, the results will be priceless for research purposes in my thesis. Thank you so very much and I'll be looking forward to hearing from you.

Sincerely,

Keith J. Yancey
Graduate Student

STILLWATER, OKLAHOMA, 74074 405-624-6043

Name ______________________

Address ______________________

Listed below are 14 general types of buildings with three budget categories for each (tight budget, medium budget, and no budget). From the attached list of system types place the letter and/or the number of the particular system which you would most likely select for that building type in your particular climatic region under each of the three budget categories.

Example:

	Tight Budget	Medium Budget	No Budget
Office - Large	2,D,K	1,D,L	1,C

Tight Budget - Single duct VAV with other (hot water baseboard radiation)-Rooftop

Medium Budget - Single duct VAV with other (fan powered VAV boxes) - central system

No Budget - Multizone - 3 deck - central system

Comments - Rooftop unit on tight budget only if building is three stories or less.

BUILDING TYPE	Tight Budget	Medium Budget	No Budget
• Clinic			
• Community Center			
• Gymnasium			
• Hospital			
• Motel			
• Multifamily High Rise			
• Nursing Home			
• Office - Large			
• Office - Small			
• School (Elementary/Secondary)			
• Shopping Center			
• Store			
• Theatre/Auditorium			
• Warehouse			

SYSTEM TYPES

A. Single Zone

B. Multizone 2 Deck

C. Mulitzone 3 Deck

D. Single Duct VAV

E. Dual Duct

F. Single Zone w/Reheat

G. Induction

H. Fan Coil Units

I. Hydronic Heat Pumps

J. Unitary Units

K. Other (specify)

L. Other (specify)

M. Other (specify)

N. Other (specify)

1. Central System

2. Rooftop System

3. Packaged

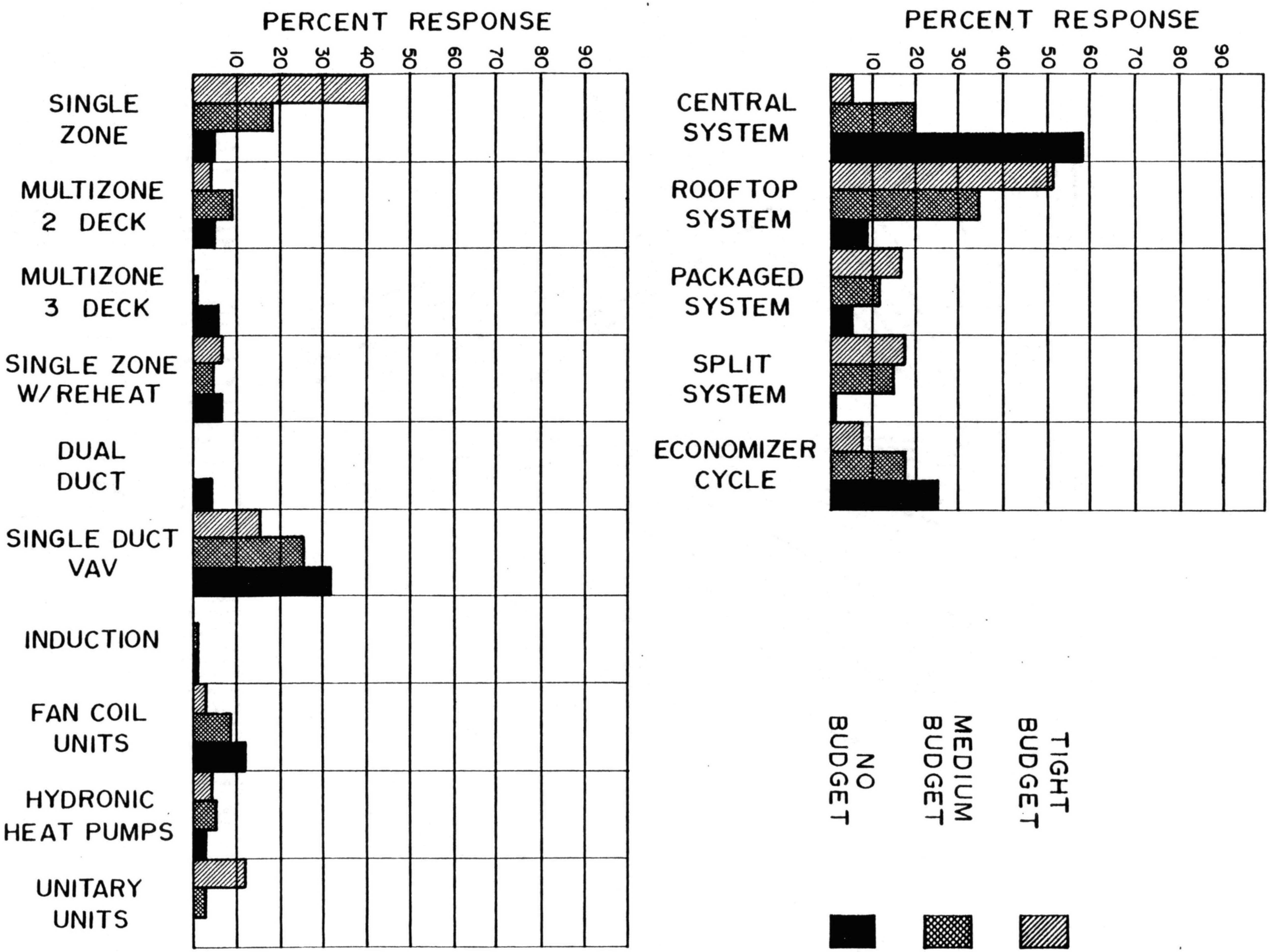
4. Split System

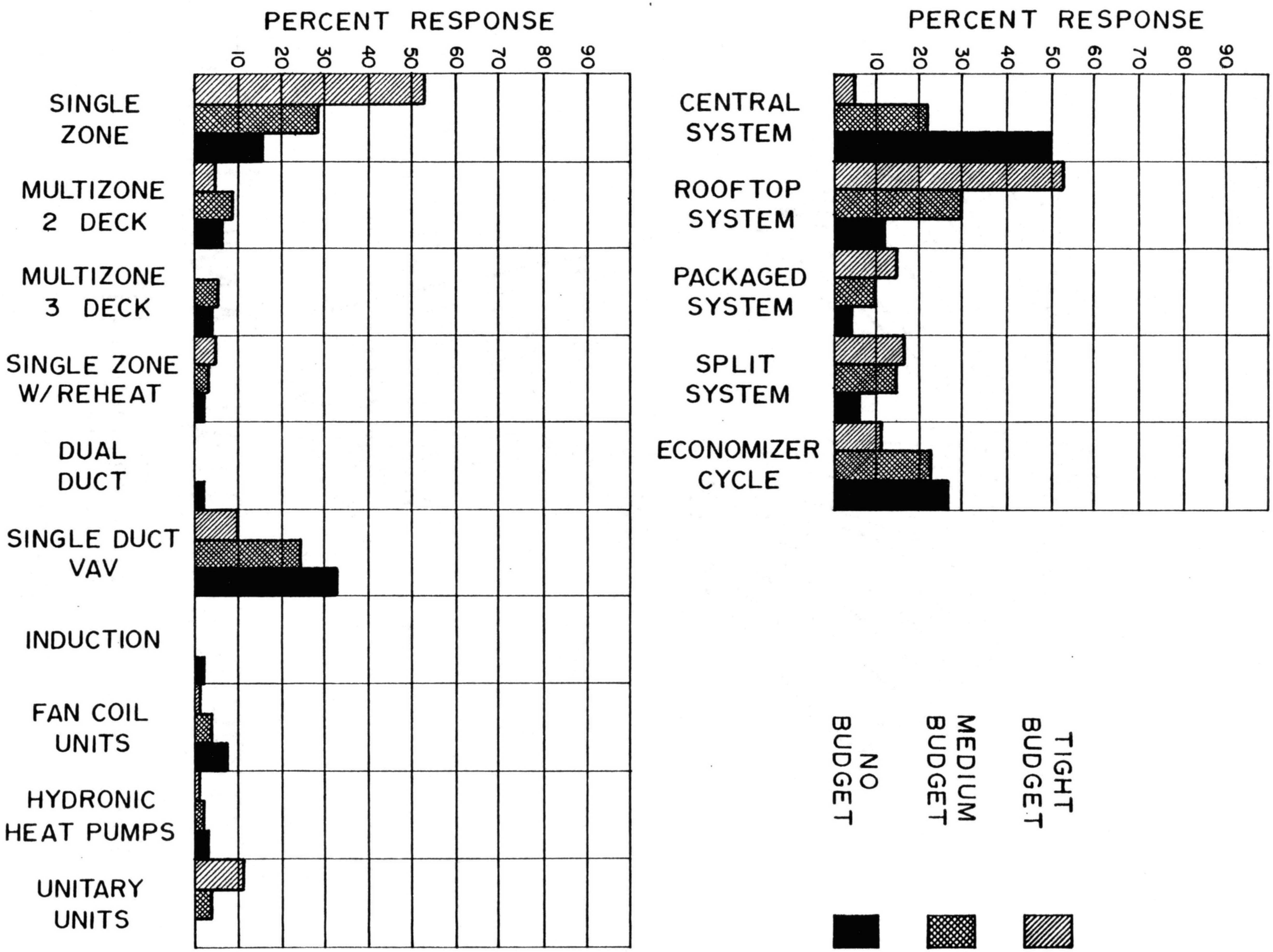
5. Economizer

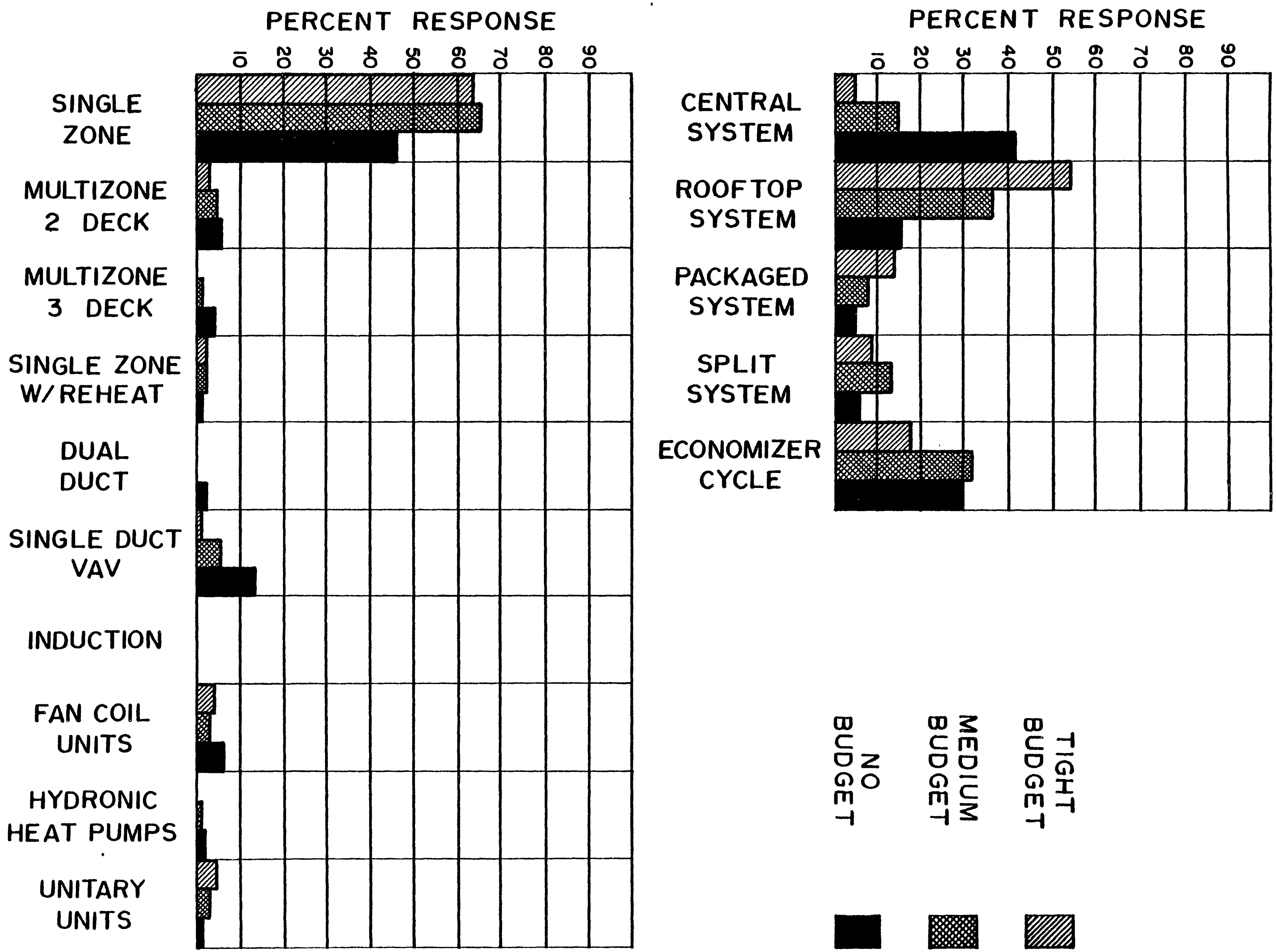
Comments & Discussion:

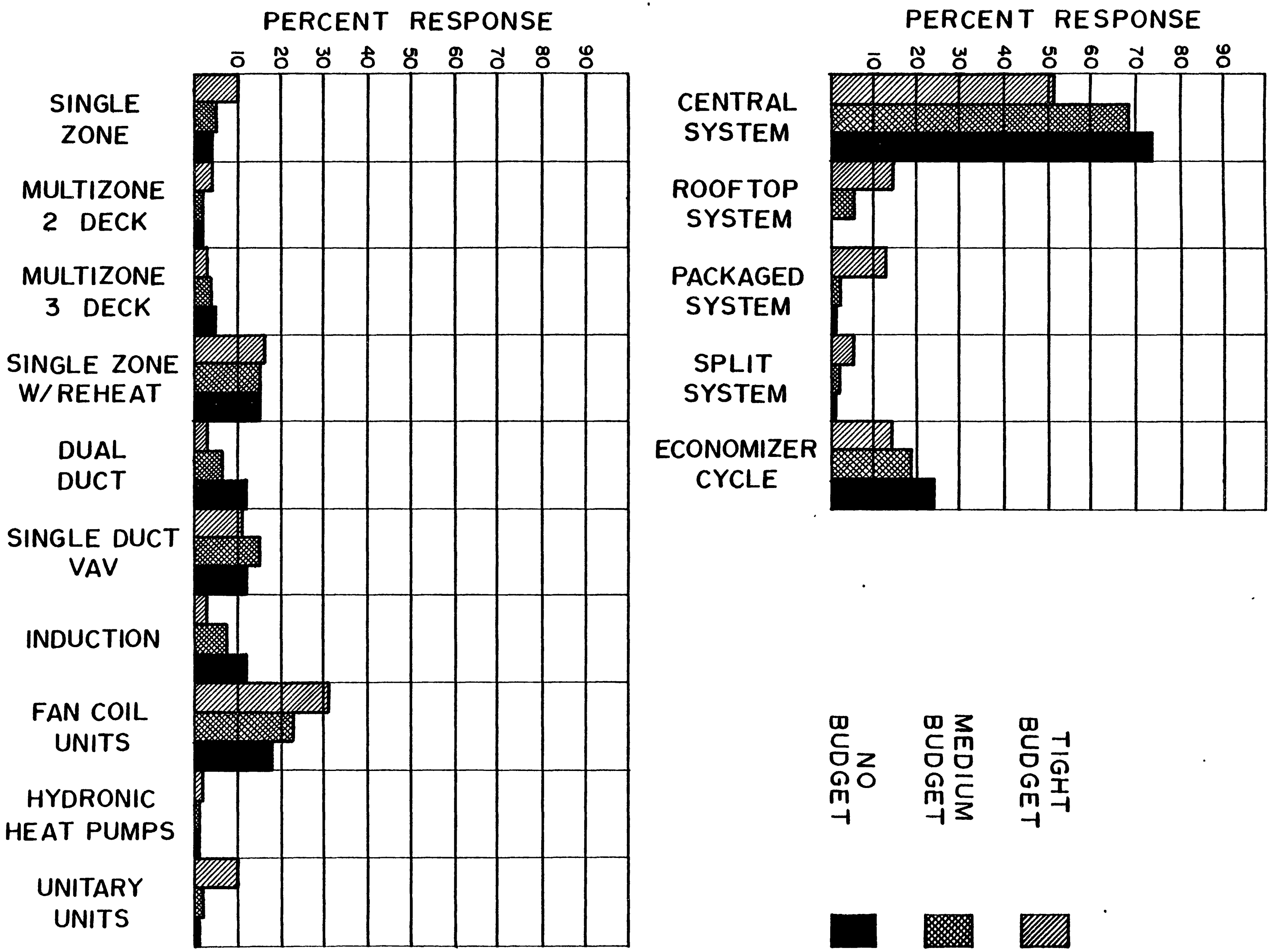
APPENDIX B

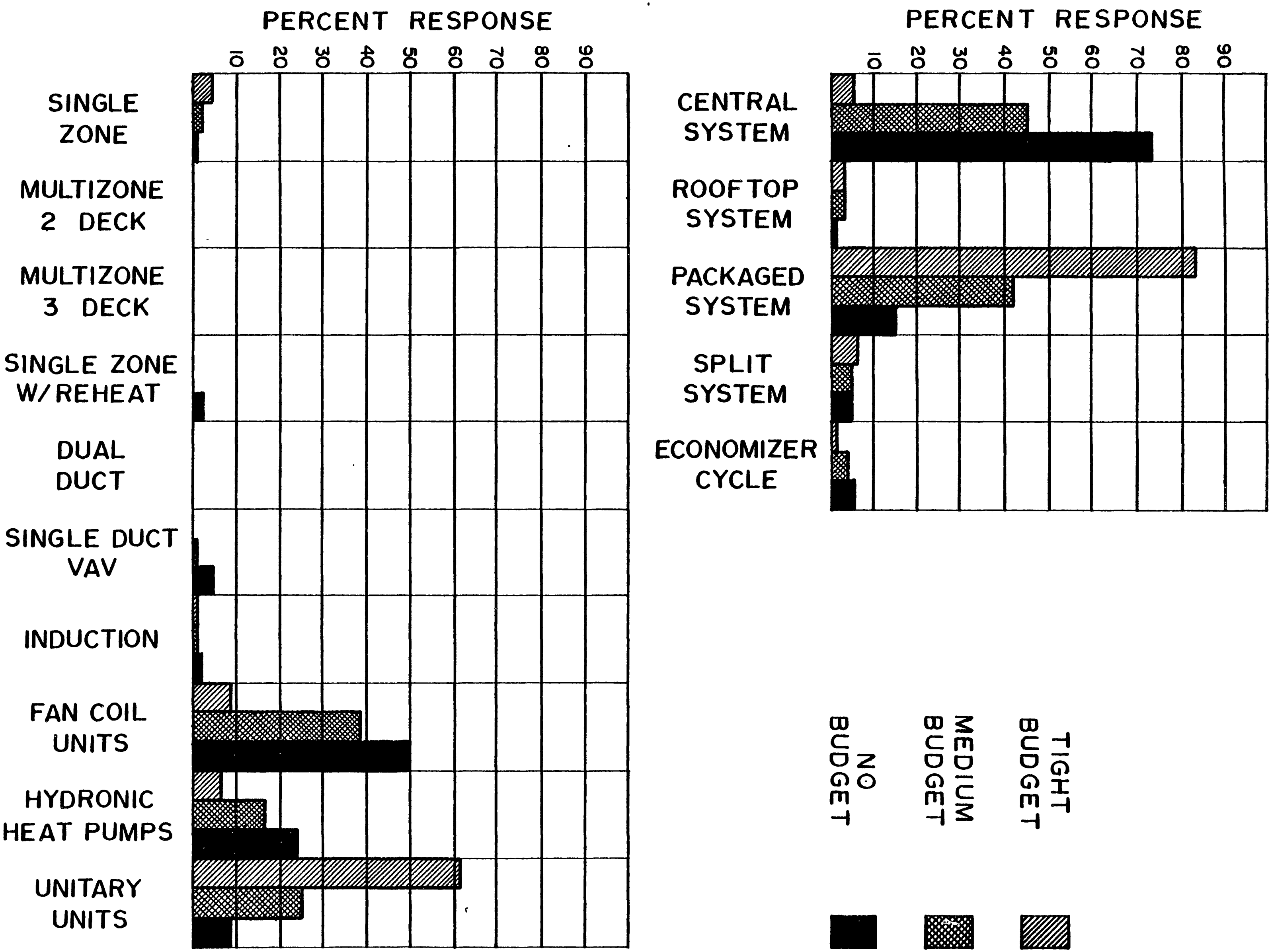
SYSTEM SELECTION SURVEY RESULTS

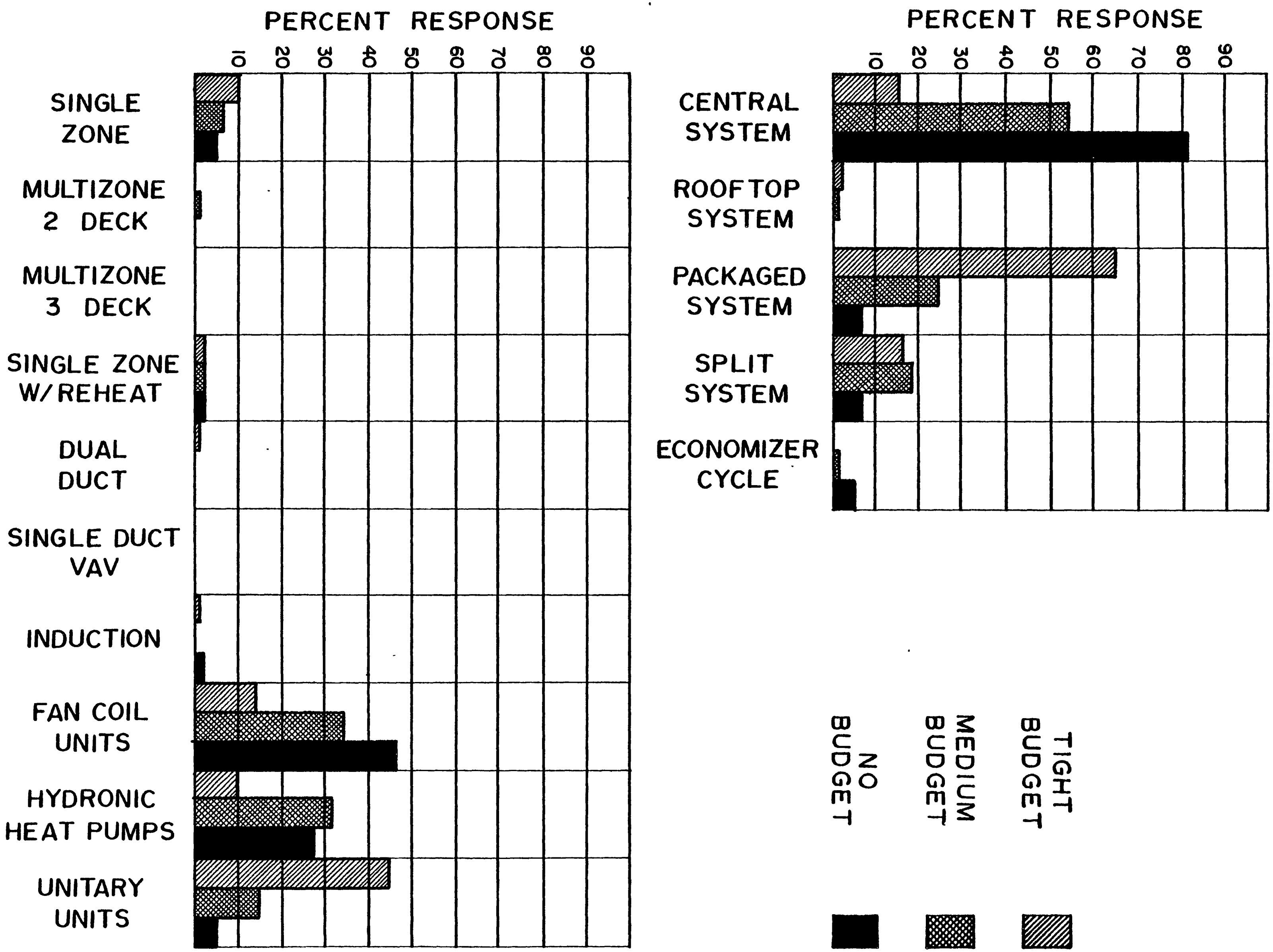

PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
CENTRAL SYSTEM
ROOFTOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET


PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
CENTRAL SYSTEM
ROOFTOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET

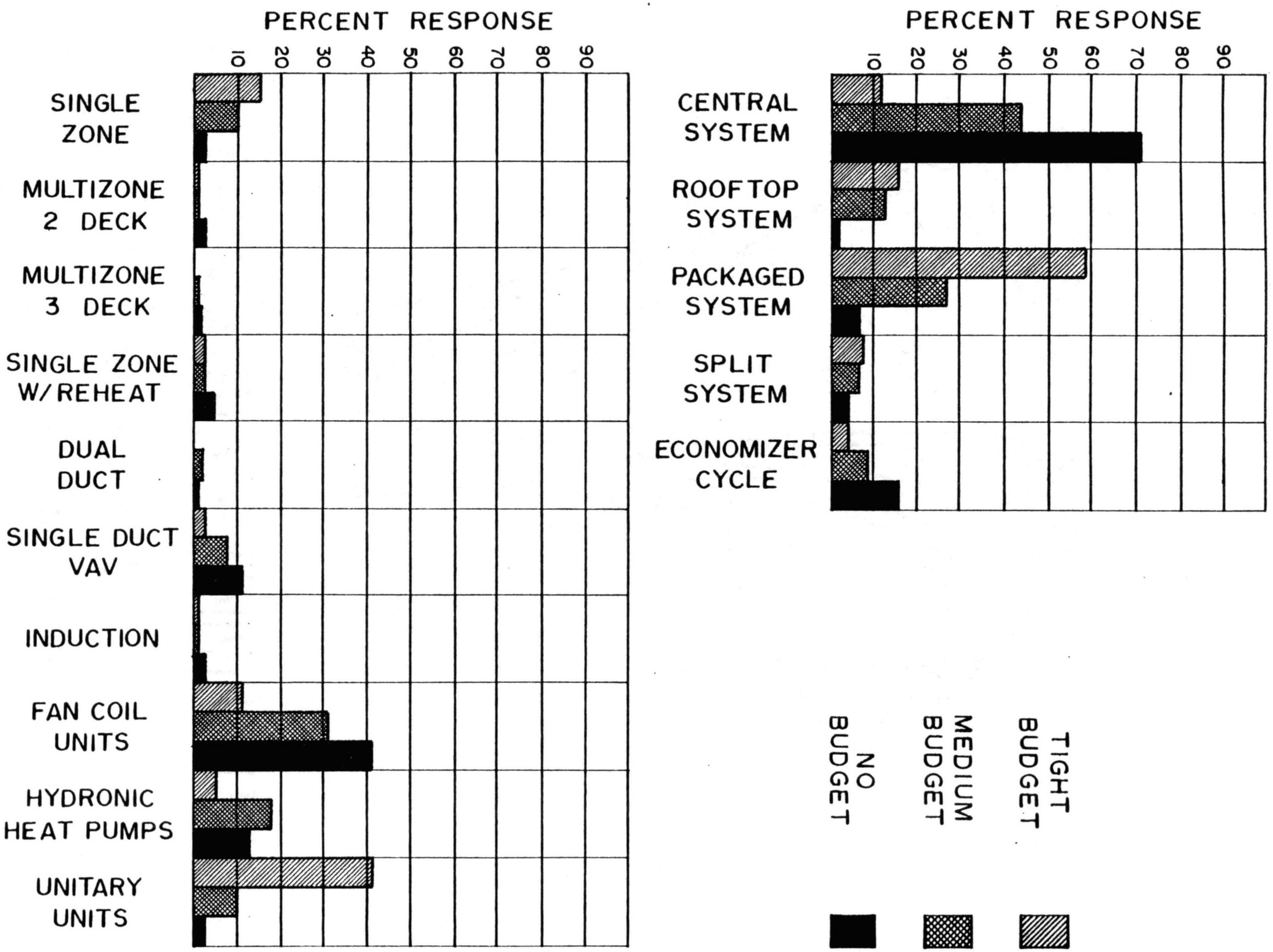

PERCENT RESPONSE
10 20 30 40 50 60 70 80 90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
10 20 30 40 50 60 70 80 90
CENTRAL SYSTEM
ROOFTOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET

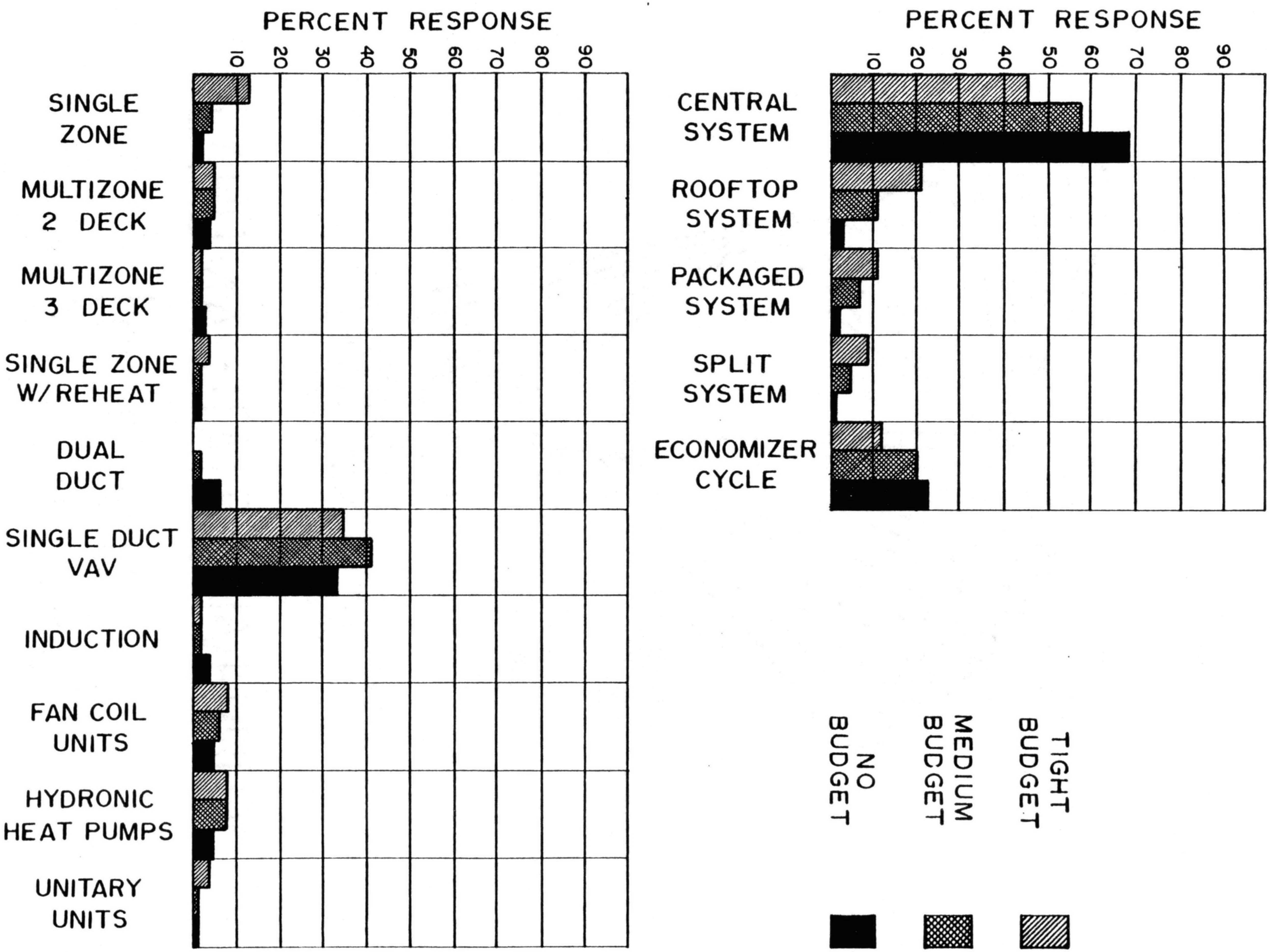

PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
CENTRAL SYSTEM
ROOF TOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET


PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
CENTRAL SYSTEM
ROOFTOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET

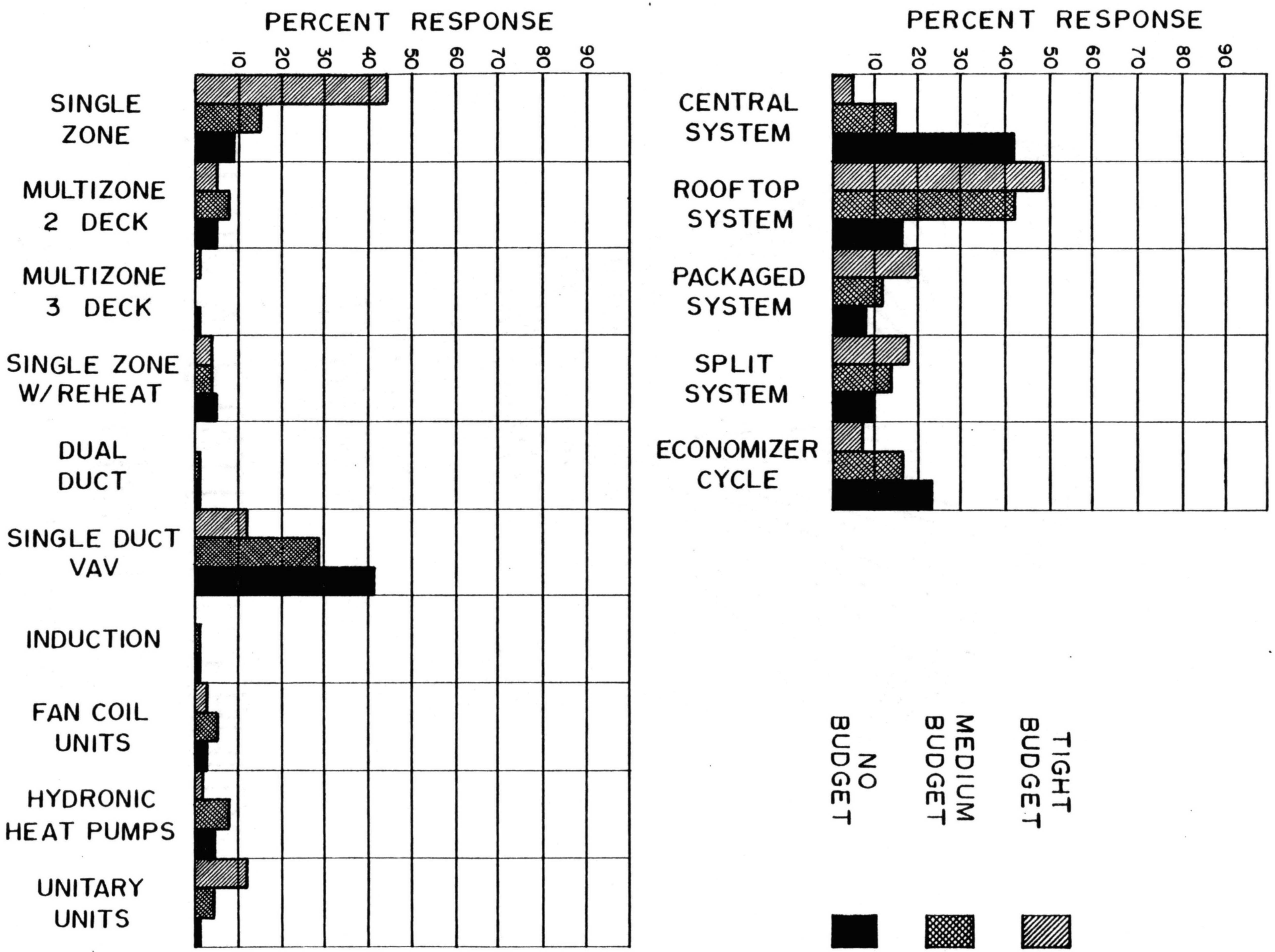


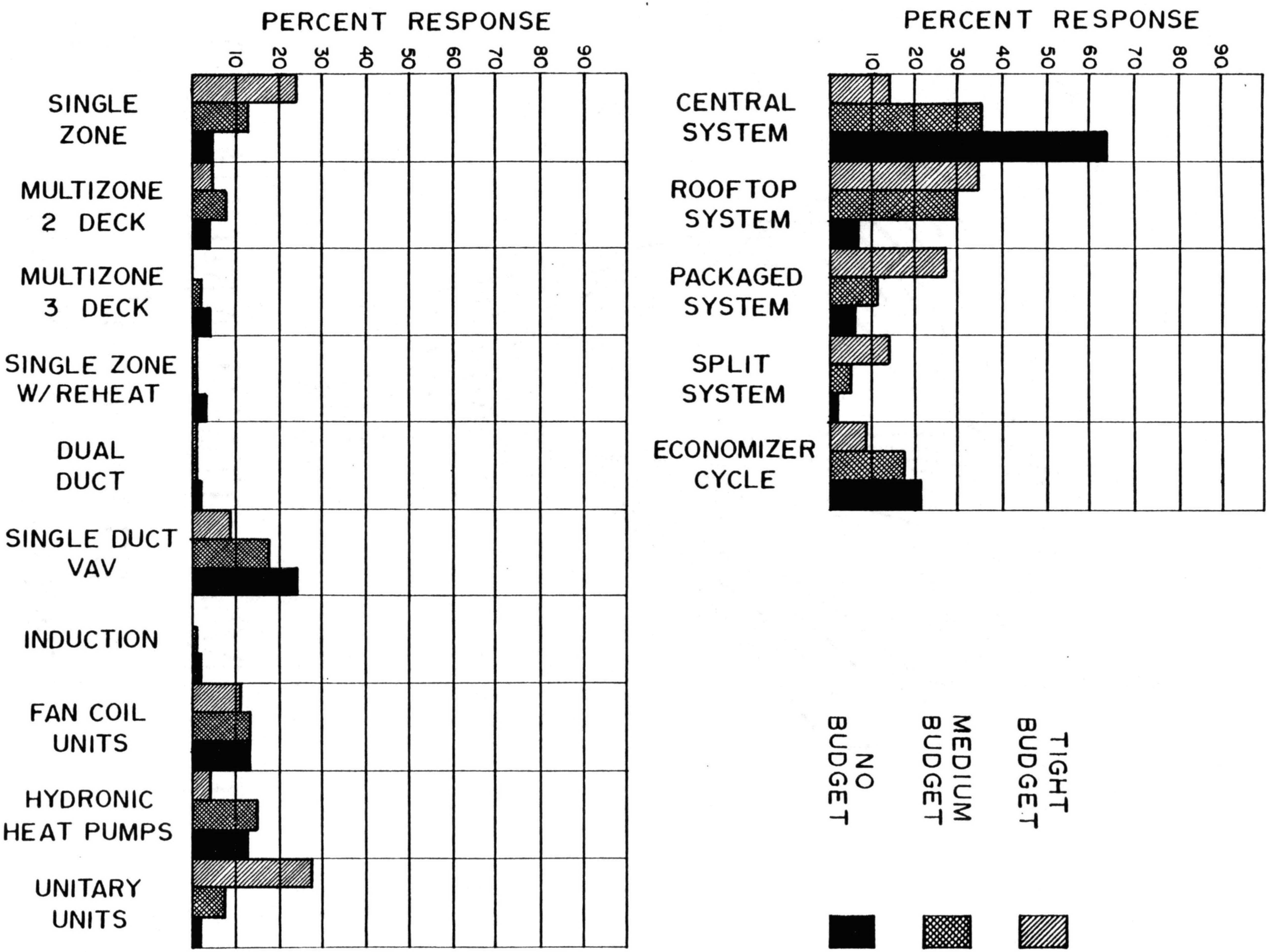
Survey Results - Multifamily High Rise


PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
CENTRAL SYSTEM
ROOFTOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET

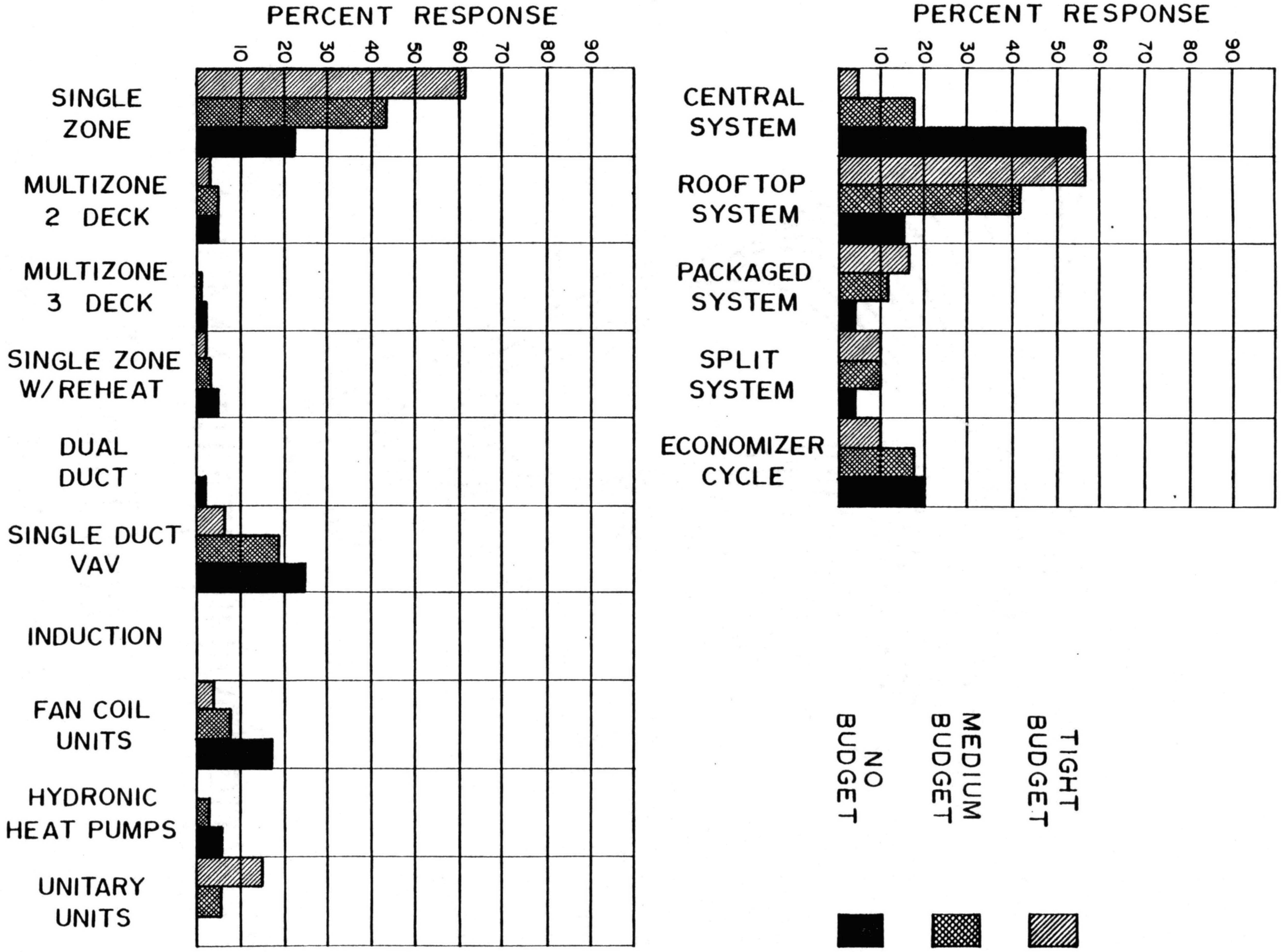


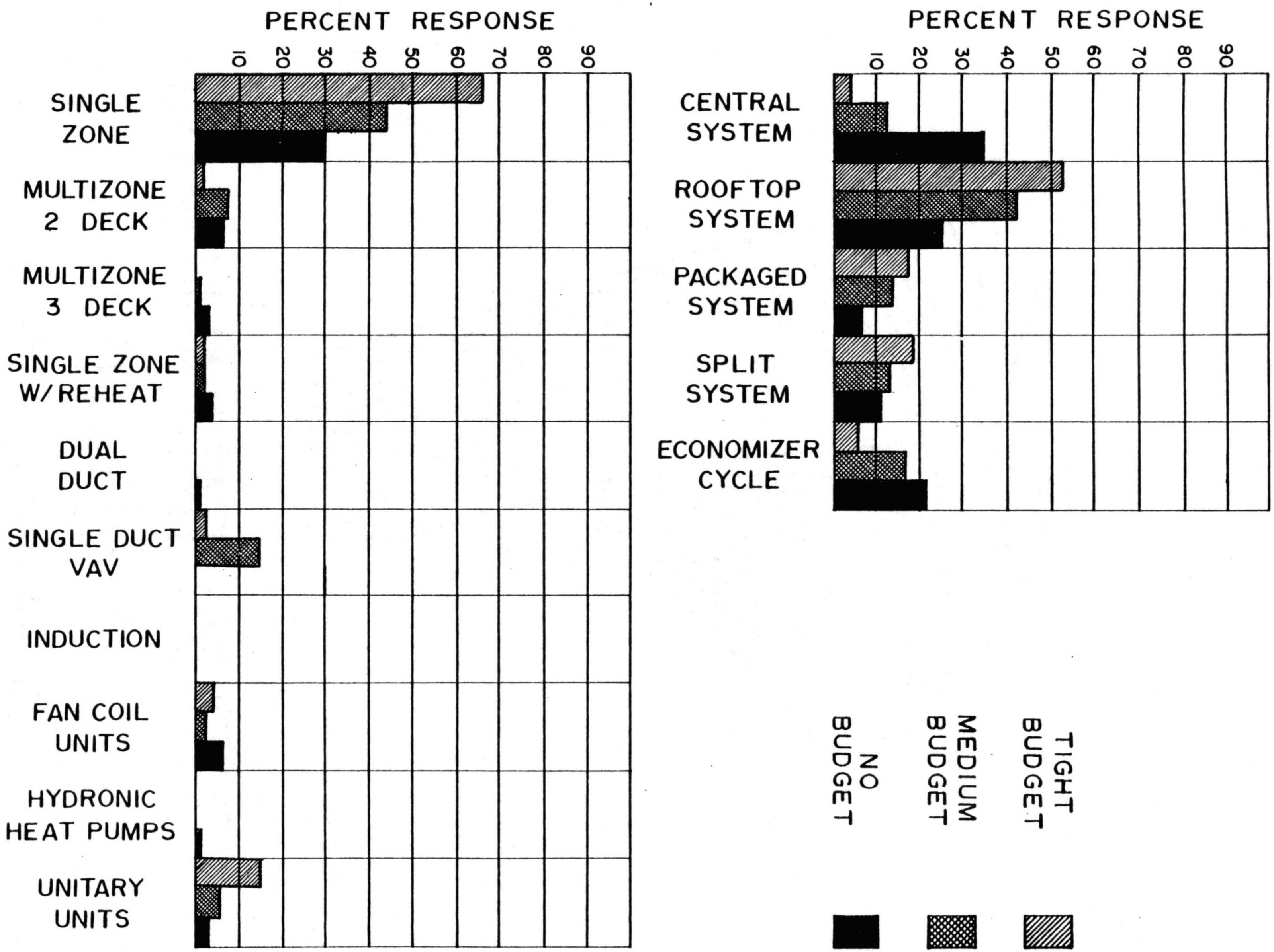
Survey Results - Office - Large

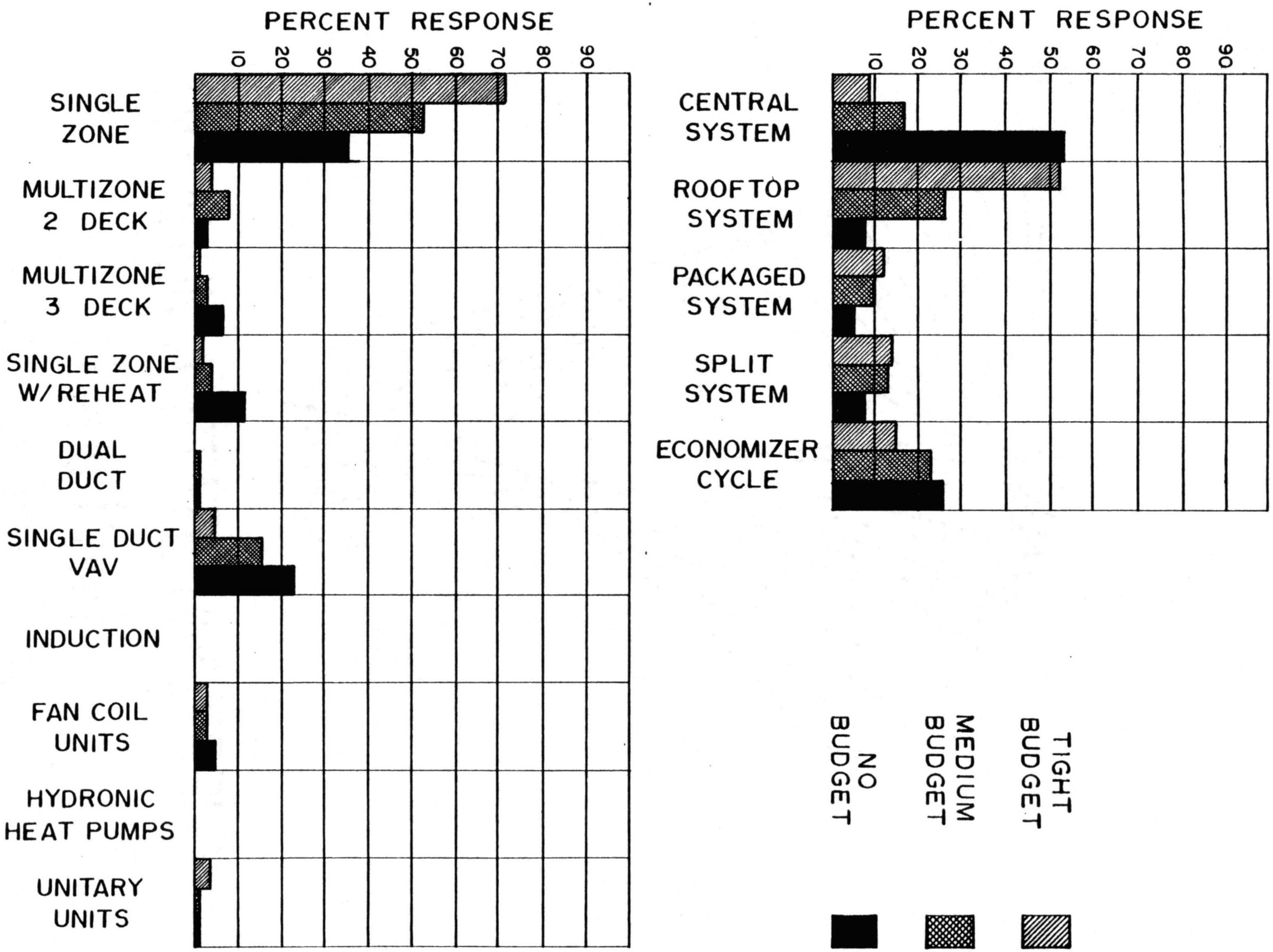

PERCENT RESPONSE
10 20 30 40 50 60 70 80 90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
10 20 30 40 50 60 70 80 90
CENTRAL SYSTEM
ROOFTOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET

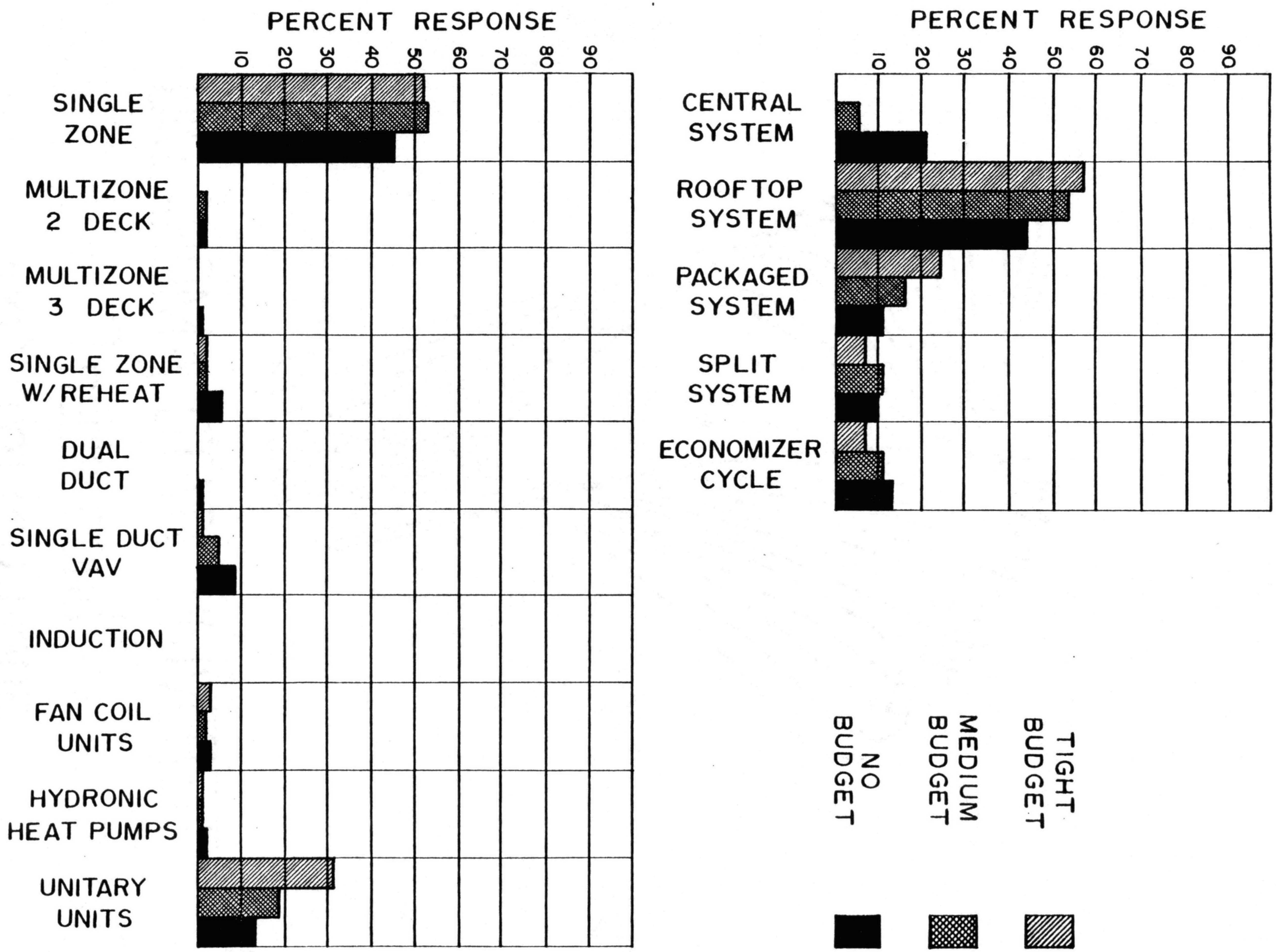


Survey Results - School (Elementary/Secondary)


PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
CENTRAL SYSTEM
ROOFTOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET


PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
CENTRAL SYSTEM
ROOFTOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET


PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
10
20
30
40
50
60
70
80
90
CENTRAL SYSTEM
ROOFTOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET


PERCENT RESPONSE
10 20 30 40 50 60 70 80 90
SINGLE ZONE
MULTIZONE 2 DECK
MULTIZONE 3 DECK
SINGLE ZONE W/REHEAT
DUAL DUCT
SINGLE DUCT VAV
INDUCTION
FAN COIL UNITS
HYDRONIC HEAT PUMPS
UNITARY UNITS
PERCENT RESPONSE
10 20 30 40 50 60 70 80 90
CENTRAL SYSTEM
ROOFTOP SYSTEM
PACKAGED SYSTEM
SPLIT SYSTEM
ECONOMIZER CYCLE
NO BUDGET
MEDIUM BUDGET
TIGHT BUDGET

Many of the results from the surveys included systems not mentioned in the initial survey form. A list of those systems or combinations of systems appears according to building type in the following pages. Those which are specifically related to local climatic conditions are identified.

CLINIC

- Hot water and electric reheat on perimeter
- Fan powered induction units
- Multiple air handling units with VAV diffusers
- Perimeter downfall diffusers
- Off peak cooling
- Ice storage cooling
- Circulation condenser water loop to cooling tower and boiler
- Dual duct VAV at perimeter with single duct VAV for interior zones
- Electric radiant ceiling panel heating
- Water source heat pump with thermal storage (North Dakota)
- Single zone system with chilled water coils in ductwork to zones and air-cooled cold generator with glycol (Minnesota)
- Hot water and electric baseboard radiation

COMMUNITY CENTER

- Fan powered terminal units
- Air to air heat pumps
- Hot water and electric baseboard radiation
- VAV with reheat
- Off peak cooling
- Multiple single zone units

- Central system with heat recovery
- Dual duct VAV

GYMNASIUM

- Air to air heat pumps
- Hot water and electric baseboard radiation
- Heating and ventilation only
- Gas fired unit heaters
- Evaporate cooling (Arizona and New Mexico)

HOSPITAL

- Fan powered terminal units
- VAV with reheat
- Perimeter downflow diffusers
- Hot water and electric baseboard radiation
- Off peak cooling
- Circulation condenser water loop to cooling tower and boiler
- Dual duct VAV
- Radiant panel system with minimum outside air
- Heat reclaim from chiller
- Steam heat with humidification
- Combination of tempered ventilation air and zoned conditioning
- Single zone system with chilled water coils in ductwork to zones and air-cooled cold generator with glycol (Minnesota)

MOTEL

- Natural ventilation
- Hot water and electric baseboard radiation
- Air to air heat pumps

•Water source heat pumps with thermal storage utilizing sprinkler pipes (North Dakota)

MULTIFAMILY HIGH RISE

•Hot water and electric baseboard radiation

•Solar assisted or geothermal fan coil units

•Heat recovery

•Water-side (cooling tower) economizer

NURSING HOME

•Air to air heat pumps

•Hot water and electric baseboard radiation

•Fan powered terminal boxes

•Water-side (cooling tower) economizer

•Water source heat pump with thermal storage utilizing sprinkler pipes (North Dakota)

OFFICE - LARGE

•Hot water and electric baseboard radiation

•Fan powered terminal boxes

•Off peak cooling

•Solar assisted or geothermal fan coil units

•Heat recapture from lights

•Hot water and electric reheat

•Dual duct VAV

•Heat recovery

•Radiant panel system with minimum outside air

•Water-side (cooling tower) economizer

•Ceiling mounted VAV induction

OFFICE - SMALL

- Air to air heat pumps
- Hot water and electric baseboard radiation
- Gas fired furnaces with electric cooling
- Fan powered terminal units
- VAV with reheat
- Off peak cooling
- Heat recovery
- Dual duct VAV
- Water-side (cooling tower) economizer
- Ceiling mounted VAV induction

SCHOOL

- Hot water and electric baseboard radiation
- Air to air heat pumps
- Unit ventilators
- Natural ventilation
- Off peak cooling
- Multiple single zone units
- Central system with heat recovery
- Evaporative cooling (Arizona and New Mexico)
- Ceiling radiant system - solar compensated)

SHOPPING CENTER

- Off peak cooling
- Air to air heat pumps
- Central system with heat recovery
- Dual duct VAV

- Gas fired indirect heating
- Hot water and electric baseboard radiation

STORE

- Hot water and electric baseboard radiation
- Gas fired furnaces with electric cooling
- VAV with reheat
- Multiple single zone units
- Unit heaters
- Air to air heat pumps

THEATRE/AUDITORIUM

- Hot water and electric baseboard radiation
- Multiple air handling units with VAV diffusers
- Air to air heat pumps
- Off peak cooling
- Ice storage cooling
- Heat recovery

WAREHOUSE

- Exhaust/ventilation
- Heating and ventilation only
- Gas fired unit heaters
- Evaporative cooling (Arizona and New Mexico)

Some of the most beneficial information gathered from the surveys were the general comments from the engineers. Listed below in outline form (no particular order) are general comments from engineers around the country concerning system types, system selection, and the format of the survey.

- Economizer control should be used as a minimum for all air handling systems. A combination economizer-enthalpy control is better and does not add much to the system cost. Most rooftop manufacturers do offer this feature with their packaged units. (Georgia)
- A three deck multizone is hardly used these days. (Georgia)
- A single zone with reheat is not economical and outdated. (Georgia)
- For large jobs, a combination of many system types may be used. (Georgia)
- A three deck multizone is not permitted in buildings over 10,000 sq. ft. (California)
- "No budget" is not realistic, all buildings have a budget set in the early stages of construction and design. (Georgia)
- Local code governs system and application in clinics, hospitals, and nursing homes. (Florida)
- Packaged rooftop units with concentric duct arrangement or regular ducted systems are extremely popular in stores, shopping centers, theatres, community centers, etc.--single story buildings only. (Florida)
- Engineers don't really select systems based on building types and budget. Their decisions are based on the architecture of the

specific building, owners specific requirements, population density, noise considerations, quality of maintenance expected, available space for equipment in the building, on the roof or on grade, whether there is a basement or attic space, serviceability, fuel availability, cost, etc. (Michigan)

•Economizer would be provided on all air systems over approximately 7.5 tons. (Tennessee)

•Rooftop units with one story-split system are OK. Otherwise ducts through floors (fire dampers, etc.) are a headache. (Kentucky)

•Try to stay away from reheat or multizone. They are expensive and the controls are a problem. (Kentucky)

•Select perimeter radiation on tight budget with inexpensive duct system. This allows for another degree of control while not being terribly expensive. (Kentucky)

•Use economizer cycle on all central air handling units over 5000 CFM with enthalpy controls. (Alabama)

•Each job usually has architectural constraints which often dictate the final mechanical system. (Florida)

•Dual duct systems are no longer used in Florida.

•Heat recovery systems can be incorporated when dealing with large volumes of air and exhaust. (Oklahoma)

•Usually more than one system type is incorporated into a project depending on the type and function of the building. (Oklahoma)

•I consider single zone VAV with separate perimeter heating system best for economy and performance. This sytem cannot be used for hospitals due to minimum air changes required by public health service. Therefore constant volume, 2 stage induction system is most suitable. (Louisiana)

- Hydronic heat pumps, unless properly used, are not desirable, except for first cost. Good for apartments and other structures with at least 16 hours operation. Would not use in schools, despite present popular application. (Louisiana)
- Economizer system in this climate would be used in most occupancy groups with high internal loads from lights, people, process, etc. (Georgia)
- In most cases, budget is of less technical importance than is proper control. This is not to say that poorly operating systems will not be installed when money is tight. (Georgia)
- System selection should be based on size, layout, use, and owner desires. Proper system selection cannot be based on knowing only the building type. Owner desires of low first cost or operating cost along with available fuels and cost of fuels are major items in the selection of systems. (Georgia)
- Circumstances such as local labor rates and skills, design fees, building configuration, energy conservation, etc. all affect the decision for a system. (New York)
- Consider different central plant types--water vs. air cooled chiller. (Arizona)
- Certainly, there are many other reasons to select a particular type system than building type and budget limitation. These include zoning needs, single or multiple metering, length of ownership, etc. (Tennessee)
- It is not possible to pick a system on price alone.
  1. Hydronic heat pumps should only be used when there is a good balance between interior air conditioning loads and exterior heating loads.

2. Multizones are known as energy wasters, but if the building is of the size where more than one of these units can be used (say one for the centrol area, one for the east, one for the south, one for west, one for the north), the multizone unit is a good system. (Oregon)

•Many buildings need more than one type of system. For example, schools needs separate systems for gyms, locker rooms, shop, auditoriums, classrooms, etc. (Oregon)

•The chain of events in the selection of a mechanical system might go as follows:

1. What is the size of the building?
2. Is air-conditioning required in all areas (gyms, locker rooms, shop, etc.?
3. Is the building adaptable to rooftop equipment? (multi-story buildings may not)
4. Does the interior air-conditioning load balance with the exterior heating load?
5. Can a reduction of air quantity be tolerated? (not in surgery areas; probably not in cooking and eating areas).
6. Is there space for ductwork?
7. Select several systems that best fit the building.
8. Select the system that provides the best return on owner's money (consider first cost, maintenance, energy, etc.)
9. First cost must be within the owner's budget. (Oregon)

•Two deck multizone units are rarely used any longer in this area. (New Jersey)

•Most low rise (3 stories or less) have rooftop equipment either packaged or served from central system. (California)

- Single duct VAV systems with reset and electric or hydronic reheat served from a variety of cooling sources are widely used in this area. (California)
- A split system is used only when rooftop units cannot be applied or when an unusual load requires special psychrometric applications not available from packaged rooftop equipment. (Kansas)
- System selection is affected by many factors including (but not limited to) building size, style (number of stories, amount of glazing, etc.), location, orientation, fuel and utility availability, building construction, etc. (New York)
- Most sedentary type occupancies type occupancies require perimeter fin tube radiation. (Michigan)
- Some warehouses require dehumidify only. (Michigan)
- Hospitals require good filters thus must be a central system. (Michigan)
- Generally attention to winter comfort must equal or exceed attention to summer comfort. (Michigan)
- No electric resistance heat of any configuration except in unitary, small-capacity units for such applications as motel rooms. (Texas)
- Have liberal use of variable frequency controllers for fans, centrifugal chillers, and pumps. (Texas)
- In a large building, particularly high-rise, dispersion of air handling systems so that length of duct runs (power for transport) is reasonably short. Any system exceeding 10,000 CFM is suspect. (Texas)

•In the geographical southwest, use gas combustion for heating effect as a supplement to reclaim-from-refrigeration cycle. (Texas)

•Don't use absorption chillers or steam turbine drives for chillers. (Texas)

•Apply hydronic economizers (cold condenser water to chilled water through heat exchanger), but do not put condenser water directly into chilled water systems. (Texas)

•Do not expect an "air" vent cycle to perform satisfactorily unless it employs a return air fan. (Texas)

•Do not apply DX coils in field-erected coil banks or to VAV systems. (Texas)

•Do not get caught up in applying one technique too broadly. VAV is at this point in time an overkill; it is in fact only one more tool in the knowledgeable designer's kit. (Texas)

•Pay attention to the historic data on research and application of air diffusion in occupied spaces, and the data on human comfort. Slot diffusers at perimeters, delivering air downward, are very popular just now, but they contradict good design principles. (Texas)

•We have tended to use, in many of the different building types, water source heat pump systems employing, where possible, thermal storage. We feel such systems are far more economical to operate in that they have the ability to 1.) heat and cool; 2.) can move heat from areas of excess to areas of need; 3.) are very simple controlwise; 4.) equilment failure doesn't generally impact a total building. (North Dakota)

APPENDIX C

HVAC SYSTEM SELECTION AND SIZING DESIGN TOOL

INTRODUCTION

Through the ages man has built shelters for protection against the harsh elements of nature as well as created an environment conducive to his highest level of performance. Controlling this environment has always been a major concern. When the outside environment was too cold, man would build a fire; when it was too hot, he would seek a body of water. Today we have the ability to control our immediate environment through the use of air-conditioning, and a comfortable environment is considered a necessity if man is expected to operate efficiently. The application of available technology and modern processes and products makes it possible to achieve such a condition.

Traditionally the architect has created the building environment and the engineer has controlled it. Today it can be seen that the more each discipline (architecture and engineering) knows about the other, the more efficiently a building can perform as a totally integrated system. Exposing the architect to the mechanical system selection and sizing process in an early phase of design would allow him to utilize this knowledge in order to arrive at an optimum workable design solution.

It is the purpose of this manual to set forth some general rules-of-thumb as well as estimating procedures for the selection and sizing of HVAC systems for architectural projects. It is intended for preliminary design decisions concerning conventional HVAC systems. The scope does not include any state of the art systems, passive or active solar systems, or large scale power plants, therefore care must be taken in using this method so that final results attained from it are as accurate and helpful as possible.

HVAC SYSTEM TYPES

There are many different HVAC systems and combinations of systems available for use in an architectural design project. It is desirable, then, that the architect have an understanding of the functional performance of these different system types as well as their relative impact on an architectural design project.

All air-conditioning systems basically fall into four major classifications:

1. all-air
2. air-water
3. all-water
4. unitary (refrigerant)

The classification refers to the energy transport medium that is delivered into the conditioned space.

All-air Systems

There are two basic types of all-air systems: single-path and dual-path. In a single-path system the main heating and cooling coils are in a series flow air path using a common duct with air at the same temperature to supply all the terminal outlets. In a dual-path system the coils are in either a parallel or series parallel flow air path. With this system type, the warm and cool air flows can be mixed at the central unit and then travel in a single duct to the conditioned space, or they can travel in two separate parallel ducts to be mixed in a terminal outlet at the conditioned space. These classifications can be broken down as follows:

Single-path systems

- single zone, constant volume
- single zone with reheat, constant volume
- variable volume
- variable volume induction
- variable volume with reheat

Dual-path systems

- dual-duct, constant volume
- dual-duct, variable volume
- two-deck multizone
- three-deck multizone

■ Air-water Systems

In an air-water system, both air and water are delivered to the conditioned space in order to perform the air-conditioning function. In most air-water systems, the heating and cooling is achieved by changing the temperature of the air and/or water to maintain constant control of comfort conditions throughout the year. A major advantage of an air-water system over an all-air system is that less space is required for distribution: most ductwork is replaced by piping.

Air-water systems are generally classified as two-pipe, three-pipe, and four-pipe systems. A two-pipe system employs one supply and one return circuit. In a three-pipe system there are two supply circuits--hot and cold water--and one return circuit. A four-pipe system uses both two supply and two-return circuits. The advantage of a three-pipe system over a two-pipe system is flexibility. A three-pipe system offers simultaneous heating and cooling as well as better control from one zone to another. The advantage of a four-pipe system over a three-pipe system is energy efficiency. In a three-pipe system hot and cold circuits are mixed in the return circuit and separated at the chiller and boiler. In a four-pipe system the two circuits never mix, therefore cool water returns to the chiller and warm water to the boiler, thus using less energy to recondition the water than with a three-pipe layout. Four common types of air-water systems are:

- air-water induction
- fan coil with supplementary air
- radiant panel with supplementing air
- hydronic heat pump with supplementary air

■ All-water Systems

An all-water system conditions a space by circulating water from a central refrigeration or heating plant through coils or panels in terminal units located within the conditioned space. The most common all-water systems that belong to this category are:

- valance units
- baseboard radiation
- fan coil system
- hydronic heat pump system

Unitary Equipment Systems

These systems, often referred to as refrigerant or multiple packaged systems, consist of factory matched refrigerant cycle components for the extraction or addition of heat. These systems are normally located within or near the conditioned space and consist of only those elements essential to the production of heating and cooling. Included in this category are:

- window air-conditioning units
- air-to-air heat pumps
- unit heaters

In general, all HVAC systems, without regard to the system classification, can be categorized as built-up or packaged. "Built-up" refers to equipment in which each component is selected separately and combined to form a complete system. The term "packaged" means it is a factory matched piece of equipment which can be pretested prior to arrival at the job site.

Various applications yield a broad scope of equipment types: outdoor or indoor unitary, central station, multiple units, or split and single systems. Most outdoor applications are roof-top units, central or multiple. Indoor equipment is often located in service areas adjacent to the conditioned space. An overriding question to the architect should be, "Does the system concept fit the architectural concept?" Figure A helps clarify four basic system concepts and should be used to decide if the architectural and system concepts are compatible.

HVAC EQUIPMENT

The types of equipment comprising the HVAC system generally fall into three major sections: refrigeration equipment, heating equipment, and air handling equipment (see Figure B).

In most large air-conditioning applications, a liquid chilling system is utilized. A liquid chiller refrigerates a liquid (usually water) which, in turn, is supplied to cooling coils in air handling units throughout the building. One of these types of chillers may be employed in an air-conditioning system: reciprocating, centrifugal, or absorption. Reciprocating chillers are mostly used for small colling loads; up to approximately 100 tons. Centrifugal chillers are the most common and most versatile. Absorption chillers are used when significant amounts of waste or solar heat are available. These are more common in industrial applications.

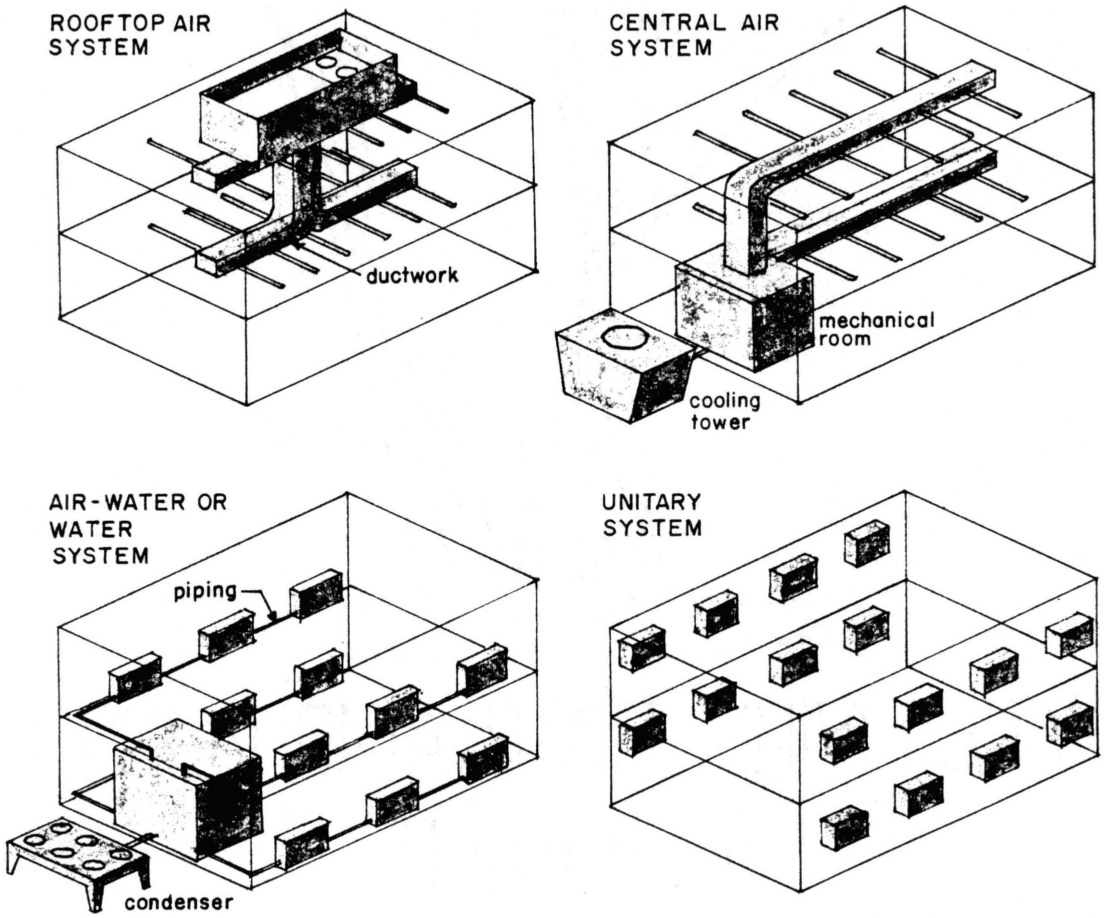


Figure A. Basic System Concepts

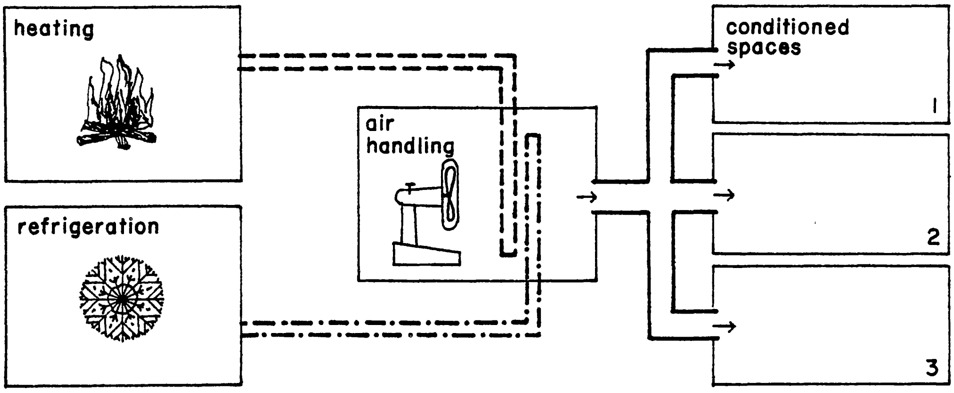


Figure B. Types of HVAC Equipment

The heating system is substantially less complex than the refrigeration system. The major component in a central heating system is the boiler. The boiler heats the water which is supplied to various air handling units throughout the building, as is the chilled water.

Most often the refrigeration and heating equipment are contained in a central mechanical room while fan rooms are dispersed throughout the building which contain air handling units. The number and location of fan rooms is primarily a design decision so long as each room is sufficiently sized to incorporate the air handling equipment. There are several different concepts in the placement of fan rooms. Figure C shows various arrangements for the mechanical and fan rooms. Each arrangement is equally valid but the architect should decide which is optimum for his design.

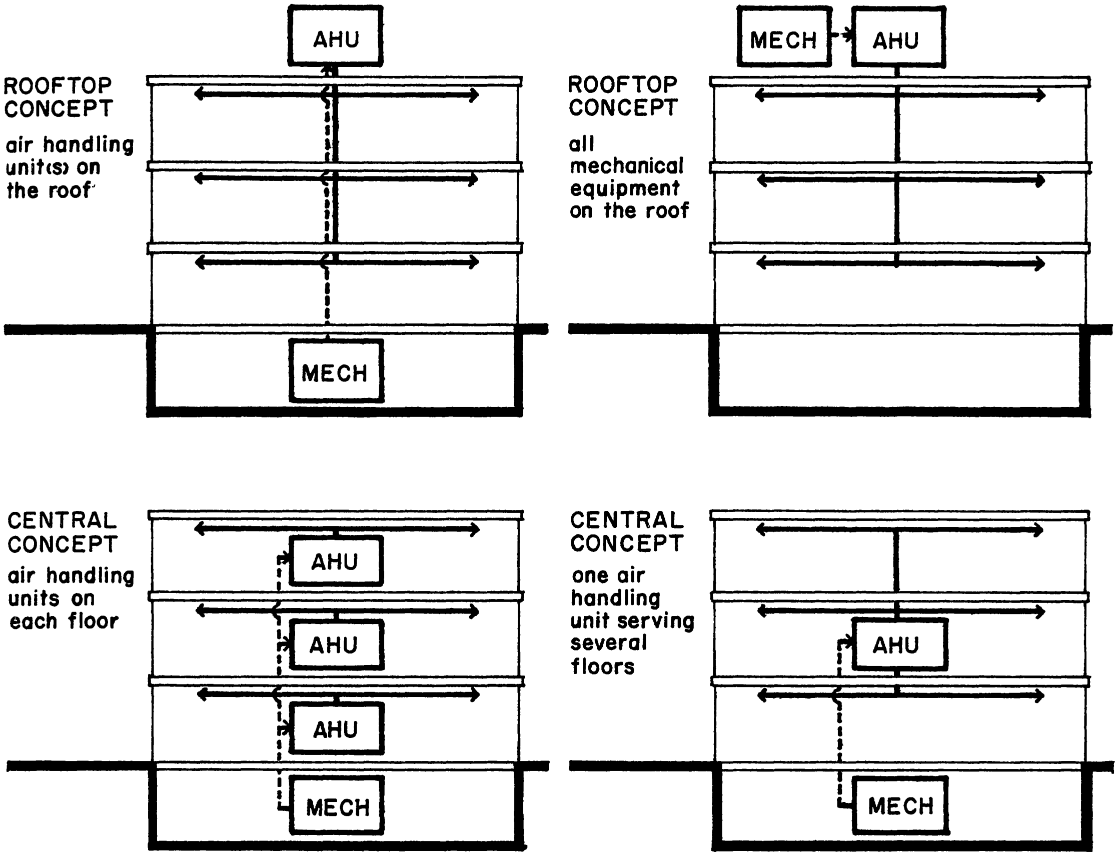


Figure C. Conceptual Arrangements of Mechanical and Fan Rooms

PROGRAMMING PHASE

Rules-of-thumb for system space planning used in the early design phases are often postulated as a function of a building's total floor area. These rules-of-thumb are usually quick and accurate enough for the programming phase.

Main mechanical room:	2% of gross building area
Fan rooms:	2 to 7% of gross building area
Distribution:	Vertical shafts--optimum cross sectional ratio = 2:1 to 4:1 at 0.3 to 0.4% of gross building area.

■ SCHEMATIC DESIGN PHASE

Generally during the schematic design phase more information is known about the project, and from this information more accurate estimates can be made. In order to use this method, the following data must be known:

- Building type ______________________
- Number of stories ______________________
- Gross floor area (sq. ft.) ______________________
- Floor area per story (sq. ft.) ______________________
- Total wall area (sq. ft.) ______________________
- Total roof area (sq. ft.) ______________________
- Perimeter around base (lin. ft.) ______________________
- Location (city) ______________________

■ System Selection

Figure D shows typical systems most used in several different building applications according to a 1984 HVAC system selection survey. The letters along the left hand side of the matrix are building types. They include:

A. Clinic

B. Community Center

C. Gymnasium

D. Hospital

E. Motel

F. Multifamily High Rise

G. Nursing Home

H. Office - Large

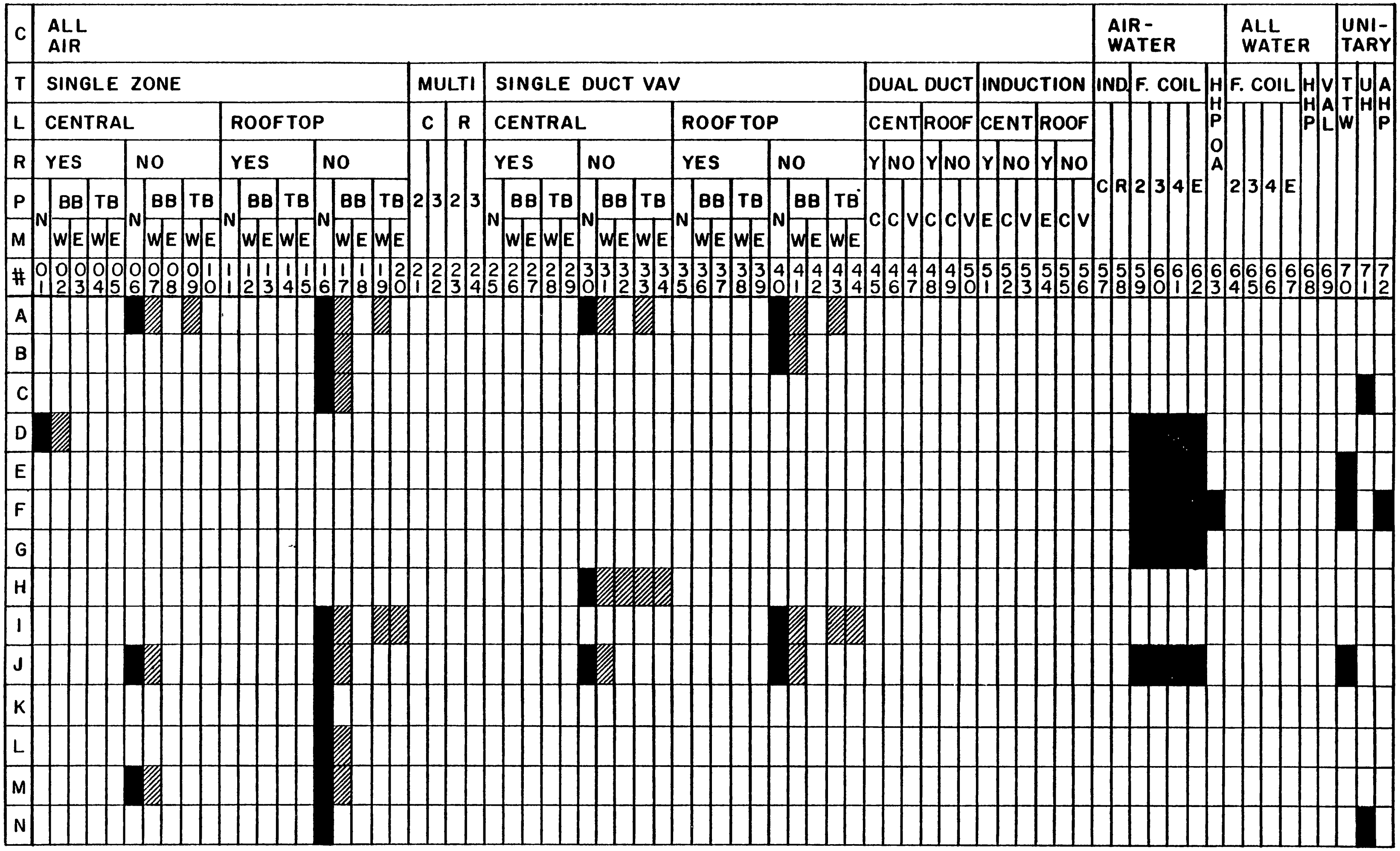


Figure D. System Selection Matrix - Survey Results

I. Office - Small

J. School (Elementary/Secondary)

K. Shopping Center

L. Store

M. Theatre/Auditorium

N. Warehouse.

The system types (along the top) are divided into all-air, air-water, all-water, and unitary. Each classification is in turn divided into subheadings: rooftop or central; with or without reheat; and baseboard or fan powered terminal boxes utilizing water or electric to condition the perimeter zone. Each system specifically, according to number (#), is as follows:

All-air Systems

01 - central single zone/reheat

02 - central single zone/reheat, with hot water baseboard radiation

03 - central single zone/reheat, with electric baseboard radiation

04 - central single zone/reheat, with hot water, fan powered terminal boxes

05 - central single zone/reheat, with electric heat, fan powered terminal boxes

06 through 19 - repeat pattern with and without reheat and central vs. rooftop

21 - central 2-deck multizone

22 - central 3-deck multizone

23 - rooftop 2-deck multizone

24 - rooftop 3-deck multizone

25 through 44 - repeat pattern identical to that of single zone except variable air volume

45 - central system, constant volume dual duct with reheat

46 - central system, constant volume dual duct

47 - central system, variable volume, dual duct

48 through 50 - repeat pattern of 45-47, except rooftop system

51 - central system, induction with electric reheat

52 - central system, induction, constant volume

53 - central system, induction, variable volume

54 through 56 - repeat pattern of 51-53, except rooftop system

Air-water Systems

57 - central system, induction

58 - rooftop system, induction

59 - 2-pipe fan coil system

60 - 3-pipe fan coil system

61 - 4-pipe fan coil system

62 - 2-pipe fan coil with electric heating coil

63 - hydronic heat pump with outside air

All-water Systems

64 through 68 - repeat pattern of 59-63 except no outside air

69 - valance system

Unitary Systems

70 - through-the-wall units

71 - unit heaters

72 - air-to-air heat pumps.

The black squares in the matrix designate the upper 60 percentile of systems selected for that particular application according to the survey and is worth consideration in a comparison method. Single zone and single duct VAV take up the most space in the selection matrix because these systems are the most common and lend themselves to various combinations with other systems. The grey (hatched) boxes indicate contributary systems in the upper 50 percentile that are commonly associated with the single zone and single duct VAV systems. Select as many of these systems as wished to be compared. Rate each of the parameters (a through j) listed below with a relative importance based on 1 to 100, so long as the total adds up to 100. From Figure E, use the numbers in the column of the system selected and multiply them by the relative values. Sum all these values. The system with the highest end result is estimated to be the best suited based on input data. Note that for systems 59 through 68, items c, e, and h have two values. The top value refers to a unit used in the ceiling plenum, and the lower number refers to a unit if it is used in the wall.

	RELATIVE		SYSTEM TYPE			
CATEGORIES	RATING		1	2	3	4
a.) low initial cost	___	x	___	___	___	___
b.) energy conserving	___	x	___	___	___	___
c.) building appearance	___	x	___	___	___	___
d.) system maintainability	___	x	___	___	___	___
e.) minimal space requirements	___	x	___	___	___	___
f.) flexibility	___	x	___	___	___	___
g.) acoustical (low noise)	___	x	___	___	___	___
h.) minimal plenum	___	x	___	___	___	___
i.) durability	___	x	___	___	___	___
j.) thermal comfort	___	x	___	___	___	___
Totals:	100		___	___	___	___

C	ALL AIR																							
T	SINGLE ZONE																				MULTI			
L	CENTRAL										ROOFTOP										C		R	
R	YES					NO					YES					NO								
P	N	BB		TB		N	BB		TB		N	BB		TB		N	BB		TB		2	3	2	3
M		W	E	W	E		W	E	W	E		W	E	W	E		W	E	W	E				
#	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
a	7	6	7	6	7	8	6	7	6	7	7	6	7	6	7	8	6	7	6	7	6	5	7	6
b	8	8	6	7	6	10	10	8	9	8	8	8	6	7	6	10	10	8	9	8	3	3	3	3
c	10	8	8	6	6	10	8	8	6	6	3	3	3	3	3	3	3	3	3	3	10	10	3	3
d	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	10	10	10
e	2	2	2	1	1	2	2	2	1	1	8	8	8	7	7	8	8	8	7	7	3	3	7	7
f	5	3	3	3	3	3	2	2	2	2	5	3	3	3	3	3	2	2	2	2	1	1	1	1
g	8	8	8	6	6	8	8	8	6	6	8	8	8	6	6	8	8	8	6	6	8	8	8	8
h	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2	2
i	10	9	8	9	8	10	9	8	7	8	3	3	3	3	3	3	3	3	3	3	10	10	3	3
j	8	10	10	10	10	6	10	10	10	10	8	10	10	10	10	6	10	10	10	10	10	10	10	10

C	ALL AIR																			
T	SINGLE DUCT VAV																			
L	CENTRAL										ROOFTOP									
R	YES					NO					YES					NO				
P	N	BB		TB		N	BB		TB		N	BB		TB		N	BB		TB	
M		W	E	W	E		W	E	W	E		W	E	W	E		W	E	W	E
#	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
a	5	4	5	4	5	6	4	5	4	5	5	4	5	4	5	6	4	5	4	5
b	8	8	6	7	6	10	10	8	9	8	8	8	6	7	6	10	10	8	9	8
c	10	8	8	6	6	10	8	8	6	6	3	3	3	3	3	3	3	3	3	3
d	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5	10	8	8	5	5
e	2	2	2	1	1	2	2	2	1	1	8	8	8	7	7	8	8	8	7	7
f	7	5	5	5	5	5	4	4	4	4	7	5	5	5	5	5	4	4	4	4
g	7	7	7	5	5	7	7	7	5	5	7	7	7	5	5	7	7	7	5	5
h	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
i	9	8	7	8	7	9	8	7	8	7	3	3	3	3	3	3	3	3	3	3
j	8	10	10	10	10	6	10	10	10	10	8	10	10	10	10	6	10	10	10	10

C	ALL AIR												AIR-WATER							ALL WATER						UNITARY		
T	DUAL DUCT						INDUCTION						IND.		F. COIL				HHPOA	F. COIL				HHP	VAL	TTW	UHH	AHP
L	CENT			ROOF			CENT			ROOF																		
R	Y	NO		Y	NO		Y	NO		Y	NO																	
P													C	R	2	3	4	E		2	3	4	E					
M	C	C	V	C	C	V	E	C	V	E	C	V																
#	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
a	3	3	3	3	3	3	5	4	4	5	4	4	1	1	4	3	2	4	3	5	4	3	5	7	7	10	10	9
b	2	3	3	2	3	3	2	3	3	2	3	3	3	3	3	3	4	2	6	4	4	5	3	6	2	1	1	1
c	10	10	10	3	3	3	6	6	6	3	3	3	6	3	10/1	10/1	10/1	10/1	10/1	10/1	10/1	10/1	10/1	10/1	6	1	1	1
d	10	10	10	10	10	10	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	1	1	1
e	3	3	3	7	7	7	6	6	6	8	8	8	6	8	9/6	9/6	9/6	9/6	9/6	9/7	9/7	9/7	9/7	9/7	9	10	10	10
f	2	1	1	2	1	1	4	3	3	4	3	3	5	5	5	5	5	5	5	7	7	7	7	7	10	10	10	10
g	8	8	7	8	8	7	2	2	2	2	2	2	2	2	4	4	4	4	3	4	4	4	4	3	10	1	1	1
h	1	1	1	1	1	1	7	7	7	7	7	7	8	8	3/8	3/8	3/8	3/8	3/8	3/10	3/10	3/10	3/10	3/10	10	10	10	10
i	10	10	10	3	3	3	6	6	6	3	3	3	6	3	6	6	6	5	6	5	6	6	5	5	10	1	1	1
j	10	10	10	10	10	10	10	10	10	10	10	10	10	10	2	4	5	4	4	2	4	5	4	4	2	4	4	4

Figure E. System Selection Matrix - Weighting Factors

Note that the relative values in the selection matrix are based on an arbitrary rating scale of 1 to 10 for each category. If more is known about the system's proficiency in any of these categories, the numbers may be changed and the procedure then carried out similarly.

■ Load Estimation

Codes and energy standards have been established that regulate the amount of energy expended in various building types. ASHRAE Standard 90 --"Energy Conservation in New Building Design"--set forth some basic criteria for the envelope of a building and its interaction with the outside climate. Through the use of these graphs, it is possible to estimate a building's heating and cooling loads based on climatological influences. U_o (overall U-value) and OTTV (overall thermal transfer value) are the tools used for estimating the design heating load and cooling load, respectively.

From Table 1 find the latitude, winter Δt, and heating degree days (HDD) for the location of the project. If a particular city is not found in this table, other sources should be consulted.

□ Heating Load

- From Graph 1 or 3 find U_o (wall) from HDD:

  Heat loss (walls) =

_____ (U_o) x _______________ (wall area) x ______ Δt = _______________ Btuh

- From Graph 2 or 4 find U_o (roof) from HDD:

  Heat loss (roof) =

_____ (U_o) x _______________ (roof area) x ______ Δt = _______________ Btuh

• From Table 2 find the infiltration/outside air coefficient corresponding to building type:

Heat loss (infilt.) =

_____ (U_o) x _______________ (gross floor area) x ______ Δt = _______________ Btuh

• Heat loss from the slab edge =

0.5 x _______________ (footprint in lin. ft.) x ______ Δt = _______________ Btuh

Total heating load = _______________ Btuh

☐ Cooling Load

• From Graph 5 find OTTV (wall) from latitude:

Cooling load (walls) =

_____ (OTTV) x _______________ (wall area) = _______________ Btuh

• Cooling load (roof) =

8.5 x _______________ (roof area) = _______________ Btuh

• From Table 2 find interior gains corresponding to building type:

Cooling load (interior) =

_____ (int. gain) x _______________ (gross floor area) = _______________ Btuh

Total cooling load = _______________ Btuh

Total ÷ 12,000 = _______________ Tons

☐ Air Quantities

• From Table 2 find CFM per sq. ft. corresponding to building type:

Total CFM =

_____ (CFM/sq. ft.) x _______________ (gross floor area) = _______________ CFM

☐ Space Requirements

Figures F and G show a typical arrangement of a refrigeration room and boiler room.

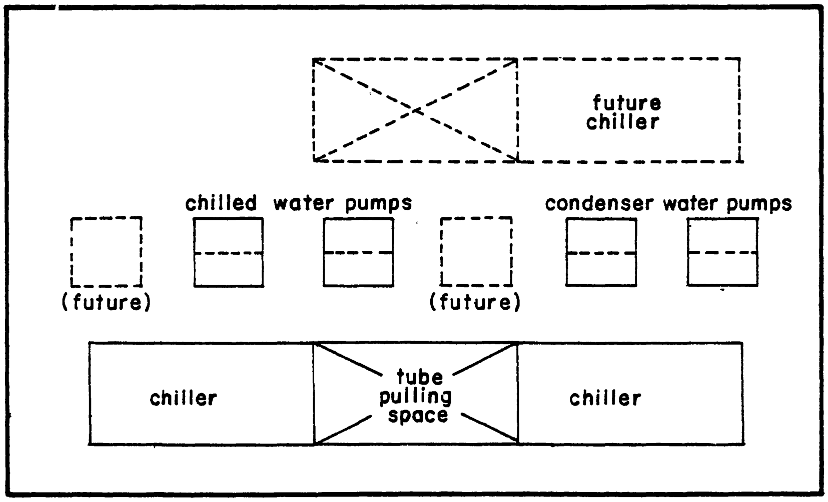


Figure F. Typical Refrigeration Room Layout

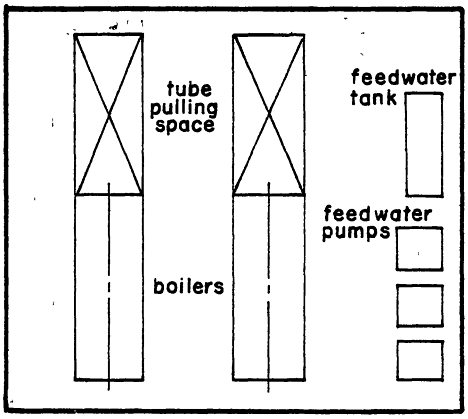


Figure G. Typical Boiler Room Layout

From Graph 6 find boiler room size from total Btuh. From Graph 7 or 8 find the refrigeration room size from total tons. If both boilers and chillers are being utilized in one main mechanical room, the area of the boiler room multiplied by 0.25 may be added to the area of the refrigeration room since some tube pulling spaces may be coordinated to overlap. The length to width ratio of the central mechanical room should be approximately 2.3.

Figure H shows a typical fan room layout. From graph 9 or 10 find the fan room size from total CFM. If more than one fan room is used, divided the total CFM by the number of fan rooms, and size each one separately. Area for vertical shafts or mixing plenums (if fan room is adjacent to an outside wall) is included in fan room size. If rooftop air handling units are used or if an air handling unit is not included on each floor, no space need be allocated for fan rooms, but vertical shafts must be considered. To determine the area for vertical shafts, find area if fan room were used and multiply that area by 0.05 (5%). The approximate room ratio of the fan room should be square.

From graph 11 or 12 find the minimum duct depth from the total CFM supplied to each floor. If more than one fan room per floor is used, divide total CFM by the number of fan rooms (or vertical shafts) and size accordingly. The minimum duct depth helps in sizing the ceiling sandwich. It is based on a single duct system with a return air plenum. It does not consider return air ducts or crossovers that may occur with a dual duct system.

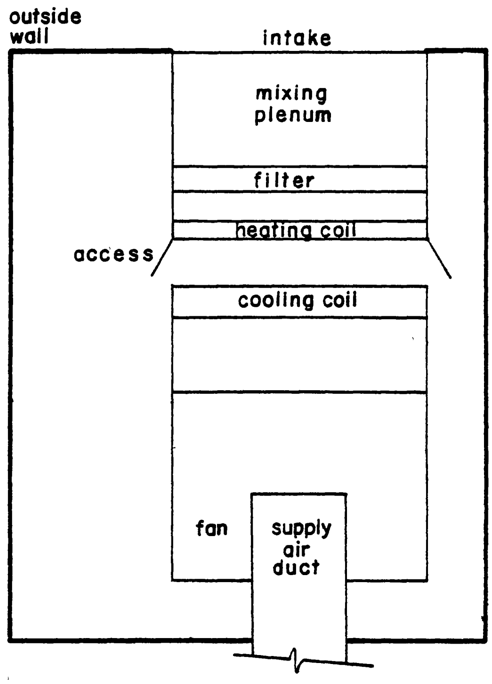
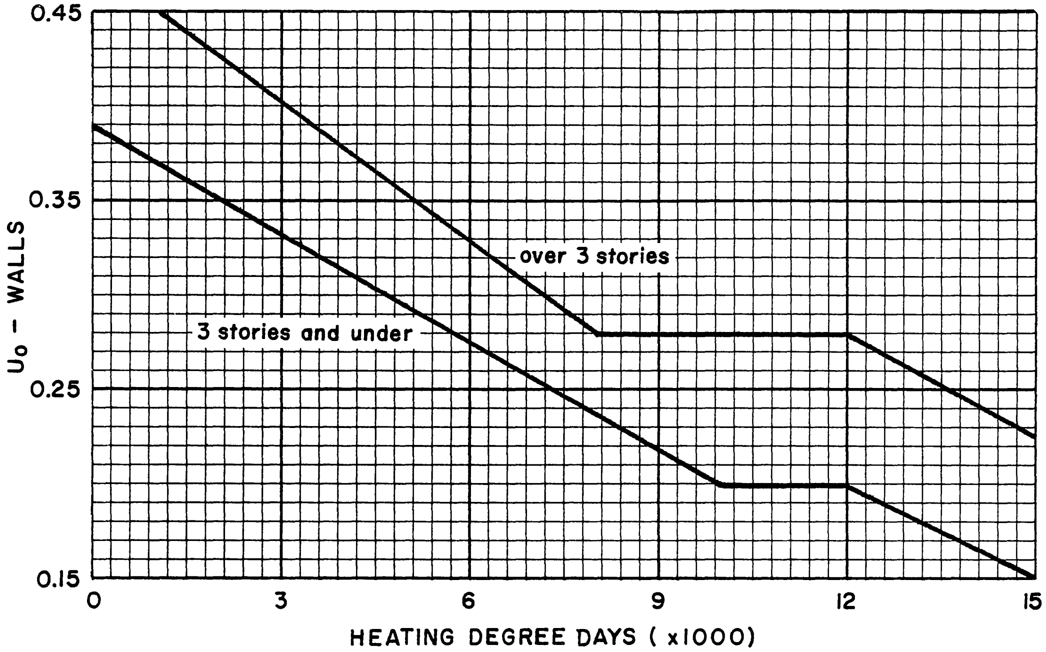
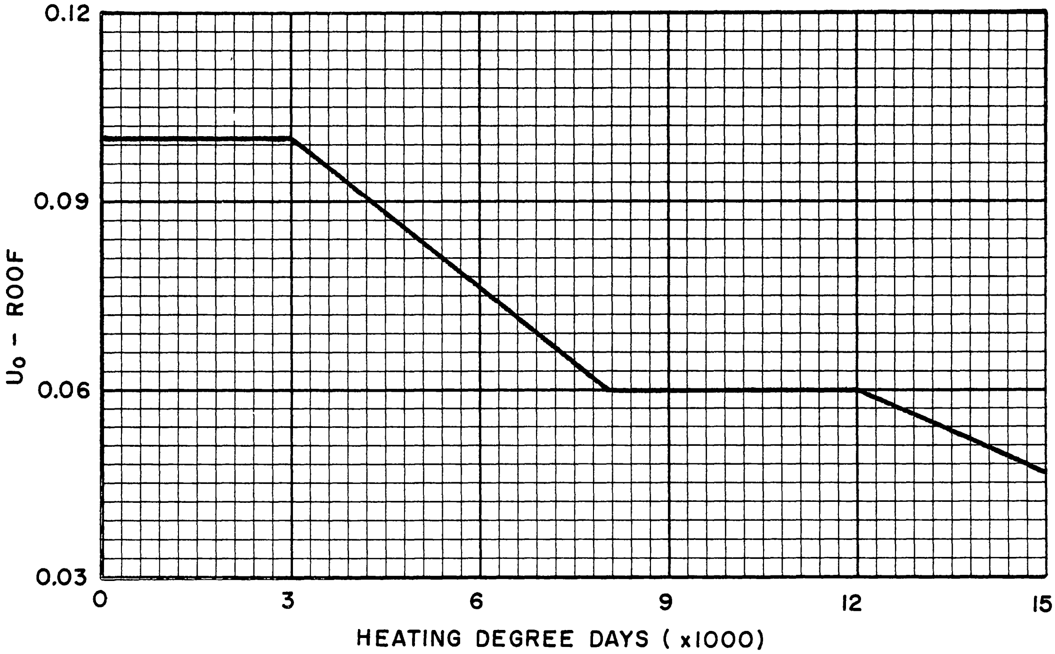


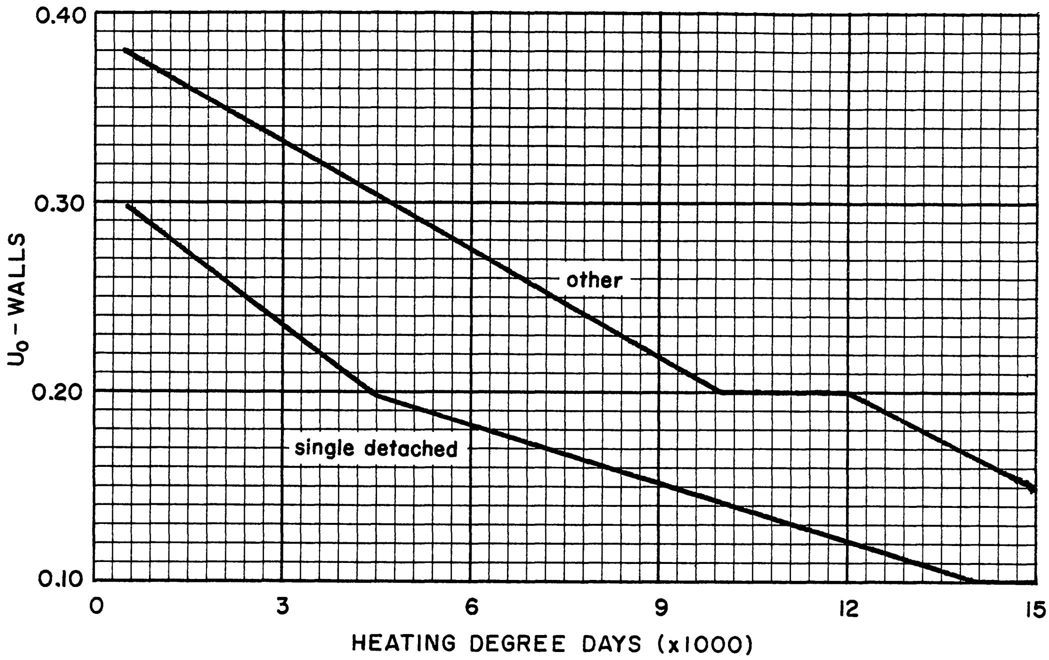
Figure H. Typical Fan Room Layout



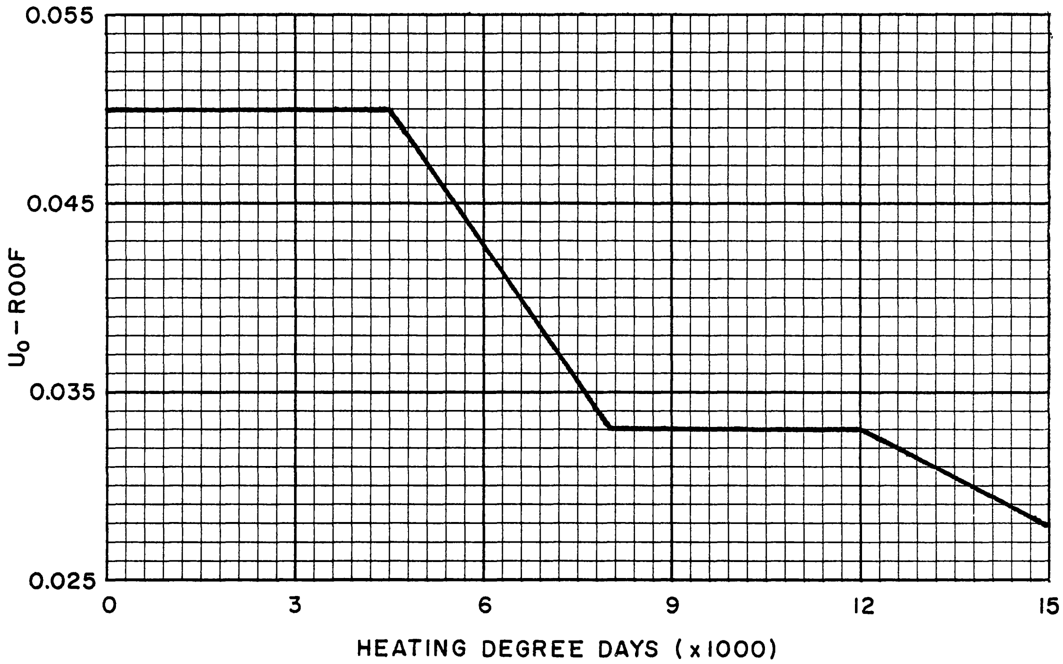
Graph 1. U_o for Walls - Commercial



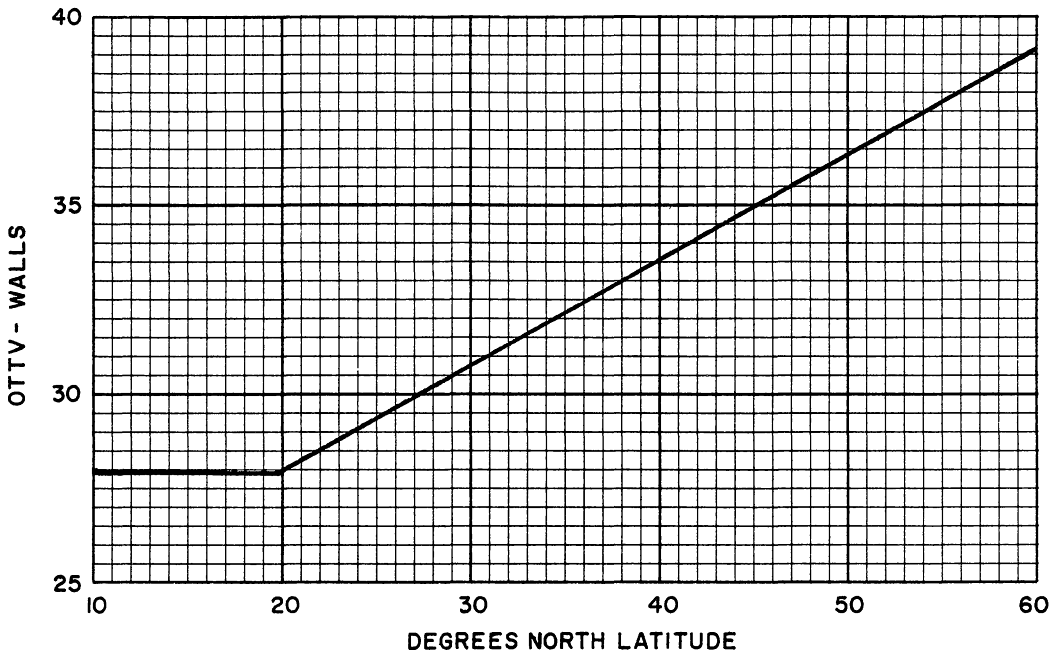
Graph 2. U_o for Roof - Commercial



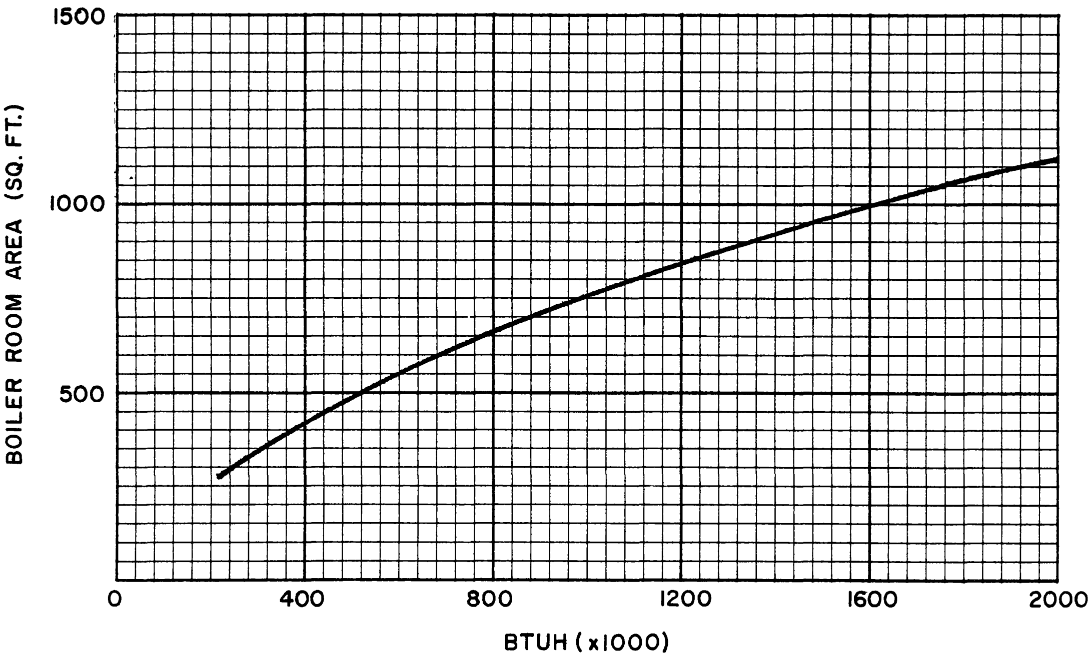
Graph 3. U_o for Walls - Residential



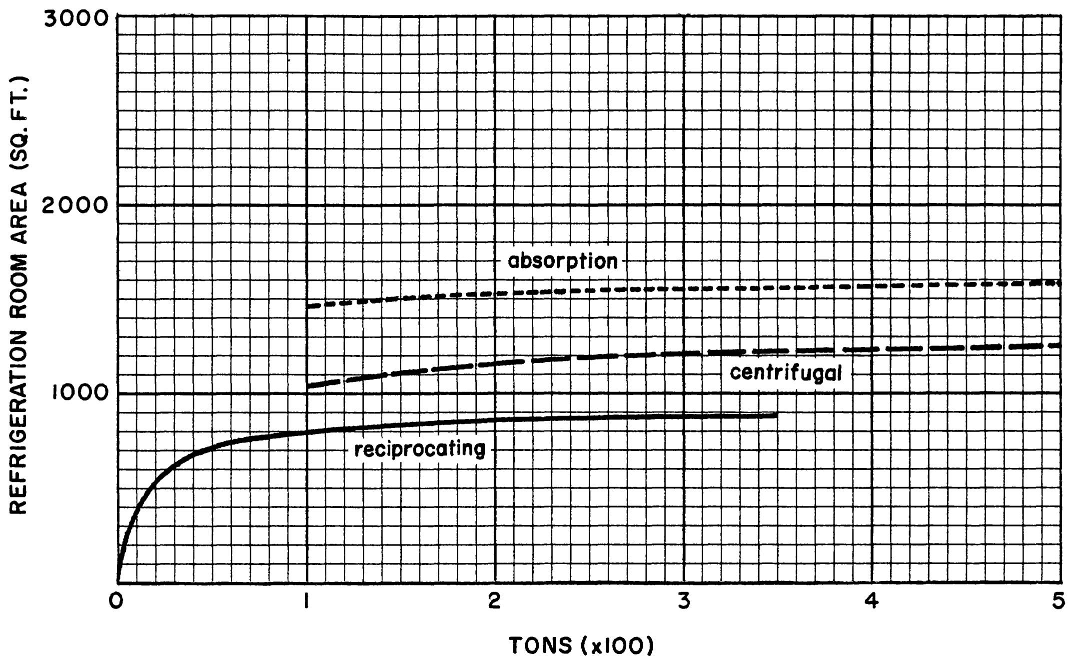
Graph 4. U_o for Roof - Residential



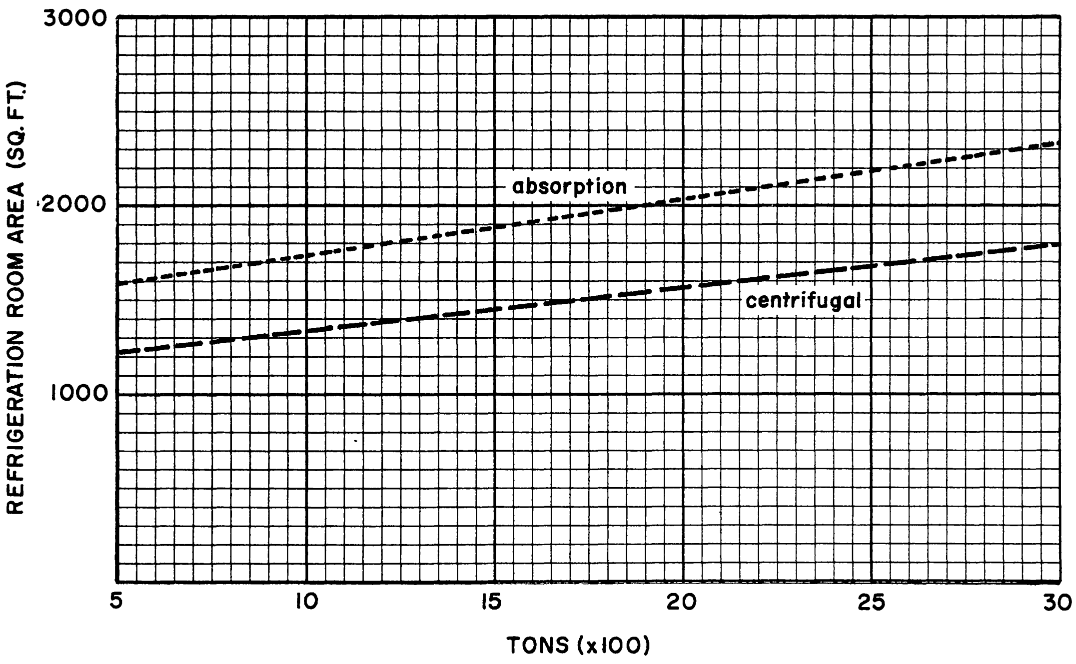
Graph 5. OTTV for Walls



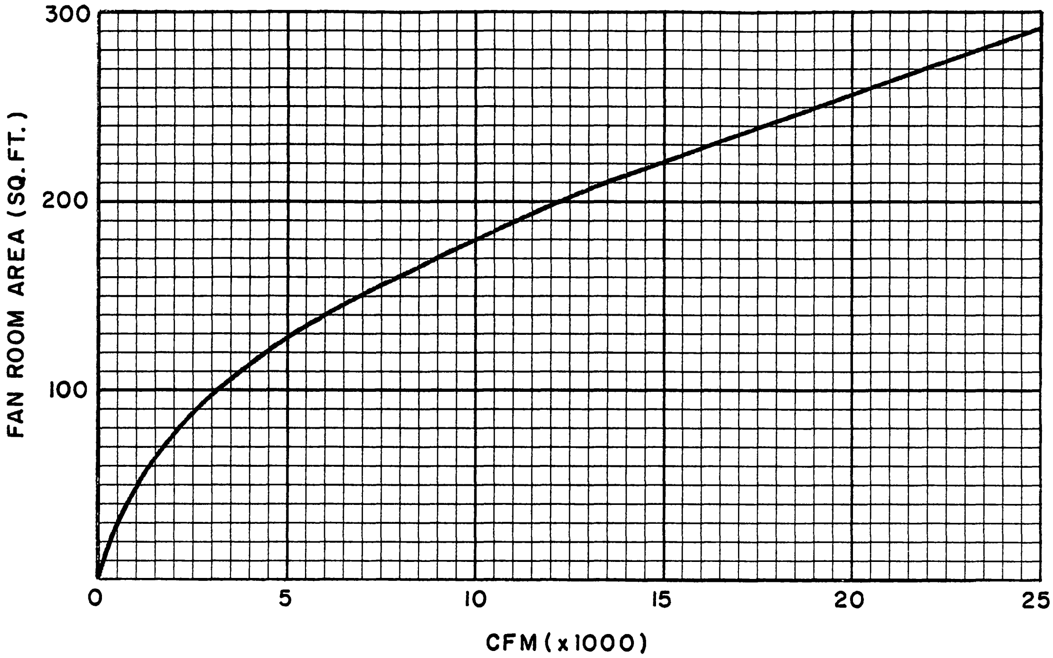
Graph 6. Boiler Room Area as a Function of Heating Load



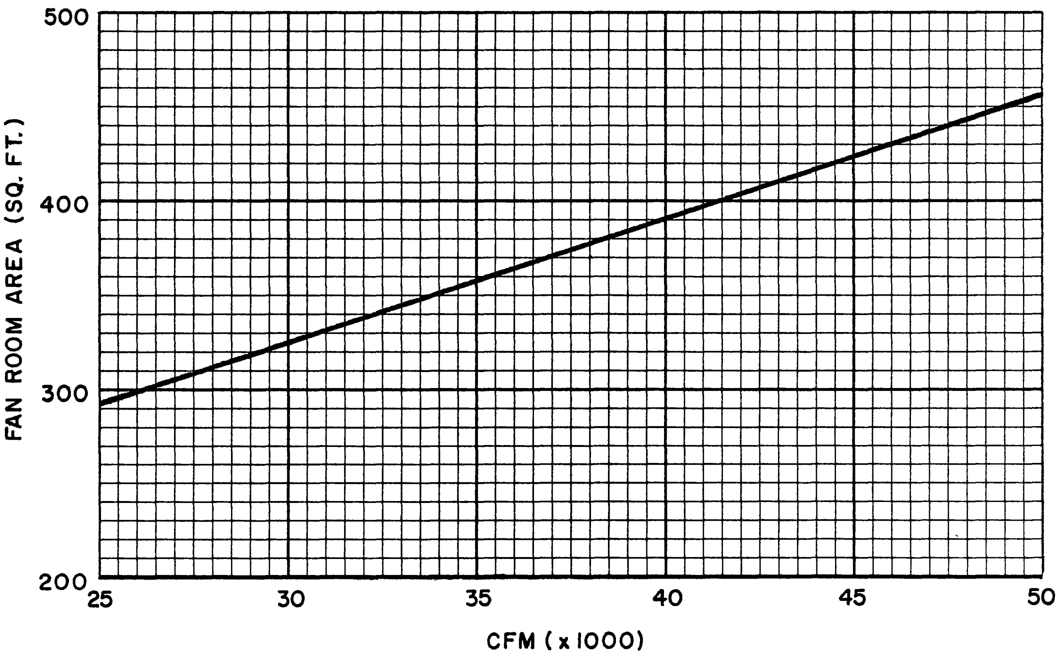
Graph 7. Refrigeration Room Area as a Function of Cooling Load (0-500 tons)



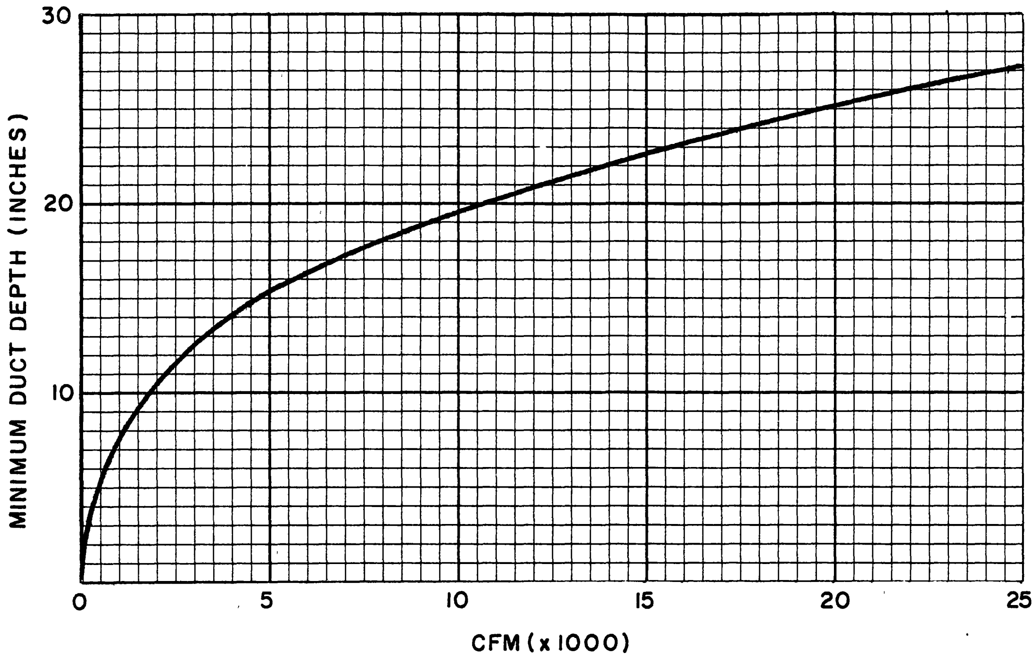
Graph 8. Refrigeration Room Area as a Function of Cooling Load (500-3000 tons)



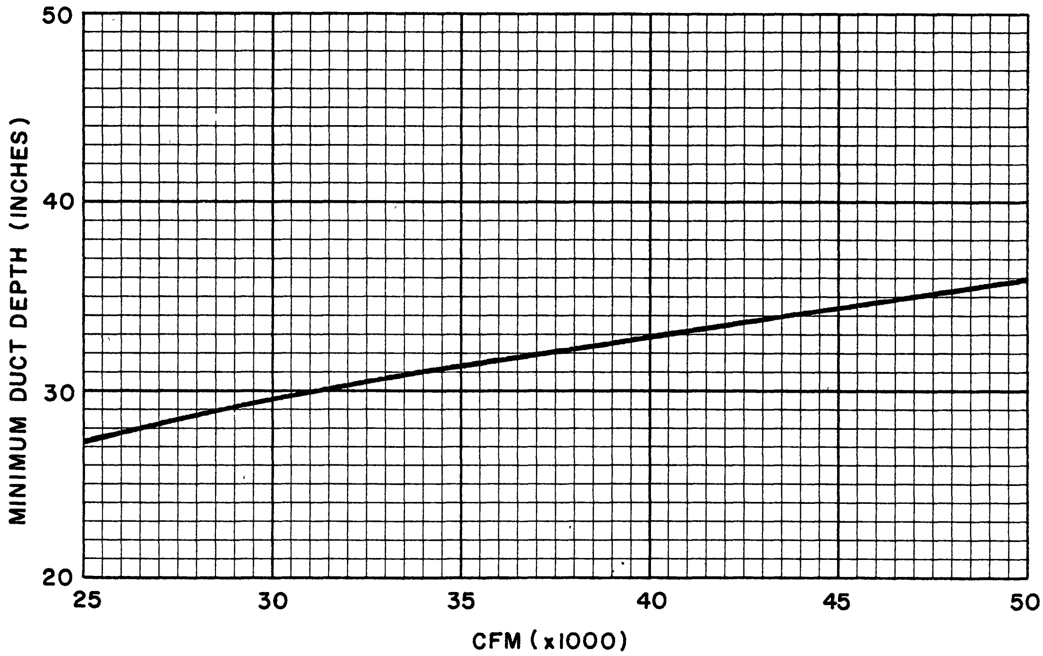
Graph 9. Fan Room Area as a Function of Air Flow Rate (0-25,000 CFM)



Graph 10. Fan Room Area as a Function of Air Flow Rate (25,000-50,000 CFM)



Graph 11. Minimum Duct Depth as a Function of Air Flow Rate (0-25,000 CFM)



Graph 12. Minimum Duct Depth as a Function of Air Flow Rate (25,000-50,000 CFM)

TABLE 1

Location	Latitude	Winter Δt	HDD
Alabama:			
Mobile	31°	41°F	1560
Montgomery	32°	45°F	2291
Alaska:			
Anchorage	61°	88°F	10864
Fairbanks	65°	117°F	14279
Arizona:			
Phoenix	34°	36°F	1765
Tucson	32°	38°F	1800
Arkansas:			
Fort Smith	36°	53°F	3292
Little Rock	35°	50°F	3219
California:			
Los Angeles	34°	27°F	1349
San Francisco	38°	30°F	3001
Colorado:			
Colorado Springs	39°	68°F	6423
Denver	40°	69°F	5524
Connecticut:			
Bridgeport	41°	61°F	5617
New Haven	41°	63°F	5897

TABLE 1 (Continued)

Location	Latitude	Winter Δt	HDD
Delaware:			
Wilmington	40°	56°F	4930
District of Columbia:			
Washington	39°	53°F	4224
Florida:			
Miami	26°	23°F	214
Orlando	29°	32°F	766
Georgia:			
Atlanta	34°	48°F	2961
Savannah	32°	43°F	1819
Hawaii:			
Hilo	20°	0	0
Honolulu	21°	0	0
Idaho:			
Boise	44°	60°F	5809
Pocatello	43°	71°F	7033
Illinois:			
Chicago	42°	74°F	6639
Springfield	40°	68°F	5429

TABLE 1 (Continued)

Location	Latitude	Winter Δt	HDD
Indiana:			
Evansville	38°	61°F	4435
Indianapolis	40°	68°F	5699
Iowa:			
Burlington	41°	73°F	6114
Des Moines	42°	75°F	6588
Kansas:			
Dodge City	38°	65°F	4986
Topeka	39°	66°F	5182
Kentucky:			
Lexington	38°	62°F	4683
Louisville	38°	60°F	4660
Maine:			
Caribou	47°	83°F	9767
Portland	44°	71°F	7511
Maryland:			
Baltimore	39°	53°F	4111
Frederich	40°	58°F	5087
Massachusetts:			
Boston	42°	61°F	5634
Worcester	42°	66°F	6969

TABLE 1 (Continued)

Location	Latitude	Winter Δt	HDD
Michigan:			
Detroit	42°	64°F	6232
Grand Rapids	43°	65°F	6894
Minnesota:			
Duluth	47°	86°F	10000
Minneapolis	45°	82°F	8382
Mississippi:			
Jackson	32°	45°F	2239
Vicksburg	32°	44°F	2041
Missouri:			
Kansas City	39°	64°F	4711
St. Louis	39°	62°F	4484
Montana:			
Billings	46°	80°F	7049
Helena	47°	86°F	8129
Nebraska:			
Lincoln	41°	72°F	5864
Omaha	41°	73°F	6612
Nevada:			
Las Vegas	36°	42°F	2709
Reno	40°	60°F	6332

TABLE 1 (Continued)

Location	Latitude	Winter Δt	HDD
New Hampshire:			
Concord	43°	73°F	7383
New Jersey:			
Atlantic City	40°	57°F	4812
Trenton	40°	56°F	4980
New Mexico:			
Albuquerque	35°	54°F	4348
Raton	37°	69°F	6228
New York:			
Albany	43°	69°F	6201
New York City	41°	55°F	4871
North Carolina:			
Asheville	36°	56°F	4042
Charlotte	35°	48°F	3191
North Dakota:			
Bismark	47°	89°F	8851
Fargo	47°	88°F	9226
Ohio:			
Cincinnati	39°	64°F	4410
Columbus	40°	65°F	5211

TABLE 1 (Continued)

Location	Latitude	Winter Δt	HDD
Oklahoma:			
Oklahoma City	35°	57°F	3725
Tulsa	36°	57°F	3860
Oregon:			
Eugene	44°	48°F	4726
Portland	46°	46°F	4109
Pennsylvania:			
Philadelphia	40°	56°F	4486
Pittsburgh	41°	63°F	5053
Rhode Island:			
Providence	42°	61°F	5954
South Carolina:			
Charleston	33°	42°F	1794
Spartenburg	35°	48°F	2980
South Dakota:			
Rapid City	44°	77°F	7345
Sioux Falls	44°	81°F	7839
Tennessee:			
Memphis	35°	52°F	3015
Nashville	36°	56°F	3578

TABLE 1 (Continued)

Location	Latitude	Winter Δt	HDD
Texas:			
Austin	30°	42°F	1711
Dallas	33°	48°F	2363
Utah:			
Salt Lake City	41°	62°F	6052
Vermont:			
Burlington	45°	77°F	8269
Virginia:			
Norfolk	37°	48°F	3421
Richmond	38°	53°F	3865
Washington:			
Olympia	47°	48°F	5236
Seattle	48°	44°F	4424
West Virginia:			
Charleston	38°	59°F	4476
Huntington	38°	60°F	4446
Wisconsin:			
Green Bay	45°	79°F	8029
Madison	43°	77°F	7863

TABLE 1 (Continued)

Location	Latitude	Winter Δt	HDD
Wyoming:			
Casper	43°	75°F	7410
Cheyenne	41°	71°F	7381

TABLE 2

Building Type	Infiltration and Outside Air Coefficient (Btuh/ft^2•°F)	Interior Gains (Btuh/ft^2)	Supply Air (CFM/ft^2)
Clinic	0.13	17.20	0.9-1.3
Community Center	0.59	75.85	1.3-1.7
Gymnasium	1.66	171.88	1.3-1.7
Hospital	0.36	28.00	1.1-3.0
Motel	0.16	15.08	1.0-1.4
Multifamily High Rise	0.38	16.82	1.0-1.4
Nursing Home	0.16	20.88	0.9-1.3
Office - Large	0.14	23.83	0.7-1.1
Office - Small	0.14	23.83	0.7-1.1
School	0.28	41.50	1.1-1.5
Shopping Center	0.32	33.21	1.6-2.0
Store	0.22	38.11	0.8-1.2
Theatre/Auditorium	1.30	124.58	1.7-2.2
Warehouse	0.46	4.97	0.3-0.7

APPENDIX D

GLOSSARY

Air conditioning - Process of treating air to control simultaneously its temperature, humidity, cleanliness, and distribution to meet the comfort requirements of the occupants of the conditioned space.

Cooling tower - An enclosed device for evaporatively cooling water by contact with air.

Economizer operation - A control sequence of an air supply system that modulates the quantity of outdoor air supplied for the purpose of space conditioning in order to reduce or eliminate the use of refrigeration energy for cooling.

Heating degree day - A unit, based upon temperature, difference and time, used in estimating fuel consumption and specifying nominal heating load of a building in winter.

Latent heat - The heat which must be added or subtracted from a substance to change its state.

Plenum (ceiling) - Space between the hung ceiling and the underside of the floor slab above that is frequently used for returning air back to the air handling unit to reduce sheet metal work.

Sensible heat - The heat which, when added to a substance, changes only its drybulb temperature.

Terminal box - A factory made assembly for air distribution purposes.

Ventilation air - Air that is supplied to or removed from any space by natural or mechanical means. Such air may or may not have been conditioned.

Zone - A space or group of spaces within a building with heating and/or cooling requirements sufficiently similar so that comfort conditions can be maintained throughout by a single controlling device.

VITA

Keith Julian Yancey

Candidate for the Degree of

Master of Architectural Engineering

Thesis: A METHOD OF SELECTING AND SIZING HVAC SYSTEMS FOR THE ARCHITECTURAL PROFESSION

Major Field: Architectural Engineering

Biographical:

Personal Data: Born in Paterson, New Jersey, January 28, 1960, the son of Mr. and Mrs. Jon K. Yancey.

Education: Graduated from Don Bosco Technical High School, Paterson, New Jersey, in May 1978; received the Bachelor of Science in Architectural Studies degree from Oklahoma State University in May, 1982; completed requirements for the Master of Architectural Engineering degree at Oklahoma State University in December, 1984.

Professional Experience: Graduate Teaching Assistant, Oklahoma State University, January 1984 to June 1984; Graduate Research Assistant, Oklahoma State University, August 1983 to December 1983; Graduate Teaching Assistant, Oklahoma State University, August 1982 to May 1983; Engineer's assistant, Lee T. Purcell Associates, Paterson, New Jersey, May 1982 to August 1982.

Professional Organizations: Student Chapter of American Institute of Architects; Student Chapter of the Construction Specifications Institute; student member of the American Society of Heating, Refrigerating, and Air Conditioning Engineers; student member of the National Society of Architectural Engineers.