NAVAL FACILITIES ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4328

Contract Report
CR 95.003

ENERGY SAVINGS ANALYSIS FOR ENERGY MONITORING AND CONTROL SYSTEMS

An Investigation Conducted by

Computer Sciences Corporation
711 Daily Drive
Camarillo, CA 93010-6089

March 1995

[redacted]

Approved for public release, distribution is unlimited

METRIC CONVERSION FACTORS

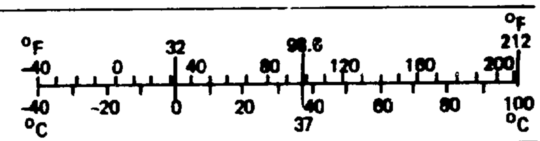
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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13. ABSTRACT *(Maximum 200 words)*

The energy savings analysis report and software was developed to calculate savings when implementing typical energy conservation startegies. The analysis is based on ASHRAE Bin methods. Strategies include: scheduled start/stop, optimized start/stop, and temperature reset.

14. SUBJECT TERMS
Energy savings, energy monitoring and control systems (EMCS), utility control system (UCS), BINs/energy management systems

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Section I. INTRODUCTION

1-1 PLEASE READ THIS FIRST. You should glance through this entire manual before starting any savings calculation. If you must start calculating before reading, at least:

- Become familiar with the Energy Monitoring and Control Systems (EMCS) applications software discussed in Chapter 3, Section II of Energy Monitoring and Control Systems, Technical Manual TM5-815-2/NAVFAC DM-4.09/AFM 88-36.

- Read Appendix A, Variables.

- Read Appendix B, Constants and Conversion Factors.

1-2 PURPOSE. This manual provides methods for estimating energy savings obtainable through the use of EMCS applications programs as described in Chapter 3, Section II of Energy Monitoring and Control Systems. Software known as the Energy Savings Analysis (ESA) program has been developed to largely automate the savings calculation process. This manual should be used in conjunction with the ESA program to provide portions of the input data and to explain the basis for factors and calculations. The manual also aids the user in performing manual calculations when necessary.

The calculations are intended to provide reasonable approximations of savings but not a detailed energy analysis of each building. Best results are obtained by use of energy analysis (simulation) computer programs.

> Note: Simulation programs are required for Optimum Start/Stop and Economizer calculations and provide better accuracy for others.

Twenty-seven typical HVAC systems to which EMCS conservation programs may be applied are shown in Figure 5-1. System schematics and I/O summary tables may be found in the Energy Monitoring and Control Systems manual.

1-3 ARRANGEMENT.

1-3.1 Section I. INTRODUCTION. This section describes the contents of the manual and presents a brief background for EMCS savings calculations.

1-3.2 Section II. FIELD SURVEY DATA COLLECTION. This section describes the field data required for EMCS savings calculations.

1-3.3 Section III. ESA COMPUTER PROGRAM. This section contains the ESA program users manual.

1-3.4 Section IV. FACTOR CALCULATIONS. This section describes the development of climate and building based factors which are required for the savings calculations.

1-3.5 Section V. SAVINGS CALCULATIONS. This section presents the EMCS savings calculations.

1-3.6 Section VI. EXAMPLE SAVINGS CALCULATION. This section provides a complete savings calculation for a hypothetical building using data collected in Section II, factors derived in Section IV, and the methodology of Section V.

1-3.7 Appendix A. DEFINITIONS OF VARIABLES. This appendix contains definitions for the variables used throughout the manual.

1-3.9 Appendix B. CONSTANTS and CONVERSION FACTORS. This appendix contains descriptions of the constants and conversion factors used in the manual and contains brief derivations where applicable.

1-3.10 Appendix C. ASHRAE DATA. Data reproduced, with permission, from ASHRAE Handbooks. Data includes "U" factors, "R" factors, psychrometric chart, and compressor performance values.

1-3.11 Appendix D. ACRONYMS.

1-3.12 Appendix E. REFERENCES.

1-3.13 Appendix F. BLANK DATA INPUT FORMS.

1-4 GENERAL APPROACH. The three methods for energy analysis discussed below are the most widely used.

1-4.1 Bin Weather Data Method. This method uses weather data which is separated in 5 degree increments known as bins. The purpose is to determine, using engineering calculations, the amount of heating or cooling energy that a building will require at any given outdoor temperature. The energy consumption is determined by multiplying the energy requirement at any given temperature by the number of hours at that temperature and summing. This is the least accurate of the three methods but will generally yield acceptable results.

1-4.2 Energy Analysis Computer Programs. These programs fall under a variety of commercial names which are generally known as simulation programs. Most programs perform energy balance calculations hourly over the analysis period, typically one year, and require hourly weather data and hourly estimates of internal loads such as lighting and occupants. They model building systems and conditions while allowing the user to easily do repeated "what if" investigations of alternatives. Output values can vary widely with a 25% difference not being uncommon.

1-4.3 <u>Energy Use Evaluation</u>. Much information can be obtained from building utility records. The quantity and type of data available depend on the type of metering installed. Analyzing this data can allow a precise determination of the quantities of energy used for various purposes in the building. The analysis eliminates the need for estimates and can, therefore, yield accurate results.

1-5 WEATHER DATA SOURCES.

- <u>Engineering Weather Data</u>
  Air Force Manual AFM 88-29
  Army Technical Manual TM 5-785
  Navy Manual NAVFAC P-89

- <u>Bin and Degree Hour Weather Data Software</u>
  Software written in Basic for PC/MS-DOS.
  Available from:

  ASHRAE, Inc.
  Publication Sales
  1791 Tullie Circle NE
  Atlanta, GA 30329-2305

1-6 POINT OF CONTACT. This manual was prepared for the Naval Facilities Engineering Service Center (formerly the Naval Civil Engineering Laboratory), Port Hueneme, California. Comments or requests for additional information should be directed to:

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Section II. DATA

2-1 INTRODUCTION. This section consists of field survey data takeoff sheets and screen data input sheets. Sheets may be duplicated as necessary.

2-1.1 <u>ESA Program Field Survey Data Sheets</u>. These sheets may be used in conjunction with an EMCS feasibility base survey to filter, simplify, and tailor data specifically for use by the ESA program.

2-1.2 <u>ESA Program Screen Data Input Forms</u>. These input forms are copies of the ESA program screens. They may be used as part of the data input process.

> NOTE: Six different input forms (screens) are used for all twenty-seven system types. The strategies listed in the System Strategy Selection and Annual Savings block cover all possibilities for the input form but not all strategies apply to every system. Refer to Figure 5-1 for strategy applications.

ESA Program Field Survey Data Sheets

GROUP

NOTE - UNITS OF MEASURE: Area = ft², Temperature = °F

See Appendix A for explanation of terms.

GROUP DATA

Group Desc ____________________

Location ____________________

Buildings in Group ____________________

Sketch project layout - locations, distances between buildings, important features, etc.

GROUP	BUILDING

BUILDING DATA (1/3)

Building Hours of Operation: 0100-0800 0900-1600 1700-2400 Other ______________

Heating Fuel Type: ____

Sketch Building - Locate Zones, Windows, Doors, etc.

Page ________ of ________

GROUP	BUILDING

BUILDING DATA (2/3)

WALLS, EXTERIOR COMPONENTS	R-VALUES	SKETCH CROSS SECTION
Outside Air Film	______	
1.______	______	
2.______	______	
3.______	______	
4.______	______	
5.______	______	
6.______	______	
7.______	______	
Inside Air Film	______	
TOTAL R VALUE	______	
$1/R = <U_{wall}> =$	______	

ROOF COMPONENTS	R-VALUES	SKETCH CROSS SECTION
Outside Air Film	______	
1.______	______	
2.______	______	
3.______	______	
4.______	______	
5.______	______	
6.______	______	
7.______	______	
Inside Air Film	______	
TOTAL R VALUE	______	
$1/R = <U_{roof}> =$	______	

No. of Floors (above ground) ______	Calculated Total Areas (above ground):
Avg. Floor to Floor Height ______	Walls, gross ______
No. of Basement Levels ______	Windows $<A_{window}>$ ______
Gross Floor Area <Af> ______	Doors $<A_{door}>$ ______
Roof Area $<A_{roof}>$ ______	Other ______
Estimated total bldg. air infiltration (cfm) <I> ______	Walls, net $<A_{wall,\ net}>$ ______

Page ______ of ______

GROUP	BUILDING

BUILDING DATA (3/3)

WINDOW TYPE ______	R-VALUE ______	<U_{window}> ______
WINDOW TYPE ______	R-VALUE ______	<U_{window}> ______
WINDOW TYPE ______	R-VALUE ______	<U_{window}> ______
DOOR TYPE ______	R-VALUE ______	<U_{door}> ______
DOOR TYPE ______	R-VALUE ______	<U_{door}> ______
DOOR TYPE ______	R-VALUE ______	<U_{door}> ______
OTHER ______	R-VALUE ______	<U_{other}> ______
OTHER ______	R-VALUE ______	<U_{other}> ______
OTHER ______	R-VALUE ______	<U_{other}> ______

$$U_oA_o = U_{wall} \times A_{wall,\ net} + U_{window} \times A_{window} + U_{door} \times A_{door} + U_{roof} \times A_{roof}$$

Remarks - Note air leaks, structural damage, broken/defective windows, fit of windows and doors, vents that remain open, etc.

GROUP	BUILDING

ZONE DATA

ZONE ID ____________

Location ____________

Function ____________

Floor Area ____________

Occupied Summer Setpoint <SSP> ____________

Occupied Winter Setpoint <WSP> ____________

Days/Week Heating Equipment Operation <Dh> ______

Days/Week Cooling Equipment Operation <Dc> ______

Systems Serving Zone ____________

Nominal hours/week occupied <OH> ____________

Warmup time before occupancy (hr) <WU> ______

Low Temperature Limit <LTL> ____________

Summer Setpoint Reset <SSPR> ____________

(SSPR ≤ AST-SSP)

Winter Setpoint Reset <WSPR> ____________

(WSPR ≤ WSP-AWT, ≤ WSP-LTL)

SPECIAL REQUIREMENTS

Can ventilation be shut down for duty cycling? (Y/N) ______ For what % time? <DCST> ____________

Can ventilation be shut down for demand limiting? (Y/N) ______ For what % time? <DLST> ____________

Can ventilation be shut down during unoccupied hours? (Y/N) ____________

If yes, what is the required OA purge time before occupancy? <PT> ____________

REMARKS

ZONE DATA

ZONE ID ____________

Location ____________

Function ____________

Floor Area ____________

Occupied Summer Setpoint <SSP> ____________

Occupied Winter Setpoint <WSP> ____________

Days/Week Heating Equipment Operation <Dh> ______

Days/Week Cooling Equipment Operation <Dc> ______

Systems Serving Zone ____________

Nominal hours/week occupied <OH> ____________

Warmup time before occupancy (hr) <WU> ______

Low Temperature Limit <LTL> ____________

Summer Setpoint Reset <SSPR> ____________

(SSPR ≤ AST-SSP)

Winter Setpoint Reset <WSPR> ____________

(WSPR ≤ WSP-AWT, ≤ WSP-LTL)

SPECIAL REQUIREMENTS

Can ventilation be shut down for duty cycling? (Y/N) ______ For what % time? <DCST> ____________

Can ventilation be shut down for demand limiting? (Y/N) ______ For what % time? <DLST> ____________

Can ventilation be shut down during unoccupied hours? (Y/N) ____________

If yes, what is the required OA purge time before occupancy? <PT> ____________

REMARKS

GROUP	BUILDING	SYSTEM

Applicable Systems

A. Single Zone AHU	D. Multi-zone AHU	G. Two Pipe Fan Coil Unit
B. Terminal Reheat AHU	E. Single Zone DX-A/C	H. Four Pipe Fan Coil Unit
C. Variable Volume AHU	F. Multi-zone DX-A/C	

System Desc ________________ Zones Served ________________

Location ________________ Total Area Served <Az> ________________

System Efficiency <HSE> ________________ Unit Supplying Heating Energy ________________

Reheat Coil Reset <RHR> ________________ Heating Energy Fuel Source ________________

Present percent of OA used (decimal) <POA> ________ Unit Supplying Cooling Energy ________________

Energy Used/Ton Refrigeration <CPT> ________ Cooling Energy Fuel Source ________________

CURRENT OPERATING SCHEDULE	PROPOSED OPERATING SCHEDULE
Hours/Week Heating System <Hh> ________	Hours/Week Heating System <HhEMCS> ________
Hours/Week at WSP <Hwsp> ________	Hours/Week Cooling System <HcEMCS> ________
Hours/Week Cooling System <Hc> ________	Can system be shut down when
Hours/Week at SSP <Hssp> ________	zone(s) unoccupied? (Y/N) ________

FAN DATA			PUMP DATA		AUX DATA	
Function	<CFM>	<HP>	Function	<HP>	Function	<HP>
Supply Air						
Return Air						

MULTI-ZONE DATA

Percent of air passing through Hot Deck <Phd> ______ Summer Hot Deck Reset <SHDR> ________

Percent of air passing through Cold Deck <Pcd> ______ Winter Hot Deck Reset <WHDR> ________

Operating Hours/Week Dual Deck <Hhc> ________ Summer Cold Deck Reset <SCDR> ________

MAX/MIN ZONE DATA			
	<WSP> ________	<SSP> ________	<WU> ________
	<LTL> ________	<WSPR> ________	<Dh> ________
	<OH> ________	<SSPR> ________	<Dc> ________
	<DCST> ________	<LLST> ________	<PT> ________

Page ________ of ________

GROUP	BUILDING	SYSTEM

Applicable Systems

I. Electric Unit Heater	M. Direct Fired Boiler	Q. Hot Water Radiation
J. Electric Radiation	N. Steam Unit Heater	U. HTHW/Steam Converter
K. Heating/Ventilating Unit	O. Hot Water Unit Heater	V. HTHW/HW Convertor
L. Direct Fired Furnace	P. Steam Radiation	

System Desc ____________________

Location ____________________

Electric Heater Power Rating (Kw) <PWR> ________

System Efficiency <HSE> ____________

Present percent of OA used (decimal) <POA> ______

Zones Served ____________________

Total Area Served <Az> ____________

Unit Supplying Heating Energy ____________

Heating Energy Fuel Source ____________

Max Total Input Rating (Btu/hr) <CAP> ________

Heating system Efficiency Increase <OAEI> ______

CURRENT OPERATING SCHEDULE

Hours/Week Heating System <Hh> ________

Hours/Week at WSP <Hwsp> ________

PROPOSED OPERATING SCHEDULE

Hours/Week Heating System <HhEMCS> ______

FAN DATA Function	<CFM>	<HP>	PUMP DATA Function	<HP>	AUX DATA Function	<HP>
Supply Air						
Return Air						

MAX/MIN ZONE DATA			
	<WSP> ______	<OH> ______	<WU> ______
	<LTL> ______	<WSPR> ______	<Dh> ______
	<DCST> ______	<DLST> ______	

REMARKS

Page ________ of ________

GROUP	BUILDING	SYSTEM

Applicable Systems

R. Steam Boiler	S. Hot Water Boiler

System Desc ______ Zones Served ______

Location ______ Heating Energy Fuel Type ______

Efficiency Increase Max Total Capacity (Btu/hr) <CAP> ______

when Changing Boilers <BCEI> ______ Heating system Efficiency Increase <OAEI> ______

System Availability (days/year) ______ System Efficiency <HSE> ______

REMARKS

GROUP	BUILDING	SYSTEM

Applicable Systems

W. Water Cooled DX Compressor
X. Air Cooled DX Compressor
Y. Air Cooled Chiller
Z. Water Cooled Chiller

System Desc ______
Location ______
Chiller Type: (1) Centrifugal (2) Absorption (3) Reciprocal (4) Screw Comp
Centrifugal Chiller Motor HP <CHP> ______
Centrifugal Chiller Motor Efficiency <CME> ______
System Availability (days/year) ______
Zones Served ______
Energy Used/Ton Refrigeration <CPT> ______
Chiller Capacity (tons) <TON> ______
Present Condenser Water Temperature <PCWT> ______
Is the condenser fan continuous or cycling? ______
Chiller water temperature reset <CWTR> ______

Efficiency increase when changing chillers <CSEI> ______
Can the centrifugal chiller be shut down for demand limiting? (Y/N) ______ For what % time? <SDT> ______
Can the centrifugal chiller capacity be stepped down for demand limiting? (Y/N) ______ By what %? <SDC> ______

CURRENT OPERATING SCHEDULE
Hours/Week Cooling System <Hc> ______

PROPOSED OPERATING SCHEDULE
Hours/Week Cooling System <HcEMCS> ______

FAN DATA Function	<HP>	PUMP DATA Function	<HP>

REMARKS

Page ______ of ______

GROUP	BUILDING	SYSTEM

Applicable Systems

AA. Lighting Control

System Desc ______________________ Zones Served ______________________

Location ______________________ Total Wattage <TC_L> ______________________

CURRENT OPERATING SCHEDULE

Hours/Week Lighting System <H_L> ____________

PROPOSED OPERATING SCHEDULE

Hours/Week Lighting System <H_LEMCS> ____________

REMARKS

GROUP	BUILDING	SYSTEM

PROJECT REMARKS

ESA Program Screen Data Input Forms

GROUP	BUILDING

Climate

Variable Description	Symbol	Value	Units
Avg Entering Condenser Water Temperature	ACWT	________	°F
Annual Number of Days for Morning Warmup	ANDW	________	days/year
Average Summer Temperature	AST	________	°F
Average Winter Temperature	AWT	________	°F
Cooling Full-Load Hours	CFLH	________	hrs/year
Heating Full-Load Hours	HFLH	________	hrs/year
Weeks of Cooling	WKC	________	wks/year
Weeks of Heating	WKH	________	wks/year
Average Outside Air Enthalpy	OAE	________	Btu/lb
Percent Run Time	PRT	________	percent

Building

[ ] Check here if Chiller uses steam.

Heating Fuel Type: ** choice list

Variable Description	Symbol	Value	Units
Heating Value of Fuel	HV	________	Btu/________
Mod Comb Thermal Transmittance	UoAo	________	Btu/hr•°F
Total Air Infiltration	I	________	cfm
Gross Floor Area	Af	________	ft²
Building Thermal Transmission	BTT	***	Btu/hr•ft²•°F

** Heating Fuel Type:

Electricity (at the meter)	3413 Btu/kWh
Electricity (at point of generation)	11,600 Btu/kWh
Fuel oil, distillate #2	138,690 Btu/gallon
Fuel oil, residual #6	149,690 Btu/gallon
Natural gas (methane)	1,025 Btu/cf
Propane, gas	2500 Btu/cf
Propane, liquid	91,500 Btu/gallon
Bituminous coal	26,260,000 Btu/short ton
Steam (at point of consumption)	1000 Btu/lb
Steam (at point of generation)	1390 Btu/lb

*** BTT is calculated by the program.

Page ________ of ________

GROUP	BUILDING	SYSTEM

Applicable Systems

A. Single Zone AHU	D. Multi-zone AHU	G. Two Pipe Fan Coil Unit
B. Terminal Reheat AHU	E. Single Zone DX-A/C	H. Four Pipe Fan Coil Unit
C. Variable Volume AHU	F. Multi-zone DX-A/C	

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Area of zone	Az	______	ft²
Winter thermostat setpoint, occupied	WSP	______	°F
Low temperature limit	LTL	______	°F
Heating operation without EMCS	Hh	______	hours/week
Heating operation with EMCS	HhEMCS	______	hours/week
Heating system efficiency	HSE	______	decimal
Summer thermostat setpoint, occupied	SSP	______	°F
Return air enthalpy when unoccupied	RAE	______	Btu/lb
Cooling operation without EMCS	Hc	______	hours/week
Cooling operation with EMCS	HcEMCS	______	hours/week
Cooling energy consumption per ton	CPT	______	****
Supply air capacity	CFM	______	cfm
Present fraction of outside air used	POA	______	decimal
Equipment motor horsepower	HP	______	hp
Equipment motor load factor	L	______	decimal
Zone occupied hours	OH	______	hours/week
Duty cycling shutdown time	DCST	______	percent
Demand limiting shed time	DLST	______	percent
Winter thermostat setpoint reset	WSPR	______	°F
Winter setpoint equipment operation	Hwsp	______	hours/week
Summer thermostat setpoint reset	SSPR	______	°F
Summer setpoint equipment operation	Hssp	______	hours/week

**** kW/ton or lb-ton/hr

Page ________ of ________

GROUP	BUILDING	SYSTEM

Applicable Systems

A. Single Zone AHU	D. Multi-zone AHU	G. Two Pipe Fan Coil Unit
B. Terminal Reheat AHU	E. Single Zone DX-A/C	H. Four Pipe Fan Coil Unit
C. Variable Volume AHU	F. Multi-zone DX-A/C	

System Data Entry (continued)

Shutdown system when bldg unoccupied?		______	Y or N
Present warmup time before occupancy	WU	______	hours/day
Heating equipment operating schedule	Dh	______	days/week
Cooling equipment operating schedule	Dc	______	°F
Purge time before occupancy	PT	______	°F
Fraction of total air thru hot deck	Phd	______	decimal
Hot/cold deck equipment operation	Hhc	______	hours/week
Summer hot deck reset	SHDR	______	°F
Winter hot deck reset	WHDR	______	°F
Fraction of total air thru cold deck	Pcd	______	decimal
Summer cold deck reset	SCDR	______	°F
Reheat cooling coil discharge reset	RHR	______	°F
Optimum start/stop heating savings		______	MBtu
Optimum start/stop htg-vent savings		______	MBtu
Optimum start/stop htg aux savings		______	kWh
Optimum start/stop cooling savings		______	MBtu or kWh
Optimum start/stop clg-vent savings		______	MBtu or kWh
Optimum start/stop clg aux savings		______	kWh
Economizer cooling savings		______	MBtu or kWh

Page ________ of ________

GROUP	BUILDING	SYSTEM

Applicable Systems

A. Single Zone AHU	D. Multi-zone AHU	G. Two Pipe Fan Coil Unit
B. Terminal Reheat AHU	E. Single Zone DX-A/C	H. Four Pipe Fan Coil Unit
C. Variable Volume AHU	F. Multi-zone DX-A/C	

System Data Entry (continued)

Scheduled start/stop labor savings		______	mh
Optimum start/stop labor savings		______	mh
Duty cycling labor savings		______	mh
Demand limiting labor savings		______	mh
Day/night setback labor savings		______	mh
Economizer labor savings		______	mh
Vent/recirc labor savings		______	mh
Hot deck/cold deck labor savings		______	mh
Reheat coil labor savings		______	mh
Run time recording labor savings		______	mh
Safety alarm labor savings		______	mh

System Strategy Selection and Annual Savings

[ ] Scheduled Start/Stop	[ ] Run Time Recording
[ ] Optimum Start/Stop	[ ] Safety Alarm
[ ] Duty Cycling	
[ ] Demand Limiting	
[ ] Day/Night Setback	
[ ] Economizer	
[ ] Ventilation/Recirculation	
[ ] Hot/Cold Deck Reset	
[ ] Reheat Coil Reset	

GROUP	BUILDING	SYSTEM

Applicable Systems

I. Electric Unit Heater	L. Direct Fired Furnace	T. Steam/Hot Water Converter
J. Electric Radiation	M. Direct Fired Boiler	V. HTHW/Hot Water Converter
K. Heating/Ventilating Unit	Q. Hot Water Radiation	

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Area of zone	Az	______	ft^2
Winter thermostat setpoint, occupied	WSP	______	°F
Low temperature limit	LTL	______	°F
Heating operation without EMCS	Hh	______	hours/week
Heating operation with EMCS	HhEMCS	______	hours/week
Heating system efficiency	HSE	______	decimal
Supply air capacity	CFM	______	cfm
Present fraction of outside air used	POA	______	decimal
Equipment motor horsepower	HP	______	hp
Equipment motor load factor	L	______	decimal
Zone occupied hours	OH	______	hours/week
Power rating of resistance unit	PWR	______	Kw
Duty cycling shutdown time	DCST	______	percent
Demand limiting shed time	DLST	______	percent
Winter thermostat setpoint reset	WSPR	______	°F
Winter setpoint equipment operation	Hwsp	______	hours/week
Shutdown system when bldg unoccupied?		______	Y or N
Present warmup time before occupancy	WU	______	hours/day
Heating equipment operating schedule	Dh	______	days/week
Purge time before occupancy	PT	______	minutes
Total input rating of boilers	CAP	______	Btu/hr
Heating system efficiency increase	OAEI	______	decimal

Page ________ of ________

GROUP	BUILDING	SYSTEM

Applicable Systems

I. Electric Unit Heater	L. Direct Fired Furnace	T. Steam/Hot Water Converter
J. Electric Radiation	M. Direct Fired Boiler	V. HTHW/Hot Water Converter
K. Heating/Ventilating Unit	Q. Hot Water Radiation	

System Data Entry (continued)

Optimum start/stop cooling savings		______	MBtu or kWh
Optimum start/stop clg-vent savings		______	MBtu or kWh
Optimum start/stop clg aux savings		______	kWh
Scheduled start/stop labor savings		______	mh
Optimum start/stop labor savings		______	mh
Duty cycling labor savings		______	mh
Demand limiting labor savings		______	mh
Day/night setback labor savings		______	mh
Vent/recirc labor savings		______	mh
HW outside air reset labor savings		______	mh
Run time recording labor savings		______	mh
Safety alarm labor savings		______	mh

System Strategy Selection and Annual Savings

[ ] Scheduled Start/Stop [ ] Optimum Start/Stop [ ] Duty Cycling [ ] Demand Limiting [ ] Day/Night Setback [ ] Ventilation/Recirculation [ ] HW OA Reset [ ] Run Time Recording [ ] Safety Alarm	

GROUP	BUILDING	SYSTEM

Applicable Systems

N. Steam Unit Heater	P. Steam Radiation
O. Hot Water Unit Heater	U. HTHW/Steam Converter

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Area of zone	Az	______	ft²
Winter thermostat setpoint, occupied	WSP	______	°F
Low temperature limit	LTL	______	°F
Winter thermostat set point reset	WSPR	______	°F
Winter setpoint equipment operation	Hwsp	______	hours/week
Heating system efficiency	HSE	______	decimal
Day/night setback labor savings		______	mh
Run time recording labor savings		______	mh
Safety alarm labor savings		______	mh

System Strategy Selection and Annual Savings

[ ] Day/Night Setback [ ] Run Time Recording [ ] Safety Alarm	

GROUP	BUILDING	SYSTEM

Applicable Systems

R. Steam Boiler	S. Hot Water Boiler

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Heating system efficiency	HSE	______	decimal
Total input rating of boilers	CAP	______	Btu/hr
Boiler conversion efficiency increase	BCEI	______	decimal
Heating system efficiency increase	OAEI	______	decimal
Steam boiler selection labor savings		______	mh
HW boiler selection labor savings		______	mh
HW Outside air reset labor savings		______	mh
Run time recording labor savings		______	mh
Safety alarm labor savings		______	mh

System Strategy Selection and Annual Savings

[ ] Steam Boiler Selection [ ] HW Boiler Selection [ ] HW OA Reset [ ] Run Time Recording [ ] Safety Alarm	

GROUP	BUILDING	SYSTEM

Applicable Systems

W. Water Cooled DX Compressor	Y. Air Cooled Chiller
X. Air Cooled DX Compressor	Z. Water Cooled Chiller

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Cooling operation without EMCS	Hc	______	hours/week
Cooling operation with EMCS	HcEMCS	______	hours/week
Cooling energy consumption per ton	CPT	______	**
Equipment motor horsepower	HP	______	hp
Equipment motor load factor	L	______	decimal
Zone occupied hours	OH	______	hours/wk
Duty cycling shutdown time	DCST	______	percent
Demand limiting shed time	DLST	______	percent
Total capacity of chillers	TON	______	tons
Chiller selection efficiency increase	CSEI	______	percent
Chiller water temperature reset	CWTR	______	°F
Chiller type		______	choice list ***
Present condenser water temperature	PCWT	______	°F
Present fan operation		______	choice list ****
Centrifugal chiller motor horsepower	CHP	______	hp
Centrifugal chiller motor efficiency	CME	______	decimal
Step down percent of capacity	SDC	______	percent
Step down percent of time	SDT	______	percent
Optimum start/stop cooling savings		______	MBtu or kWh
Optimum start/stop clg-vent savings		______	MBtu or kWh
Optimum start/stop clg aux savings		______	kWh

** kW/ton or lb-ton/hr

*** Chiller types: (1) Centrifugal (2) Absorbtion (3) Reciprocal (4) Screw Comp

**** Present fan operation (1) Fan now cycles (0) Fan now runs continuously, but will cycle

GROUP	BUILDING	SYSTEM

Applicable Systems

W. Water Cooled DX Compressor	Y. Air Cooled Chiller
X. Air Cooled DX Compressor	Z. Water Cooled Chiller

System Data Entry (continued)

Scheduled start/stop labor savings		______	mh
Optimum start/stop labor savings		______	mh
Duty cycling labor savings		______	mh
Demand limiting labor savings		______	mh
Chiller selection labor savings		______	mh
Chiller water reset labor savings		______	mh
Condenser water reset labor savings		______	mh
Chiller demand limit labor savings		______	mh
Run time recording labor savings		______	mh
Safety alarm labor savings		______	mh

System Strategy Selection and Annual Savings

[ ] Scheduled Start/Stop	
[ ] Optimum Start/Stop	
[ ] Duty Cycling	
[ ] Demand Limiting	
[ ] Chiller Selection	
[ ] Chiller Water Temp Reset	
[ ] Condenser Water Temp Reset	
[ ] Chiller Demand Limit	
[ ] Run Time Recording	[ ] Safety Alarm

GROUP	BUILDING	SYSTEM

Applicable Systems

AA. Lighting Control

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Total power consumption of lights	TCl	______	kW
Lighting operation without EMCS	HI	______	hours/week
Lighting operation with EMCS	HIEMCS	______	hours/week
Lighting control labor savings		______	mh
Run time recording labor savings		______	mh
Safety alarm labor savings		______	mh

System Strategy Selection and Annual Savings

[ ] Lighting Control [ ] Run Time Recording [ ] Sa[illegible]y Alarm	

Section III. ESA COMPUTER PROGRAM

3-1 INTRODUCTION. The Energy Savings Analysis (ESA) computer program largely automates the procedures outlined in the Energy Monitoring and Control Systems Savings Manual. The program requires minimal computer knowledge and is designed to guide the user while not suppressing creativity.

ESA is, for the most part, designed to work without referencing the manual; HOWEVER, the manual does have additional information and may be of great help if problems are encountered. Context-sensitive help is available within the program by pressing F1 at any point. This help supplements the brief function description shown at the bottom of the screen.

Several files can be customized by the user to meet individual requirements. See paragraph 3-5.

3-2 PACKING LIST. The following files are included on the ESA program distribution disk:

CLIMATE .100	Climate data. See paragraph 3-5.1.
DEFAULTS.100	Program data non-zero defaults. See paragraph 3-5.2.
ESA .BAT	Batch file which may be used to start the program.
ESACL .100	Choice list file. See paragraph 3-5.3.
ESAHELP .100	Help file. See paragraph 3-5.4.
ESA100 .EXE	Main program. Do not modify.
ESA100 .VVD	Screen file. Do not modify.
README .100	Last-minute information which didn't make it into the manual (if any).

3-3 HARDWARE REQUIREMENTS. The following is the minimum recommended hardware to run the ESA program:

- IBM AT class computer or compatible
- EGA color monitor
- 640 KB RAM with 520 KB free
- MS-DOS 3.3
- Hard drive with 500 KB free. Additional space will be needed when data files are written to the hard drive.
- Printer

3-4 GETTING STARTED. The ESA program may be loaded in any directory desired by the user. The following instructions are an example and assume that you are using floppy drive A for your program diskette, hard drive C for your working disk, and hard drive program subdirectory ESA. Make drive and subdirectory selections appropriate to your situation.

- Make a backup copy of the program diskette.

- Place the program diskette in floppy drive A. From the DOS prompt, type each of the following commands ending each command by pressing the Enter key. Do not type in the comments shown to the right of each command.

```
C:           <enter> Changes to the C drive.
CD\          <enter> Changes to the root directory.
MD ESA       <enter> Creates the ESA subdirectory.
CD ESA       <enter> Changes to the ESA subdirectory.
COPY A:*.*   <enter> Copies all files from the program
                     diskette to the ESA subdirectory on the
                     hard drive.
ESA100       <enter> Starts the program.
```

The program may also be started from the ESA.BAT batch file which can be placed in any directory on the DOS path. Use any plain text editor to change the C:\ESA path in the batch file if necessary.

3-5 MODIFYING FILES. It is HIGHLY RECOMMENDED that you make backup copies of files before performing any modifications and DO NOT modify any files on the program diskette.

3-5.1 CLIMATE.100 contains the climate data which is accessed when the user chooses a location from the ESA program. Data is generated using the methods discussed in Section IV of this manual. The Location Field may contain up to 30 characters.

If a factor does not apply due to equipment operating constraints or lack of data within the specified temperature range, enter NA in the field. The program recognizes NA and will use appropriate numbers (not necessarily zero) internally to null-out any calculations which use the factor.

> Note: When NA is entered in the CLIMATE.100 file, the corresponding field in the ESA program will be inaccessible to the user. If NA is no longer appropriate, either revise the CLIMATE.100 file entry or enter a new location with new data from within the ESA program. If climate data is being entered from within the program, NA may not be entered directly; instead, refer to the help file for instructions by pressing the F1 key.

CLIMATE.100 is written in ASCII and may be added to or modified using any plain text editor but must maintain the following format:

```
             ←   30 characters maximum  →  ← Comments...   →
    Location: AL, Huntsville
        ACWT: 76.0
        ANDW: 230
         AST: 76.7
         AWT: 46.7
        CFLH: 956
        HFLH: 408
         WKC: 19.8
         WKH: 27.3
         OAE: 32.73
         PRT: 7.5
```

3-5.2 DEFAULTS.100 contains program data non-zero defaults. The file is written in ASCII and may be modified using any plain text editor. The user may want to modify these values while working on large projects to avoid having to change default data on every input screen.

3-5.3 ESACL.100 is the choice list file for Fuel Type, Heating Value, Fuel Units, Chiller Type, and Chiller Fan. A typical listing follows:

```
*Fuel_type
Electricity                          3,413 Btu/kWh
Fuel oil, distillate #2            138,690 Btu/gal
Fuel oil, residual #6              149,690 Btu/gal
Natural gas (methane)                1,025 Btu/cf
Propane, gas                         2,500 Btu/cf
Propane, liquid                     91,500 Btu/gal
Bituminous coal                 26,260,000 Btu/ST
Steam                                1,000 Btu/lb
```

ESACL.100 is written in ASCII and may be modified using any plain text editor. You can add to or modify entries for fuel type, heating value of fuel, and fuel units by editing this file. The file may be up to 50 lines long.

<u>WARNING! Do not modify chiller type or chiller fan data!</u>

3-5.4 ESAHELP.100 contains the Help file and is accessed with the F1 key. A typical listing follows:

```
*BMnFile.Quit
Quit this program. Choose to save or discard changes to the
current file.
```

ESAHELP.100 is written in ASCII and may be customized using any plain text editor. The file may be up to 1200 lines long.

3-6 GENERATED FILES.

3-6.1 A PRINTER.100 file is generated and placed in the ESA program subdirectory whenever the printer configuration is saved. Although the default settings will work with most printers, the program should be configured for your printer. See Figure 3-4 for details.

3-6.2 Each base name generates a subdirectory off of the program subdirectory. Each building generates files with the name format BUILDING.??# where BUILDING is the building number, ?? are the first two characters of the extension, and # is the case number. For example, for a program subdirectory called ESA on hard drive C, a base named HUNTSVLE, building Q33, test case 7, and a base named ADAK, building 24663F14, test case R, the program will generate this file structure:

```
C — ESA
     ├──── HUNTSVLE
     │        ├─ Q33.DL7
     │        ├─ Q33.ES7
     │        └─ Q33.SM7
     └──── ADAK
              ├─ 24663F14.DLR
              ├─ 24663F14.ESR
              └─ 24663F14.SMR
```

3-6.2.1 BN.DL# is generated when a detailed report is sent to the screen, disk, or printer. If program data is changed, this file will need to be re-generated.

3-6.2.2 BN.ES# contains program data. Do not modify.

3-6.2.3 BN.SM# is generated when a summary report is sent to the screen, disk, or printer. If program data is changed, this file will need to be re-generated.

3-7 **GENERAL PROGRAM SCREENS.** The following pages contain a description of general program inputs. This information is also available using the context-sensitive help key F1.

> **Note:** Refer to Section II for reproductions of variable data input screens. Refer to Appendix A for a description of the variables.

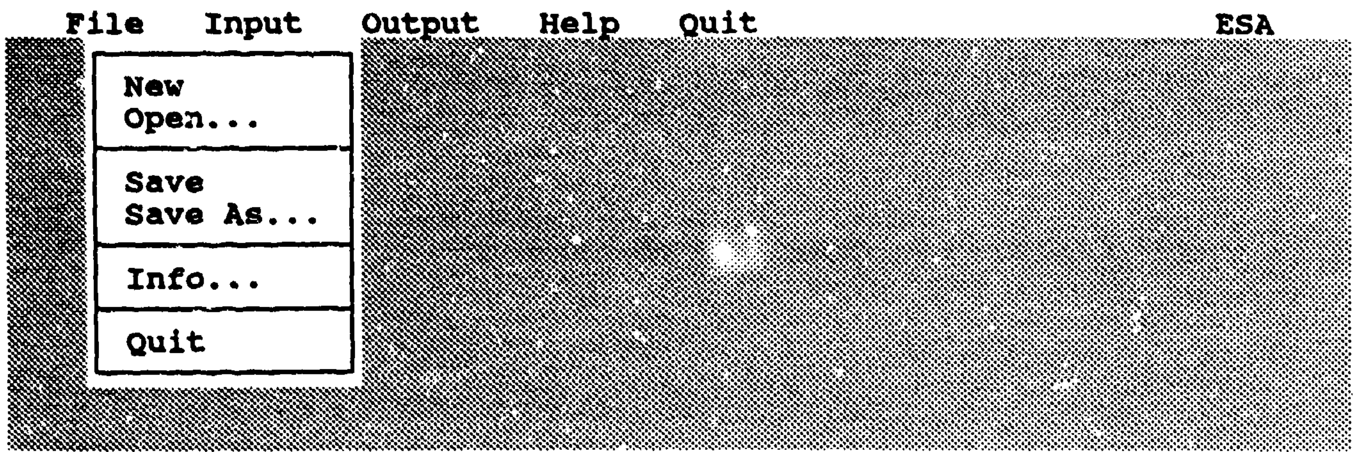

Figure 3-1. File Screen

File Select operations related to the current file.

New Create a new file. If changes have been made to the current file and you have not saved the changes, you will be asked if you wish to abandon the current file.

Open... Open a file that already exists on the disk. If changes have been made to the current file and you have not saved the changes, you will be asked if you wish to abandon the current file.

Base Name: Enter an existing Base Name or press the F2 key for a choice list.

Building Number: Enter an existing Building Number or press the F2 key for a choice list.

Case Number: Enter an existing Case Number or press the F2 key for a choice list.

Save Save the current file to disk using the current base name, building number, and case number.

Save As... Save the current file to disk using a new base name, building number, or case number.

Base Name: Enter a Base Name consisting of up to 8 alphanumeric characters with no spaces or press the F2 key for a choice list.

Building Number: Enter a Building Number consisting of up to 8 alphanumeric characters with no spaces or press the F2 key for a choice list.

Case Number: Enter a Case Number consisting of any alphanumeric character or press the F2 key for a choice list.

Description: Optional - Enter the file description consisting of up to 60 characters.

Info... Show information about the current file.

Base Name, Building Number, Case Number, Description.

Quit Quit this program. If changes have been made to the current file and you have not saved the changes, you will be asked if you wish to abandon the current file.

File   Input   Output   Help   Quit   ESA

Location
Climate
Building
System...

Figure 3-2. Input Screen

Input Select the input data categories.

Location Retrieve climatological data which has been pre-calculated for a specific time period and stored in the file CLIMATE.100. After leaving this help facility, press the F2 key for a choice list.

--OR--

Enter a new location here followed by climatological data using the Climate option below. A location entered here will be associated with THIS FILE ONLY. To add data to the CLIMATE.100 file, see Section III of the EMCS Savings Calculations Manual.

Climate Review or modify climatological data which has been pre-calculated, stored in the file CLIMATE.100, and selected using the Location option above.

--OR--

Entered climatological data for the new location specified using the Location option above.

--IN EITHER CASE--

Modified or new data will be associated with THIS FILE ONLY. To add data to the CLIMATE.100 file, see Section III of the EMCS Savings Calculations Manual.

Refer to Section II for reproductions of variable data input screens. Refer to Appendix A for a description of the variables.

Building Enter the building data as outlined on the subsequent screens. These parameters may be calculated using methods described in Section IV of the EMCS Savings Calculations Manual.

Check here if chiller uses steam Check this box if the system chiller is steam driven. Don't check this box if the system chiller is electric. If there is no system chiller, it doesn't matter whether this box is checked or not.

Heating Fuel Type Select the type of fuel used to heat the boiler(s). Press the F2 key for a choice list.

Refer to Section II for reproductions of variable data input screens. Refer to Appendix A for a description of the variables.

System... Select the HVAC systems which are being considered for the EMCS. For additional information on EMCS systems, refer to Energy Monitoring and Control Systems, Manual TM-815-2/NAVFAC DM-4.09/ AFM 88-36.

System Data Entry

System Description Enter the system description including the type/name/number/location as appropriate.

Refer to Section II for reproductions of variable data input screens. Refer to Appendix A for a description of the variables.

System Strategy Selection and Savings Use the space bar to select the desired strategies. Individual strategy savings and total selected savings are displayed.

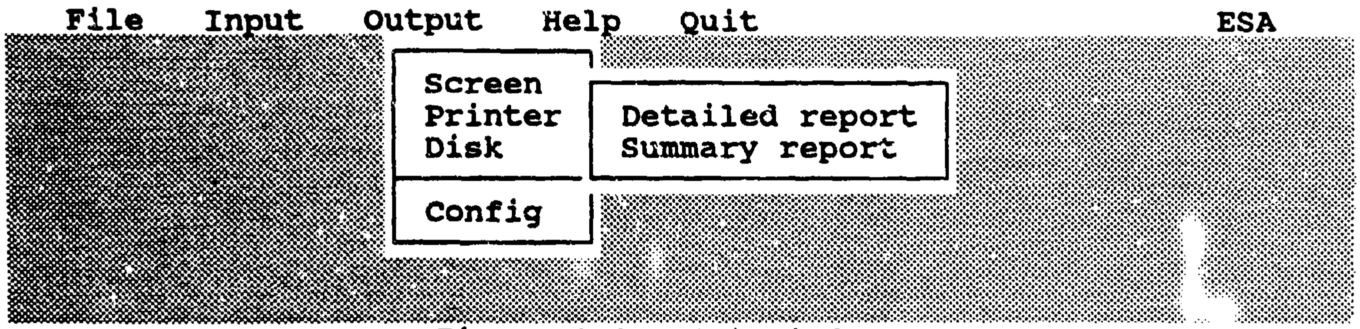

Figure 3-3. Output Screen

Output Select output format.

Screen View output report on monitor screen. Any output sent to the screen will automatically be saved to disk. For additional information, see **Disk** below.

Detailed report This choice will display a report containing both the input data used and the resultant energy savings.

Summary report This choice will display a report containing only the energy savings resulting from the calculations.

Printer Print output report. Any output sent to the printer will automatically be saved to disk. For additional information, see **Disk** below.

Detailed report This choice will send a report, containing both the input data used and the resultant energy savings, to your printer. Choose OUTPUT, SCREEN to view the report prior to printing.

Summary report This choice will send a report, containing only the energy savings resulting from the calculations, to your printer. Choose OUTPUT, SCREEN to view the report prior to printing.

Disk Write output report to disk file. Files are saved to the subdirectory with the same name as the base under the main program directory (typically ESA). For example, files for the base named HUNTSVLE would be stored as follows:

C:\ESA\HUNTSVLE\<filename>

Detailed report This choice will print a report, containing both the input data used and the resultant energy savings, to disk. Choose OUTPUT, SCREEN to view the report prior to printing.

Summary report This choice will print a report, containing only the energy savings resulting from the calculations, to disk. Choose OUTPUT, SCREEN to view the report prior to printing.

```
File   Input   Output   Help   Quit                          ESA
                 Screen
                 Printer
 ═════════════════════ Printer Setup ════════════════════════════

   [X] PC line drawing character set

   Page             Margins
      Width:  80         Top:  6     Left:  2     Header:  2
     Length:  60      Bottom:  6    Right:  2     Footer:  2

   Strings
       Header: <fn>¦¦<fd> <ft>
       Footer: ¦-<pg>-¦
      Initial:
     Terminal:

                                      Okay          Cancel
```

Figure 3-4. Configuration Screen

Config Configure the printer for printing the report.

PC line drawing character set Check this box if your printer supports the PC line drawing character set. If this box is not checked, only ASCII characters will be used for the printed reports.

Page Width The page width is represented by the number of characters that could fit on one line of a page with no margins. This value will depend on the size and orientation of the paper, and on the printer font size used.

Top Margin The top margin is the number of lines (blank lines plus header line) from the first possible line at the top of the sheet to the actual first line of printed text in the body of the report.

For example, if the printer line spacing is set at 6 lines/inch, then the default value of 6 will provide a top margin of 1 inch. Note that laser printers usually cannot print closer than 0.25 inches to the edge, so the default value would provide a top margin of about 1.25 inches in this case.

Left Margin The left margin is the number of characters from the left side of the sheet to the first character that can be printed on a line.

Header Margin The header margin is the number of blank lines following the header line to the first line of printed text in the body of the report. If the header line is blank, the header margin value has no effect.

Page Length The page length is represented by the number of lines of text that could fit on a page with no margins. On laser printers, the page length is usually in the range of 60 to 66 for portrait mode. On dot-matrix printers, the page length is usually 66.

Bottom Margin The bottom margin is the number of lines (blank lines and footer line) from the last line of text in the body of the report that can be printed on a page to the last possible line at the bottom of the sheet.

Right Margin The right margin is the number of characters from the last character that can be printed on a line to the right side of the sheet.

Footer Margin The footer margin is the number of blank lines from the last line of text in the body of the report that can be printed on a page to the footer line. If the footer line is blank, the footer margin value has no effect.

Header String Enter text to be printed at the top of each printed page. The text string has the format of: text1 ¦ text2 ¦ text3, where the vertical bars delimit text that is left, centered, and right justified. In addition, tokens can be used to indicate other information as follows:

<fn> - file name	<fd> - file date
<pg> - page number	<ft> - file time
<¦> - vertical bar	<sd> - system date
<<> - left angle bracket	<st> - system time

Example: <fn>¦¦<fd> <ft> means to print the name of the file left justified and to print the file date and file time right justified on the header line.

Footer String Enter text to be printed at the bottom of each printed page. The text string has the format of: text1 ¦ text2 ¦ text3, where the vertical bars delimit text that is left, centered, and right justified. In addition, tokens can be used to indicate other information as follows:

<fn> - file name	<fd> - file date
<pg> - page number	<ft> - file time
<¦> - vertical bar	<sd> - system date
<<> - left angle bracket	<st> - system time

Example: ¦-<pg>-¦ means to print the page number centered on the footer line.

Initial String Enter a data string to be sent to the printer when printing starts. The reports needs to be printed using a fixed width font such as Courier. If you need to set your printers font, this is the place to do it.

Tokens can be used for data that can not be represented by printable ASCII characters. The following tokens can be used:

```
<e> or <esc>    - escape character
<0> thru <254> - ASCII value
<<>             - left angle bracket
```

Example: <esc>E means, on certain laser printers, to reset the printer.

Terminal String Enter a data string to be sent to the printer when printing ends. Tokens can be used for data that can not be represented by printable ASCII characters. The following tokens can be used:

```
<e> or <esc>    - escape character
<0> thru <254> - ASCII value
<<>             - left angle bracket
```

Example: <esc>E means, on certain laser printers, to reset the printer.

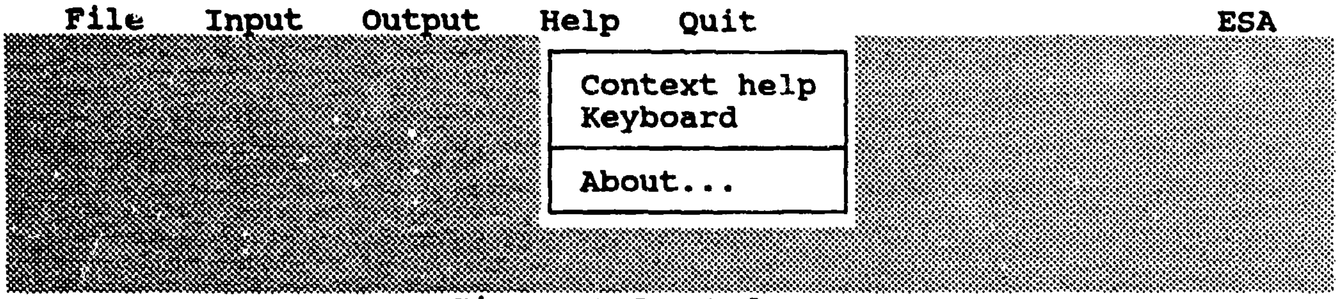

Figure 3-5. Help Screen

Help Select help topics.

Context help Get information on the help facility.

Keyboard Get information about the use of the keyboard in the program.

About... Get information on this program.

Quit Quit this program after choosing to save or discard changes to the current file (if any).

The following function keys are available while on a MENU screen:

Key	Action
Alt-F1	While in the help function (F1), toggles between split screen and full screen display.
Ctrl-End	Moves the selection bar to the last item on the menu.
Ctrl-Home	Moves the selection bar to the first item on the menu.
Ctrl-S	Saves the file to disk using current file name.
Down Arrow	Moves to the item located below the current item.
Enter	Invokes the action specified for the selected item.
Esc	Moves to the previous menu.
F1	Invokes the system help function, if enabled.
Left Arrow	Moves to the item located to the left of the current item.
Right Arrow	Moves to the item located to the right of the current item.
Up Arrow	Moves to the item located above the current item.

The following function keys are available while on a DATA screen:

Key	Action
Alt-F1	While in the help function (F1), toggles between split screen and full screen display.
Backspace	Deletes the character to the left of the cursor.
Ctrl-End	Moves to the last item on the form.
Ctrl-Home	Moves to the first item on the form.
Ctrl-S	Saves the file to disk using current file name.
Alt-D	Deletes current record.
Alt-I	Inserts new record.
Alt-N	Moves to next record.
Alt-P	Moves to previous record.
Del	Deletes the character at the current cursor position.
Down Arrow	Moves to the next item located physically below the current one.
End	Moves the cursor to the end of the field.
Enter	If a data field, enters the data into a field; if a button, invokes the action specified for the button.
Esc	Quits the form, abandoning any changes made to the form.
F1	Invokes the system help function, if enabled.
F2	Processes the attached choice list, if any, for the current field.
F6	Clears the field.
F7	Moves to the previous item on the form.
F8	Moves to the next item on the form.
F10	Exits the form, saving any changes made to the form.
Home	Moves the cursor to the beginning of the field.
Ins	Toggles between insert and overstrike mode.
Left Arrow	Moves the cursor one position to the left.

Page Down	Moves cursor to record summary screen. Press again to move cursor to choice buttons.
Page Up	Returns cursor to field which was exited when Page Down was pressed.
Right Arrow	Moves the cursor one position to the right.
Shift-F3	Clears the field and displays the original value in the field.
Shift-F6	Clears from the cursor to the end of the field.
Shift-F7	Goes to the previous form in a list of form pages.
Shift-F8	Goes to the next form in a list of form pages.
Shift-Tab	Moves to the previous item on the form.
Space	Toggles the strings for boolean toggle fields, if enabled for field.
Tab	Moves to the next item on the form.
Up Arrow	Moves to the next item located physically above the current one.

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Section IV. FACTOR CALCULATIONS

4-1 INTRODUCTION. This section describes the development of factors which are based on the location's climate and building characteristics. The information is presented so that the user can

- Understand the source of the climate and building factors used in the ESA program.
- Develop factors for locations which are not currently contained in the ESA program.

4-2 BACKGROUND. The factors in this section must be determined for use in the savings calculations. The climate related factors use data from Engineering Weather Data, AFM 88-29/TM 5-785/NAVFAC P-89. This is generalized data which will yield acceptable results.

FOR GREATER ACCURACY, ACTUAL WEATHER AND OPERATIONAL DATA FOR THE FACILITY SHOULD BE USED IF AVAILABLE.

For example, if a base has a yearly schedule for running boilers from 1 November to 15 March and chillers from 20 May to 30 September, then those time periods should be used for the Weeks of Heating (WKH) and Weeks of Cooling (WKC).

4-3 HOW TO USE THIS SECTION. The following information is presented for each factor to be calculated.

- **APPLICATION** lists the EMCS calculations where the factor will be used.
- **BASIS** describes any initial conditions or assumptions made for the calculation.
- **REQUIRED DATA** describes the information required for the calculation and where to find it.
- **EXAMPLE CALCULATION** demonstrates the calculation procedure based on conditions, assumptions, and data mentioned above. The example uses climatological data from the Springfield MAP, Missouri.

4-4 FACTOR CALCULATIONS. For clarity, factor calculations are explained using examples. Climate based factors for any location in the Engineering Weather Data manual can be derived in a manner similar to the examples.

SPRINGFIELD MAP MISSOURI

LAT 37 14N LONG 93 23W ELEV 1268 FT

MEAN FREQUENCY OF OCCURRENCE OF DRY BULB TEMPERATURE (DEGREES F) WITH MEAN COINCIDENT WET BULB TEMPERATURE (DEGREES F) FOR EACH DRY BULB TEMPERATURE RANGE

Temperature Range	MAY Obsn Hour Gp 01 to 08	MAY 09 to 16	MAY 17 to 24	MAY Total Obsn	MAY MCWB	JUNE Obsn Hour Gp 01 to 08	JUNE 09 to 16	JUNE 17 to 24	JUNE Total Obsn	JUNE MCWB	JULY Obsn Hour Gp 01 to 08	JULY 09 to 16	JULY 17 to 24	JULY Total Obsn	JULY MCWB
110/114												0		0	77
105/109												1	0	1	74
100/104							0	0	0	73		2	0	2	74
95/99							9	2	11	74	0	10	3	13	74
90/94		1	0	1	76		23	6	29	74	0	42	13	55	75
85/89		17	3	20	70	1	45	15	61	73	2	63	26	91	74
80/84	0	41	14	56	69	8	57	31	96	71	12	59	42	113	72
75/79	3	46	24	73	66	24	42	50	116	69	41	39	65	145	71
70/74	18	46	46	110	64	58	32	59	149	67	96	23	63	182	69
65/69	47	41	54	142	61	74	20	44	138	64	69	7	29	105	65
60/64	71	30	49	150	58	42	8	22	72	60	21	1	6	28	60
55/59	47	16	29	92	53	21	3	7	31	55	7		1	8	56
50/54	30	7	18	55	49	10	1	3	14	51	1			1	51
45/49	21	3	8	32	44	2		0	2	46					
40/44	8	1	1	10	40	0			0	43					
35/39	3	0	1	4	36										
30/34	1		0	1	32										
25/29															
20/24															

Temperature Range	AUGUST Obsn Hour Gp 01 to 08	AUGUST 09 to 16	AUGUST 17 to 24	AUGUST Total Obsn	AUGUST MCWB	SEPTEMBER Obsn Hour Gp 01 to 08	SEPTEMBER 09 to 16	SEPTEMBER 17 to 24	SEPTEMBER Total Obsn	SEPTEMBER MCWB	OCTOBER Obsn Hour Gp 01 to 08	OCTOBER 09 to 16	OCTOBER 17 to 24	OCTOBER Total Obsn	OCTOBER MCWB
110/114															
105/109															
100/104		2	0	2	74		0		0	70					
95/99		15	4	19	74		8	0	8	70					
90/94	0	40	10	50	74		14	3	17	70		1		1	68
85/89	1	64	25	90	72	0	33	9	42	70		7	0	7	67
80/84	7	56	42	105	71	2	42	16	60	68		24	3	27	66
75/79	31	39	63	133	70	6	46	32	84	66	0	32	8	40	63
70/74	92	21	59	172	68	32	45	53	130	65	4	41	19	64	61
65/69	67	8	30	105	64	64	30	55	149	62	18	36	39	93	60
60/64	35	2	11	48	60	54	16	36	106	58	39	35	48	122	56
55/59	10	0	3	13	56	38	6	22	66	53	48	31	39	118	52
50/54	4		0	4	51	27	2	12	41	49	43	22	37	102	48
45/49	1			1	47	13	0	3	16	45	36	11	28	75	43
40/44						3		0	3	41	32	5	18	55	39
35/39						0			0	38	17	2	6	25	35
30/34											10	1	3	14	30
25/29											2		0	2	25
20/24											0			0	22

Figure 4-1. Springfield MAP, Missouri Weather Data (sheet 1 of 2)

SPRINGFIELD MAP MISSOURI

Temperature Range	NOVEMBER Obsn Hour Gp 01 to 08	09 to 16	17 to 24	Total Obsn	MCWB	DECEMBER Obsn Hour Gp 01 to 08	09 to 16	17 to 24	Total Obsn	MCWB	JANUARY Obsn Hour Gp 01 to 08	09 to 16	17 to 24	Total Obsn	MCWB
110/114															
105/109															
100/104															
95/99															
90/94															
85/89															
80/84		0		0	63										
75/79		4		4	64		0		0	63		0		0	64
70/74	0	14	1	15	61		1	0	1	56		2	0	2	59
65/69	4	22	7	33	58	0	4	0	4	55	1	6	1	8	56
60/64	7	24	15	46	56	2	11	3	16	53	3	10	4	17	55
55/59	13	26	21	60	50	3	16	7	26	50	4	14	8	26	51
50/54	20	33	31	84	46	9	22	16	47	46	7	16	11	34	46
45/49	30	32	39	101	42	14	33	23	70	42	9	25	17	51	42
40/44	41	32	33	106	38	24	34	34	92	38	17	26	29	72	37
35/39	34	21	34	89	34	33	33	43	109	34	26	32	36	94	34
30/34	32	15	27	73	30	50	41	47	138	30	46	39	42	126	30
25/29	30	30	17	77	25	42	23	32	97	25	46	30	36	112	25
20/24	15	5	8	29	21	31	13	22	66	21	28	21	28	77	21
15/19	8	7	5	15	16	19	6	9	34	16	22	11	14	47	16
10/14	4	1	1	6	11	10	6	6	22	11	20	0	10	30	11
5/9	1	0	0	1	6	6	2	5	13	6	8	5	5	18	6
0/4						4	1	1	6	2	6	2	3	11	3
-5/-1						1			1	-3	3	1	1	5	-4
-10/-6											1	0	0	1	-7

Temperature Range	FEBRUARY Obsn Hour Gp 01 to 08	09 to 16	17 to 24	Total Obsn	MCWB	MARCH Obsn Hour Gp 01 to 08	09 to 16	17 to 24	Total Obsn	MCWB	APRIL Obsn Hour Gp 01 to 08	09 to 16	17 to 24	Total Obsn	MCWB
110/114															
105/109															
100/104															
95/99															
90/94												0		0	72
85/89							0		0	58		3	0	3	66
80/84		0		0	63		2	0	2	63		14	3	17	65
75/79		1	0	1	60		5	1	6	61	0	25	9	34	63
70/74		3	1	4	58	0	11	3	14	58	4	33	21	58	61
65/69	0	5	2	7	56	3	17	9	29	56	15	32	30	77	58
60/64	1	12	5	19	53	6	23	17	46	52	33	33	34	100	55
55/59	3	18	9	30	49	10	25	19	54	49	34	27	38	99	51
50/54	8	26	19	53	46	17	27	29	73	45	32	25	33	90	46
45/49	18	30	28	76	42	24	33	36	93	41	38	24	29	91	42
40/44	25	29	34	88	38	37	31	39	107	38	32	15	23	70	38
35/39	38	31	37	106	34	56	33	39	128	34	30	8	15	51	35
30/34	45	29	38	112	30	37	23	29	89	30	17	2	5	24	30
25/29	35	18	23	76	25	34	11	17	62	26	6	0	0	6	26
20/24	20	11	15	46	20	12	4	6	22	21	6		0	6	21
15/19	15	7	8	30	14	10	2	3	15	16	6			0	19
10/14	10	2	3	15	11	2	1	1	4	11					
5/9	3	1	1	5	6	1	0	1	2	6					
0/4	2	1	0	3	1	1			1	2					
-5/-1	0	0	0	0	-4										
-10/-6	0		0	0	-4										

Temperature Range	ANNUAL TOTAL Obsn Hour Gp 01 to 08	09 to 16	17 to 24	Total Obsn	MCWB
110/114		0		0	77
105/109		1	0	1	74
100/104		4	0	4	74
95/99	0	39	9	48	74
90/94	0	121	32	153	74
85/89	4	232	78	314	72
80/84	29	295	151	475	70
75/79	108	279	252	636	68
70/74	304	272	325	901	65
65/69	362	228	300	890	62
60/64	315	204	249	768	57
55/59	235	181	203	619	52
50/54	208	182	208	598	47
45/49	206	191	211	608	42
40/44	219	173	211	603	38
35/39	235	160	211	606	34
30/34	237	149	191	577	30
25/29	195	92	125	412	26
20/24	107	54	79	240	21
15/19	74	28	39	141	16
10/14	46	18	21	85	11
5/9	19	8	12	39	6
0/4	13	4	4	21	2
-5/-1	4	1	1	6	-4
-10/-6	1	0	0	1	-7

Figure 4-1. Springfield MAP, Missouri Weather Data, (sheet 2 of 2)

STATE / Station	Location: Lat (° ')	Location: Long (° ')	Elev (feet)	Winter Design Data, Heating, Dry Bulb: 99% (°F)	97.5% (°F)	Prev Wind (dir)	Mean Speed (knots)	Degree Days: Heating (annual)	Summer Design Data, Air Conditioning, Dry Bulb: 1% (°F)	MCWB (°F)	2.5% (°F)	MCWB (°F)	Mean Daily Range (°F)	Prev Wind (dir)	5% (°F)	MCWB (°F)	Wet Bulb: 1% (°F)	2.5% (°F)	5% (°F)	Summer Criteria Data, Air Conditioning, Dry Bulb: ≥ 93°F (hrs)	≥ 80°F (hrs)	Wet Bulb: ≥ 73°F (hrs)	≥ 67°F (hrs)
MISSOURI (CONT)	N	W																					
Hannibal	39 43	91 22	712	-2	3	NNW	11	5512	96	76	93	76	24	SSW	90	76	80	78	77	75	829	608	1607
Jefferson Barracks ANG	38 30	90 17	770	3	8	NW	9	4486	98	75	94	75	22	S	91	74	78	77	76	119	1223	645	1802
Joplin MAP	37 09	94 30	980	6	10	NNW	12	4188	100	73	97	73	24	SSW	94	73	78	77	76	214	1171	699	2058
Kansas City MAP	39 07	94 35	791	2	6	NW	9	4711	99	75	96	74	21	S	93	74	78	77	76	164	1278	654	1828
Lake City Arsenal	39 06	94 15	810	-2	3	N	8	5218	93	76	91	76	21	S	88	74	78	77	76	37	796	490	1588
Malden MAP	36 36	89 59	295	11	16	NNE	9	3908	98	78	95	76	26	SSW	92	76	81	79	78	120	1375	1054	2310
Richards-Gebaur AFB/Grandview	38 51	94 33	1090	-2	3	N	8	5218	93	76	91	76	21	S	88	74	78	77	76	37	796	490	1588
St Joseph/Rosecrans Aprt	39 46	94 55	825	-3	2	NNW	9	5440	96	77	93	76	25	S	91	76	81	79	77	93	990	678	1749
St Louis AFS	38 45	90 22	570	2	6	NW	9	4750	97	75	94	75	22	WSW	91	74	78	77	76	103	1123	645	1802
St Louis/Lambert IAP	38 45	90 23	535	2	6	NW	9	4750	97	75	94	75	22	WSW	91	74	78	77	76	103	1123	645	1802
St Louis Ordnance Depot	38 41	90 16	580	3	8	NW	6	4486	98	75	94	75	22	S	91	74	78	77	76	119	1223	645	1802
Springfield MAP	37 14	93 23	1268	3	9	NNW	10	4570	96	73	93	74	23	S	91	74	78	77	75	92	975	566	1838
Whiteman AFB/Knob Noster	38 43	93 33	869	-1	4	NNW	7	5012	95	76	92	76	22	SSW	90	75	79	78	76	58	913	601	1732
MONTANA	N	W																					
Billings/Logan IAP	45 48	108 32	3567	-15	-10	NE	9	7265	94	64	91	64	31	SW	88	63	67	66	64	50	537	1	42
Butte	45 57	112 30	5553	-24	-17	S	5	9719	86	58	83	56	37	NW	80	56	60	58	57	1	177	0	0
Cut Bank	48 37	112 22	3838	-25	-20	NNW	9	9033	88	61	85	61	32	WSW	82	60	64	62	61	6	219	0	7
Dillon	45 15	112 33	5224	-18	-10	NE	8	8354	90	61	87	60	36	SW	84	59	63	62	60	7	310	0	4
Glasgow AFB	48 25	106 32	2760	-22	-18	E	8	9251	92	64	89	63	28	S	85	62	68	66	64	23	370	1	51
Great Falls IAP	47 29	111 22	3662	-21	-15	SW	7	7652	91	60	88	60	30	WSW	85	59	64	62	60	18	364	0	6
Havre AFS	48 52	109 56	3200	-22	-15	NW	8	9058	93	63	89	62	30	SW	85	61	66	64	63	32	351	0	18
Helena	46 36	112 00	3828	-21	-16	WNW	5	8190	91	60	88	60	35	WNW	85	59	64	62	61	15	326	0	4
Kalispell AFS	48 01	114 22	6780	-31	-24	NW	15	11024	89	55	86	55	35	W	82	54	58	56	55	0	205	0	0
Lewistown	47 04	109 27	4122	-22	-16	NW	9	8586	90	62	87	61	33	NW	83	60	65	63	62	10	288	0	13
Malmstrom AFB	47 30	111 11	3525	-21	-15	WSW	6	7671	92	61	89	61	32	W	86	60	64	62	61	26	403	0	3
Miles City	46 26	105 52	2634	-20	-15	NW	7	7889	98	76	95	66	33	SE	92	65	70	68	67	123	691	6	154
Missoula	46 55	114 05	3190	-13	-6	ESE	7	7931	92	62	88	61	38	NW	85	60	65	63	62	20	346	0	8
Opheim AFS	48 52	106 28	3290	-27	-23	NW	8	9251	91	63	88	62	30	SW	84	61	67	65	63	21	278	0	32
NEBRASKA	N	W																					
Cornhusker AAP	40 55	98 29	1915	-8	-3	NNW	10	6420	97	72	94	71	27	S	91	71	75	74	73	113	818	193	1037
Grand Island	40 58	98 19	1841	-8	-3	NNW	10	6420	97	72	94	71	27	S	91	72	75	74	73	113	818	193	1037
Hastings MAP	40 36	98 26	1954	-7	-3	NNW	10	6070	97	72	94	71	28	S	91	71	75	74	73	113	818	193	1037
Lincoln MAP	40 51	96 45	1180	-6	-2	N	8	6218	99	75	95	74	26	S	92	74	78	77	76	143	991	506	1548

Figure 4-2. Springfield MAP, Missouri Winter/Summer Design Data

4-4.1 ACWT - Average Entering Condenser Water Temperature.

APPLICATION: Condenser Water Temperature Reset Savings Calculation.

This procedure determines the average entering condenser water temperature which can be obtained from a cooling tower during the cooling season at a given location. The calculated value can be used for any cooling tower in the same geographic location.

BASIS: Calculated during normal operating time period of 0900-1600 for temperature ranges above 55°F. Assumed approach temperature = 10°F. This is the difference between the outside air wet bulb temperature and the entering condenser water temperature due to heat gain from pumps, friction, and ambient conditions.

REQUIRED DATA: Using Engineering Weather Data,

1. In Chapter 3, find Total Annual Mean Coincident Wet Bulb (MCWB) temperatures for dry bulb temperature ranges above 55°F.

2. In Chapter 3, find 0900-1600 Annual Total Hours for corresponding MCWB temperatures.

EXAMPLE CALCULATION: The following example uses data from Springfield MAP, Missouri (Figure 4-1).

1. Calculate Condenser Water Temperature and Condenser Water Degree Hours for each MCWB Temperature.

Temp Range >55°F	Annual Total MCWB Temp °F	Condenser Water Temp (MCWB+10°) °F		0900-1600 Annual Total Hours		Condenser Water Degree Hours
110/114	77	87	*	0	=	0
105/109	74	84	*	1	=	84
100/104	74	84	*	4	=	336
95/99	74	84	*	39	=	3276
90/94	74	84	*	121	=	10164
85/89	72	82	*	232	=	19024
80/84	70	80	*	295	=	23600
75/79	68	78	*	279	=	21762
70/74	66	76	*	272	=	20672
65/69	62	72	*	228	=	16416
60/64	57	67	*	204	=	13668
55/59	52	62	*	181	=	11222
		TOTALS		1856 hr/yr		140224 °F•hr/yr

2. $$\text{ACWT} = \frac{\Sigma \text{ Condenser Water Degree Hours}}{\Sigma \text{ Annual Total Hours}} = \frac{140224\,°\text{F}\cdot\text{hr/yr}}{1856\text{ hr/yr}} = 75.6\,°\text{F}$$

4-4.2 ANDW - Annual Number of Days Requiring Morning Warmup.

APPLICATION: Ventilation and Recirculation Savings Calculations.

BASIS: Calculated during normal start-up time period of 0100 to 0800 for temperature ranges below 65°F when boiler is available. ANDW is limited by boiler availability; use scheduled days of boiler operation if less than ANDW.

REQUIRED DATA: Using Engineering Weather Data,

1. In Chapter 3, find 0100-0800 Annual Total Hours for specified temperature ranges.

EXAMPLE CALCULATION: The following example uses data from Springfield MAP, Missouri (Figure 4-1).

1. Calculate the sum of Annual Total Hours.

Temp Range <65°F	0100-0800 Annual Total Hours
60/64	315
55/59	235
50/54	208
45/49	206
40/44	219
35/39	235
30/34	237
25/29	195
20/24	107
15/19	74
10/14	46
5/9	19
0/4	13
-5/-1	4
-10/-6	1
TOTAL	2114 hrs/yr

2. $$\text{ANDW} = \frac{\Sigma \text{ Annual Total Hours}}{8 \text{ hrs/day}} = \frac{2114 \text{ hrs/yr}}{8 \text{ hrs/day}} = 264 \text{ days/yr}$$

4-4.3 AST - Average Summer Temperature.

APPLICATION: Scheduled Start/Stop Savings Calculation.

BASIS: Calculated during normal off-time periods of 0100-0800 and 1700-2400 for temperature ranges above 70°F.

REQUIRED DATA: Using Engineering Weather Data,

1. In Chapter 3, find 0100-0800 and 1700-2400 Annual Total Hours for specified temperature ranges.

2. Determine mean temperatures for each temperature range.

EXAMPLE CALCULATION: The following example uses data from Springfield MAP, Missouri (Figure 4-1).

1. Calculate Annual Summer Degree Hours for each Mean Temperature.

Temp Range >70°F	Mean Temp Per 5° Range °F		0100-0800 Annual Total Hours		1700-2400 Annual Total Hours		Annual Summer Degree Hours
95/99	97.5	*	(0	+	9)	=	877.5
90/94	92.5	*	(0	+	32)	=	2960
85/89	87.5	*	(4	+	78)	=	7175
80/84	82.5	*	(29	+	151)	=	14850
75/79	77.5	*	(105	+	252)	=	27667.5
70/74	72.5	*	(304	+	325)	=	45602.5
	TOTALS		442 hr/yr		847 hr/yr		99132.5 °F·hr/yr

2. $$AST = \frac{\Sigma \text{ Annual Summer Degree Hours}}{\Sigma \text{ All Annual Total Hours}}$$

$$= \frac{99{,}132.5\,°F\cdot hr/yr}{(442 + 847)\ hr/yr} = 76.9°F$$

4-4.4 AWT - Average Winter Temperature.

APPLICATION: Scheduled Start/Stop and Ventilation and Recirculation Savings Calculations.

BASIS: Calculated during 24 hour time period for temperature ranges below 65°F.

REQUIRED DATA: Using Engineering Weather Data,

1. In Chapter 3, find 24 hour Annual Total Hours for specified temperature ranges.

2. Determine mean temperatures for each temperature range.

EXAMPLE CALCULATION: The following example uses data from Springfield MAP, Missouri (Figure 4-1).

1. Calculate Annual Winter Degree Hours for each Mean Temperature.

Temp Range <65°F	Mean Temp Per 5° Range °F		Annual Total Hours		Annual Winter Degree Hours
60/64	62.5	*	768	=	48000
55/59	57.5	*	619	=	35592.5
50/54	52.5	*	598	=	31395
45/49	47.5	*	608	=	28880
40/44	42.5	*	603	=	25627.5
35/39	37.5	*	606	=	22725
30/34	32.5	*	577	=	18752.5
25/29	27.5	*	412	=	11330
20/24	22.5	*	240	=	5400
15/19	17.5	*	141	=	2467.5
10/14	12.5	*	85	=	1062.5
5/9	7.5	*	39	=	292.5
0/4	2.5	*	21	=	52.5
-5/-1	-3.5	*	6	=	-21
-10/-6	-8.5	*	1	=	-8.5
	TOTALS		5324 hr/yr		231548 °F·hr/yr

2. $$AWT = \frac{\Sigma \text{ Annual Winter Degree Hours}}{\Sigma \text{ Annual Total Hours}} = \frac{231548\,°F\cdot hr/yr}{5324\ hr/yr} = 43.5°F$$

4-4.5 CFLH - Annual Equivalent Full-Load Hours for Cooling.

APPLICATION: Chiller Selection, Chiller Water Temperature Reset, Condenser Water Temperature, and Chiller Demand Limit Reset Savings Calculations.

BASIS: Calculated during 0900 to 1600 time period for temperature ranges equal to or above 65°F. CFLH is limited by chiller availability; use scheduled days of chiller operation if less than CFLH.

REQUIRED DATA: Using Engineering Weather Data,

1. In Chapter 1 or 2, find 2.5% Summer Design Data Dry Bulb Temperature.
2. In Chapter 3, find 0900-1600 or 24 hour Annual Total Hours for specified temperature ranges.
3. Determine mean temperature for each temperature range.

EXAMPLE CALCULATION: The following example uses data from Springfield MAP, Missouri (Figure 4-1), for the 0900-1600 time period.

1. 2.5% Summer Design Data Dry Bulb Temperature (SDDDBT) = 93°F.
2. Calculate Cooling Degree Hours for each Mean Temperature.

Temp Range ≥65°F	Mean Temp Per 5° Range °F	Mean Temp minus 65°		0900-1600 Annual Total Hours		Cooling Degree Hours
105/109	107.5	42.5	*	1	=	42.5
100/104	102.5	37.5	*	4	=	150
95/99	97.5	32.5	*	39	=	1267.5
90/94	92.5	27.5	*	121	=	3327.5
85/89	87.5	22.5	*	232	=	5220
80/84	82.5	17.5	*	295	=	5162.5
75/79	77.5	12.5	*	279	=	3487.5
70/74	72.5	7.5	*	272	=	2040
65/69	67.5	2.5	*	228	=	570
				TOTAL		21267.5 °F·hr

3. $$\text{CFLH} = \frac{\Sigma\ \text{Cooling Degree Hours}}{\text{SDDDBT}-65^\circ\text{F}} = \frac{21267.5^\circ\text{F}\cdot\text{hr}}{93^\circ\text{F}-65^\circ\text{F}} = 760\ \text{hr/yr}$$

4-4.6 HFLH - Annual Equivalent Full-Load Hours for Heating.

APPLICATION: Boiler Selection and Hot Water Outside Air Reset Savings Calculation.

BASIS: Calculated during 0900-1600 time period for temperature ranges below 65°F. HFLH is limited by boiler availability; use scheduled days of boiler operation if less than HFLH.

REQUIRED DATA: Using Engineering Weather Data,

1. In Chapter 1 or 2, find 97.5% Winter Design Data Dry Bulb Temperature.

2. In Chapter 3, find 0900-1600 or 24 hour Annual Total Hours for specified temperature ranges.

3. Determine the mean temperature for each temperature range.

EXAMPLE CALCULATION: The following example uses data from Springfield MAP, Missouri (Figure 4-1), for the 0900-1600 time period.

1. 97.5% Winter Design Data Dry Bulb Temperature (WDDDBT) = 9°F.

2. Calculate Heating Degree Hours for each Mean Temperature.

Temp Range <65°F	Mean Temp Per 5° Range °F	65° Minus Mean Temp		0900-1600 Annual Total Hours		Heating Degree Hours
60/64	62.5	2.5	*	204	=	510
55/59	57.5	7.5	*	181	=	1357.5
50/54	52.5	12.5	*	182	=	2275
45/49	47.5	17.5	*	191	=	3342.5
40/44	42.5	22.5	*	173	=	3892.5
35/39	37.5	27.5	*	160	=	4400
30/34	32.5	32.5	*	149	=	4842.5
25/29	27.5	37.5	*	92	=	3450
20/24	22.5	42.5	*	54	=	2295
15/19	17.5	47.5	*	28	=	1330
10/14	12.5	52.5	*	18	=	945
5/9	7.5	57.5	*	8	=	460
0/4	2.5	62.5	*	4	=	250
-5/-1	-3.5	68.5	*	1	=	68.5
				TOTAL		29418.5 °F•hr

3. $$\text{HFLH} = \frac{\Sigma \text{ Heating Degree Hours}}{65° - \text{WDDDB}} = \frac{29418.5°\text{F}\cdot\text{hr}}{65°\text{F}-9°\text{F}} = 525 \text{ hr/yr}$$

4-4.7 WKH - Weeks of Heating.

APPLICATION: Scheduled Start/Stop, Day/Night Setback, Ventilation and Recirculation, Hot Deck/Cold Deck Temperature Reset, and Reheat Coil Reset Savings Calculations.

BASIS: For Weeks of Heating use all annual total hours below 65°F. WKH is limited by boiler availability; use scheduled days of boiler operation if less than WKH.

REQUIRED DATA: Using Engineering Weather Data,

1. In Chapter 3, find 24 hour Annual Total Hours for specified temperature ranges.

EXAMPLE CALCULATION: The following example uses data from Springfield MAP, Missouri (Figure 4-1).

1. Calculate the sum of Annual Total Hours.

Temp Range <65°F	Annual Total Hours below 65°
60/64	768
55/59	619
50/54	598
45/49	608
40/44	603
35/39	606
30/34	577
25/29	412
20/24	240
15/19	141
10/14	85
5/9	39
0/4	21
-5/-1	6
-10/-6	1
TOTAL	5324 hrs/yr

2. 7 days/wk * 24 hrs/day = 168 hrs/wk

3. $$WKH = \frac{\Sigma \text{ Annual Total Hours} <65^\circ}{168 \text{ hrs/wk}} = \frac{5324 \text{ hrs/yr}}{168 \text{ hrs/wk}} = 31.7 \text{ wks/yr}$$

4-4.8 WKC - Weeks of Cooling.

APPLICATION: Scheduled Start/Stop, Day/Night Setback, Ventilation and Recirculation, Hot Deck/Cold Deck Temperature Reset, and Reheat Coil Reset Savings Calculations.

BASIS: For Weeks of Cooling use all annual total hours above 70°F. WKC is limited by chiller availability; use scheduled days of chiller operation if less than WKC.

REQUIRED DATA: Using Engineering Weather Data,

1. In Chapter 3, find 24 hour Annual Total Hours for specified temperature ranges.

EXAMPLE CALCULATION: The following example uses data from Springfield MAP, Missouri (Figure 4-1).

1. Calculate the sum of Annual Total Hours.

Temp Range >70°F	Annual Total Hours above 70°
105/109	1
100/104	4
95/99	48
90/94	153
85/89	314
80/84	475
75/79	636
70/74	901
TOTAL	2532 hrs/yr

2. 7 days/wk * 24 hrs/day = 168 hrs/wk

3. $$WKH = \frac{\Sigma \text{ Annual Total Hours} >70^\circ}{168 \text{ hrs/wk}} = \frac{2532 \text{ hrs/yr}}{168 \text{ hrs/wk}} = 15.1 \text{ wks/yr}$$

4-4.9 OAE - Average Outside Air Enthalpy

APPLICATION: Scheduled Start/Stop and Ventilation and Recirculation Savings Calculations.

BASIS: Calculated during the normally unoccupied time periods of 0100-0800 and 1700-2400 for dry bulb temperatures above 70°F.

REQUIRED DATA: Using Engineering Weather Data,

1. In Chapter 3, find Total Annual Mean Coincident Wet Bulb (MCWB) temperatures for dry bulb temperature ranges above 70°F.

1. In Chapter 3, find 0100-0800 and 1700-2400 Annual Total Hours for corresponding MCWB temperatures.

EXAMPLE CALCULATION: The following example uses data from Springfield MAP, Missouri (Figure 4-1).

1. Calculate Annual Degree Hours for each MCWB Temperature.

Temp Range ≥70°F	Annual Total MCWB Temp °F		0100-0800 Annual Total Hours		1700-2400 Annual Total Hours		Annual Degree Hours
95/99	74	*	(0	+	9)	=	666
90/94	74	*	(0	+	32)	=	2368
85/89	72	*	(4	+	78)	=	5904
80/84	70	*	(29	+	151)	=	12600
75/79	68	*	(105	+	252)	=	24276
70/74	66	*	(304	+	325)	=	41514
	TOTALS		442 hr/yr		847 hr/yr		87328 °F·hr/yr

2. Average wet bulb temperature = $\dfrac{\Sigma \text{ Annual Degree Hours}}{\Sigma \text{ All Annual Total Hours}}$

$$= \frac{87328\,°F\cdot hr/yr}{(442 + 847)\ hr/yr} = 67.7\,°F$$

3. Using Table 4-1 and interpolating where necessary, find the enthalpy which corresponds to the wet bulb temperature of 67.7°F.

OAE = 32.14 Btu/lb

Table 4-1. Enthalpy of Air for Selected Wet Bulb Temperatures

Wet Bulb Temp °F	Enthalpy Btu/lb	Wet Bulb Temp °F	Enthalpy Btu/lb
40	15.20	70	34.00
41	15.66	71	34.86
42	16.14	72	35.74
43	16.62	73	36.64
44	17.11	74	37.56
45	17.61	75	38.50
46	18.12	76	39.47
47	18.64	77	40.46
48	19.17	78	41.47
49	19.71	79	42.50
50	20.26	80	43.57
51	20.82	81	44.65
52	21.39	82	45.77
53	21.97	83	46.91
54	22.57	84	48.08
55	23.17	85	49.28
56	23.79	86	50.52
57	24.42	87	51.78
58	25.07	88	53.07
59	25.73	89	54.40
60	26.40	90	55.76
61	27.09	91	57.16
62	27.79	92	58.59
63	28.51	93	60.06
64	29.24	94	61.57
65	29.99	95	63.12
66	30.76	96	64.70
67	31.54	97	66.33
68	32.34	98	68.01
69	33.16	99	69.73
		100	71.49

4-4.10 PRT - Percent Run Time to Maintain Low Temperature Limit.

APPLICATION: Scheduled Start/Stop Savings Calculation.

BASIS: The percent run time is the percentage of scheduled off time during unoccupied periods when the fans and pumps must come back on in order to maintain a 55°F low temperature limit. Use the actual equipment schedule if available.

REQUIRED DATA: Using Engineering Weather Data and Figure 4-3 of this manual,

1. In Chapter 1, find the annual Heating Degree Days.

2. Using Figure 4-3, find the corresponding percent run time.

EXAMPLE CALCULATION: The following example uses data from Springfield MAP, Missouri (Figures 4-1 and 4-2).

1. From Engineering Weather Data, Heating Degree Days = 4570

2. From Figure 4-3, PRT ≈ 15%

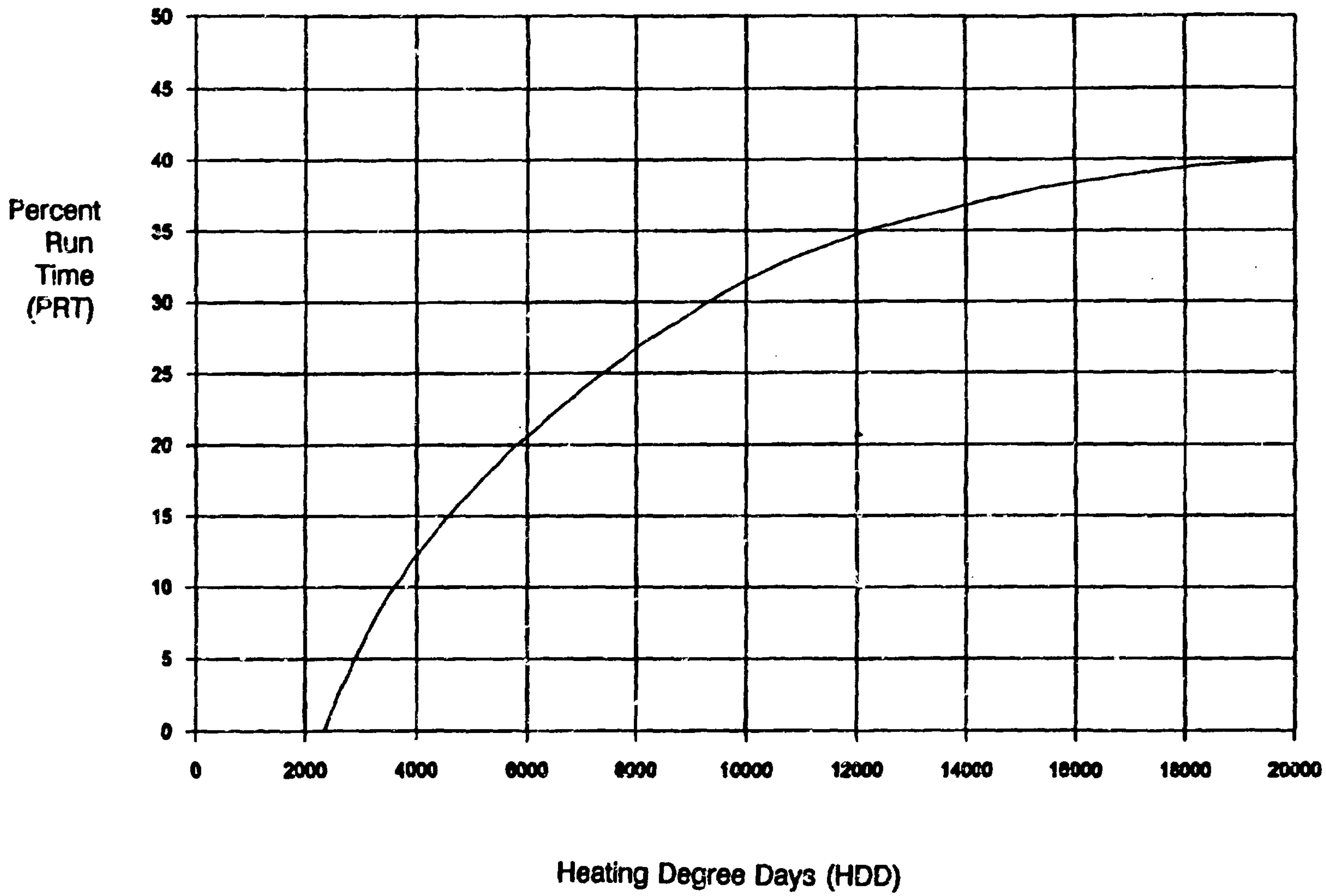


Figure 4-3. Percent Run Time to maintain Low Temperature Limit

4-4.11 BTT - Building Thermal Transmission.

APPLICATION: Scheduled Start/Stop and Day/Night Setback Savings Calculations.

BASIS: This factor reflects the amount of heat loss (gain) attributable to the building's type of construction and amount of air infiltration.

Most data needed to calculate the U factor and Infiltration have been reproduced in Appendix C from the ASHRAE Handbook, Fundamentals. For additional information, refer to the Handbook.

REQUIRED DATA:

1. **U** (Btu/hr·°F·ft²) - Thermal transmittance factor for walls, windows, doors, and roof. These factors may be calculated using methods discussed in Chapter 22 of the ASHRAE Handbook--Fundamentals. Note: U=1/R

2. **I** (cfm) - Total air infiltration for the building which may be calculated using methods discussed in Chapter 23 of the ASHRAE Handbook--Fundamentals.

3. **1.08** (Btu/cfm·hr·°F) - constant (ref Appendix A)

4. **Af** (ft²) - Gross floor area of the building which can be determined from the field survey data.

CALCULATION:

For parallel heat flow paths,

U_oA_o (Btu/hr·°F) - Modified Combined Thermal Transmittance Factor. This modified combined U factor is for all exterior surfaces (walls, windows, doors, roof) and may be calculated using methods discussed below and in Chapter 22 of the ASHRAE Handbook--Fundamentals (ref Appendix C).

Repeat the U x A calculation for each different type of wall, window, door, or roofing material.

$$U_oA_o = U_{wall} \times A_{wall,\ net} + U_{window} \times A_{window} + U_{door} \times A_{door} + U_{roof} \times A_{roof}$$

$$\text{BTT (Btu/hr·ft}^2\text{·°F)} = \frac{U_oA_o + (I \times 1.08)}{Af}$$

EXAMPLE CALCULATION:

See example calculation in Section 6 of this manual. Refer to Chapter 22 and 23 of the ASHRAE Handbook--Fundamentals for additional examples.

Ref	Factor	Calculated Value
4-4.1	ACWT =	°F
4-4.2	ANDW =	days/year
4-4.3	AST =	°F
4-4.4	AWT =	°F
4-4.5	CFLH =	hrs/year
4-4.6	HFLH =	hrs/year
4-4.7	WKH =	weeks/year
4-4.7	WKC =	weeks/year
4-4.8	OAE =	Btu/lb
4-4.9	PRT =	%
4-4.10	UoAo = I = Af = BTT =	Btu/hr·°F cfm ft^2 Btu/hr·ft^2·°F

Figure 4-4. Factor Summary

Section V. SAVINGS CALCULATIONS

5-1 INTRODUCTION. This section describes the EMCS savings calculations. The calculations use climate based and building based factors which were developed in Section IV. The information is presented so that the user can understand the development of savings figures generated by the ESA program and perform manual calculations if required.

5-2 BACKGROUND.

Figure 5-1 shows the typical HVAC related mechanical systems found in an industrial/commercial building and the EMCS strategy or strategies applicable to each. The reasoning behind the use of the strategies is discussed in Section III of Energy Monitoring and Control Systems, TM5-815-2/NAVFAC DM-4.09/AFM 88-36.

Since it is not possible to completely describe all activities involved in the engineering design process, this section is meant to be used only as a framework for EMCS analysis. Every facility is different and various calculations must be adapted, augmented, or ignored as the situation requires. The judgement required to make these decisions requires professional engineering personnel familiar with the mechanical systems, electrical systems, and EMCS.

5-3 HOW TO USE THIS SECTION. For simplicity, units of measure for constants and conversion factors have not been included in the calculations. Refer to Appendix A for variable definitions, units of measure, and typical values where applicable. Refer to Appendix B for constants and conversion factors complete with units and limited discussion.

Each calculation results in an answer with units of energy per year. The summary sheet has provision for converting units of energy to units of fuel. Savings strategies can be compared on the basis of energy used or the fuel cost of providing that energy.

Care must be taken not to calculate the same heating or cooling savings for both the secondary system and primary system serving it. For example, consider a chiller providing chilled water to the AHU which provides cooling for Zone 1 of a building. Scheduled Start/Stop cooling savings for Zone 1 may be calculated for the chiller or the AHU but not both.

Follow the procedure outlined for each calculation while paying attention to any application notes. Where applicable, use total HP for all fans, cooling, and heating pumps associated with this system. EXCEPTION: For packaged units such as Air Cooled Chillers and Air Cooled DX units, include HP as a component of the CPT factor.

REFERENCE PAGE	5-3	5-4	5-5	5-5	5-6	5-6	5-7	5-8	5-9	5-9	5-9	5-10	5-10	5-10	5-11	5-13	5-13
MECHANICAL SYSTEMS CONTROLLABLE BY EMCS / EMCS STRATEGY	Scheduled Start/Stop	Optimum Start/Stop	Duty Cycling	Demand Limiting	Day/Night Setback	Economizer (dry bulb)	Ventilation and Recirculation	Hot Deck/Cold Deck Temperature Reset	Reheat Coil Reset	Steam Boiler Selection	Hot Water Boiler Selection	Hot Water Outside Air Reset	Chiller Selection	Chiller Water Temperature Reset	Condenser Water Temperature Reset	Chiller Demand Limit (Centrifugal units only)	Lighting Control
A Single Zone AHU	●	●	●	●	●	●	●										
B Terminal Reheat AHU	●	●	●	●	●	●	●		●								
C Variable Air Volume AHU	●	●		●	●	●	●										
D Multi-zone AHU	●	●	●	●	●	●	●	●									
E Single Zone DX - A/C	●	●	●	●	●	●	●										
F Multi- Zone DX - A/C	●	●	●	●	●	●	●	●									
G Two Pipe Fan Coil Unit	●	●	●	●	●												
H Four Pipe Fan Coil Unit	●	●	●	●	●												
I Electric Unit Heater	●	●	●	●	●												
J Electric Radiation	●	●	●	●	●												
K Heating/Ventilating Unit	●	●	●	●	●		●										
L Direct Fired Furnace	●	●	●	●	●		●										
M Direct Fired Boiler	●	●		●	●		●										
N Steam Unit Heater					●												
O Hot Water Unit Heater					●												
P Steam Radiation					●												
Q Hot Water Radiation	●	●	●	●	●												
R Steam Boiler										●							
S Hot Water Boiler											●	●					
T Steam/Hot Water Converter	●	●	●		●							●					
U HTHW/Steam Converter					●												
V HTHW/Hot Water Converter	●	●	●	●	●							●					
W Water Cooled DX Compressor	●	●	●	●											●		
X Air Cooled DX Compressor	●	●	●	●													
Y Air Cooled Chiller	●	●											●	●			
Z Water Cooled Chiller													●	●	●	●	
AA Lighting Control																	●

Figure 5-1. Energy Conservation Program Applications

5-4 SAVINGS CALCULATIONS.

5-4.1 Scheduled Start/Stop

APPLICATION NOTES:

1. Use average winter temperature (AWT) in place of the low temperature limit (LTL) if:

   a. No low temperature limit is desired (set PRT = zero) or
   b. AWT > LTL.

   If PRT = zero or AWT > LTL, the ESA program will automatically use AWT in place of LTL.

2. For WKH and WKC use actual length of heating and cooling seasons if known.

3. For Hh/Hc use currently scheduled time for equipment operation or estimate using the hours of occupancy plus 2 hours per day for warmup/cooldown. For HhEMCS/HcEMCS also add warmup/cooldown times.

4. Do not shut down fans which are required for minimum ventilation or in-line circulating pumps on hot water systems.

CALCULATIONS:

1. **Heat loss/gain through the structure**

   Heating savings (MBtu/yr):

$$\frac{\text{BTT} \times \text{Az} \times (\text{WSP-LTL}) \times (\text{Hh-HhEMCS}) \times \text{WKH}}{\text{HSE} \times 10^6}$$

   Heating savings for Electric Unit Heater and Electric Radiation (kWh/yr):

$$\frac{\text{BTT} \times \text{Az} \times (\text{WSP-LTL}) \times (\text{Hh-HhEMCS}) \times \text{WKH}}{\text{HSE} \times 3413}$$

   Cooling savings with electrically driven chiller (kWh/yr with CPT in kW/ton):

$$\frac{\text{BTT} \times \text{Az} \times (\text{AST-SSP}) \times (\text{Hc-HcEMCS}) \times \text{WKC} \times \text{CPT}}{12{,}000}$$

   Cooling savings with steam driven chiller (MBtu/yr with CPT in lb/hr•ton):

$$\frac{\text{BTT} \times \text{Az} \times (\text{AST-SSP}) \times (\text{Hc-HcEMCS}) \times \text{WKC} \times \text{CPT} \times 1000}{12{,}000 \times 10^6}$$

2. **Heat loss/gain through ventilation air**

Heating savings (MBtu/yr):

$$\frac{CFM \times POA \times 1.08 \times (WSP\text{-}AWT) \times (Hh\text{-}HhEMCS) \times WKH}{HSE \times 10^6}$$

Heating savings for Electric Unit Heater and Electric Radiation (kWh/yr):

$$\frac{CFM \times POA \times 1.08 \times (WSP\text{-}AWT) \times (Hh\text{-}HhEMCS) \times WKH}{HSE \times 3413}$$

Cooling savings with electrically driven chiller (kWh/yr with CPT in kW/ton):

$$\frac{CFM \times POA \times 4.5 \times (OAE\text{-}RAE) \times (Hc\text{-}HcEMCS) \times WKC \times CPT}{12{,}000}$$

Cooling savings with steam driven chiller (MBtu/yr with CPT in lb/hr•ton):

$$\frac{CFM \times POA \times 4.5 \times (OAE\text{-}RAE) \times (Hc\text{-}HcEMCS) \times WKC \times CPT \times 1000}{12{,}000 \times 10^6}$$

3. **Auxiliary equipment operation**

Heating auxiliary savings (kWh/yr):

$$HP \times L \times 0.746 \times (Hh\text{-}HhEMCS) \times WKH \times (1\text{-}PRT)$$

Cooling auxiliary savings (kWh/yr):

$$HP \times L \times 0.746 \times (Hc\text{-}HcEMCS) \times WKC$$

5-4.2 Optimum Start/Stop

APPLICATION NOTES: The Optimum Start/Stop savings calculation is used in place of Scheduled Start/Stop to start and stop equipment on a sliding schedule. The program incorporates thermal inertia of the building, capacity of the HVAC system, and outside air conditions. Use of a computer simulation, which typically includes both Optimum and Scheduled Start/Stop, is required for accurate determination of savings therefore calculations are not presented in this manual.

5-4.3 Duty Cycling

APPLICATION NOTES:

1. Applies only to constant loads.

2. Does not apply to loads which already cycle under local control.

3. Duty cycling performed during hours of occupancy (assumes no duty cycling during warmup or cooldown).

4. Do not duty cycle fans which are required for minimum ventilation, boilers, chillers, or in-line circulating pumps.

CALCULATIONS:

Auxiliary motor savings (kWh/yr) =

$$HP \times L \times 0.746 \times OH \times DCST \times 52 \text{ wk/yr}$$

Electric Unit Heater and Electric Radiation savings (kWh/yr) =

$$PWR \times OH \times DCST \times 52 \text{ wk/yr}$$

5-4.4 Demand Limiting

APPLICATION NOTES:

1. Assumes that the system can be shed a portion of the time under peak load conditions. The shed time will vary in different parts of the country.

2. Do not shut down fans which are required for minimum ventilation.

CALCULATIONS:

Auxiliary motor savings (kW) =

$$HP \times L \times 0.746 \times DLST$$

Electric Unit Heater and Electric Radiation savings (kW) =

$$PWR \times DLST$$

5-4.5 Day/Night Setback

APPLICATION NOTES:

1. Used in place of Scheduled Start/Stop for systems where the temperature must be controlled within specified limits.

2. Make sure that the setpoints for <u>all</u> heating systems serving the zone are controlled.

3. If outside air dampers can be closed during the setback period, the Ventilation and Recirculation strategy may be applied.

4. For WSPR, use the smaller of WSPR, WSP-LTL, or WSP-AWT. If PRT is zero, use AWT instead of LTL. For SSPR, use the smaller of SSPR or AST-SSP. The ESA program will do this automatically.

5. For Hwsp/Hssp use currently scheduled time during which the system is operated at the WSP/SSP or hours of occupancy plus 1 hour per day for warmup/cooldown.

CALCULATIONS:

Heating savings (MBtu/yr) =

$$\frac{BTT \times Az \times WSPR \times (168\text{-}Hwsp) \times WKH}{HSE \times 10^6}$$

Heating savings for Electric Unit Heater and Electric Radiation (kWh/yr):

$$\frac{BTT \times Az \times WSPR \times (168\text{-}Hwsp) \times WKH}{HSE \times 3413}$$

Cooling savings with electrically driven chiller (kWh/yr with CPT in kW/ton):

$$\frac{BTT \times Az \times SSPR \times (168\text{-}Hssp) \times WKC \times CPT}{12{,}000}$$

Cooling savings with steam driven chiller (MBtu/yr with CPT in lb/hr•ton):

$$\frac{BTT \times Az \times SSPR \times (168\text{-}Hssp) \times WKC \times CPT \times 1000}{12{,}000 \times 10^6}$$

5-4.6 Outside Air Dry Bulb Economizer

APPLICATION NOTES: This savings calculation is applicable to air systems with outside air and exhaust air dampers. Use of a computer simulation is required for accurate determination of savings therefore calculations are not presented in this manual.

5-4.7 Ventilation and Recirculation

APPLICATION NOTES:

1. Used in conjunction with scheduled Start/Stop or Day/Night Setback to control outside air dampers.

2. Do not shut down fans which are required for minimum ventilation.

CALCULATIONS:

1. The following calculation applies to systems which are shut down by the Scheduled Start/Stop strategy and is applied to the warmup period prior to occupancy. Heating savings are a result of eliminating OA during the warmup period except for the ventilation purge time when OA must be introduced. No cool-down ventilation savings is included in the analysis based on the assumption that early morning outside air adds a negligible amount to the cooling load and may actually lessen the load through an economizer effect.

   Heating savings (MBtu/yr) =

$$\frac{CFM \times POA \times 1.08 \times (WSP-AWT) \times ANDW \times [WU-(PT/60)]}{HSE \times 10^6}$$

2. The following calculations apply to ventilating systems in which the temperature is set back using the Day/Night Setback Strategy. These systems may not be shut down but may eliminate outside air during building unoccupied periods except for the ventilation purge time when OA must be introduced.

   Heating savings (MBtu/yr) =

$$\frac{CFM \times POA \times 1.08 \times (WSP-AWT) \times [(168 - OH)-(PT/60 \times Dh)] \times WKH}{HSE \times 10^6}$$

   Cooling savings with electrically driven chiller (kWh/yr with CPT in kW/ton):

$$\frac{CFM \times POA \times 4.5 \times (OAE-RAE) \times [(168 - OH)-(PT/60 \times Dc)] \times WKC \times CPT}{12{,}000}$$

   Cooling savings with steam driven chiller (MBtu/yr with CPT in lb/hr•ton):

$$\frac{CFM \times POA \times 4.5 \times (OAE-RAE) \times [(168 - OH)-(PT/60 \times Dc)] \times WKC \times CPT \times 1000}{12{,}000 \times 10^6}$$

5-4.8 Hot Deck/Cold Deck Temperature Reset

APPLICATION NOTES:

1. The average discharge temperature resets (SCDR, SHDR, WHDR) are system dependent and difficult to estimate. Refer to Appendix A for reasonable estimates in lieu of actual data.

2. A computer simulation is required for accurately determining the savings from this strategy when used with economizer control.

CALCULATIONS:

Heating savings (MBtu/yr) =

$$\frac{CFM \times Phd \times 1.08 \times Hhc \times [(WKC \times SHDR) + (WKH \times WHDR)]}{HSE \times 10^6}$$

The following two equations assume that a 1°F change in cold deck temperature is equivalent to a 0.6 Btu/lb change in enthalpy.

Cooling savings with electrically driven chiller, no economizer (kWh/yr with CPT in kW/ton):

$$\frac{CFM \times Pcd \times 4.5 \times Hhc \times WKC \times SCDR \times 0.6 \times CPT}{12{,}000}$$

Cooling savings with steam driven chiller, no economizer (MBtu/yr with CPT in lb/hr·ton):

$$\frac{CFM \times Pcd \times 4.5 \times Hhc \times WKC \times SCDR \times 0.6 \times CPT \times 1000}{12{,}000 \times 10^6}$$

5-4.9 Reheat Coil Reset

APPLICATION NOTES: A computer simulation is required for accurately determining the savings from Reheat Coil Reset when used with economizer control.

CALCULATIONS:

Reheat savings (MBtu/yr) =

$$\frac{CFM \times 1.08 \times Hh \times 52\ wk/yr \times RHR}{HSE \times 10^6}$$

The following two equations assume that a 1°F change in cooling coil temperature is equivalent to a 0.6 Btu/lb change in enthalpy.

Cooling savings with electrically driven chiller, no economizer (kWh/yr with CPT in kW/ton):

$$\frac{CFM \times 4.5 \times Hh \times WKC \times RHR \times 0.6 \times CPT}{12{,}000}$$

Cooling savings with steam driven chiller, no economizer (MBtu/yr with CPT in lb/hr·ton):

$$\frac{CFM \times 4.5 \times Hh \times WKC \times RHR \times 0.6 \times CPT \times 1000}{12{,}000 \times 10^6}$$

5-4.10 Steam and Hot Water Boiler Selection

APPLICATION NOTES:

CALCULATIONS:

Heating Savings (MBtu/yr) =

$$\frac{HFLH \times BCEI \times CAP}{HSE \times 10^6}$$

5-4.11 Hot Water Outside Air Reset

APPLICATION NOTES:

CALCULATIONS:

Heating savings (MBtu/yr) =

$$\frac{HFLH \times OAEI \times CAP}{HSE \times 10^6}$$

5-4.12 Chiller Selection

APPLICATION NOTES:

1. Applicable only to chilled water plants with multiple chillers.

CALCULATIONS:

Cooling savings with electrically driven chiller, no economizer (kWh/yr with CPT in kW/ton):

$$CFLH \times TON \times CPT \times CSEI$$

Cooling savings with steam driven chiller, no economizer (MBtu/yr with CPT in lb/hr•ton):

$$\frac{CFLH \times TON \times CPT \times CSEI \times 1000}{10^6}$$

5-4.13 Chiller Water Temperature Reset

APPLICATION NOTES: The amount of reset (CWTR) generally ranges between 2°F and 5°F. A conservative estimate of 2°F is recommended for the calculation.

CALCULATIONS:

Cooling savings with electrically driven chiller, no economizer (kWh/yr with CPT in kW/ton):

$$CFLH \times TON \times CPT \times CWTR \times REI$$

Cooling savings with steam driven chiller, no economizer (MBtu/yr with CPT in lb/hr•ton):

$$\frac{CFLH \times TON \times CPT \times CWTR \times REI \times 1000}{10^6}$$

5-4.14 Condenser Water Temperature Reset

APPLICATION NOTES: Do not reduce condenser temperature below manufacturer's recommended low temperature limit.

CALCULATIONS: The calculation procedure requires four steps:

1. Calculate the average reduction in condenser water temperature which is achievable:

$$RCWT = PCWT - ACWT$$

2. Use Figure 5-2 to determine the percent efficiency increase (PEI) of the chiller based on RCWT from above.

3. Determine the adjusted efficiency increase (AEI) of the chiller:

   a. If fan runs continuously, but will be cycled,

$$AEI = \frac{PEI + 5.5}{100}$$

   b. If fan cycles,

$$AEI = \frac{PEI - 2.8}{100}$$

4. Calculate the cooling savings:

   Cooling savings with electrically driven chiller, no economizer (kWh/yr with CPT in kW/ton):

$$CFLH \times TON \times CPT \times AEI$$

   Cooling savings with steam driven chiller, no economizer (MBtu/yr with CPT in lb/hr•ton):

$$\frac{CFLH \times TON \times CPT \times AEI \times 1000}{10^6}$$

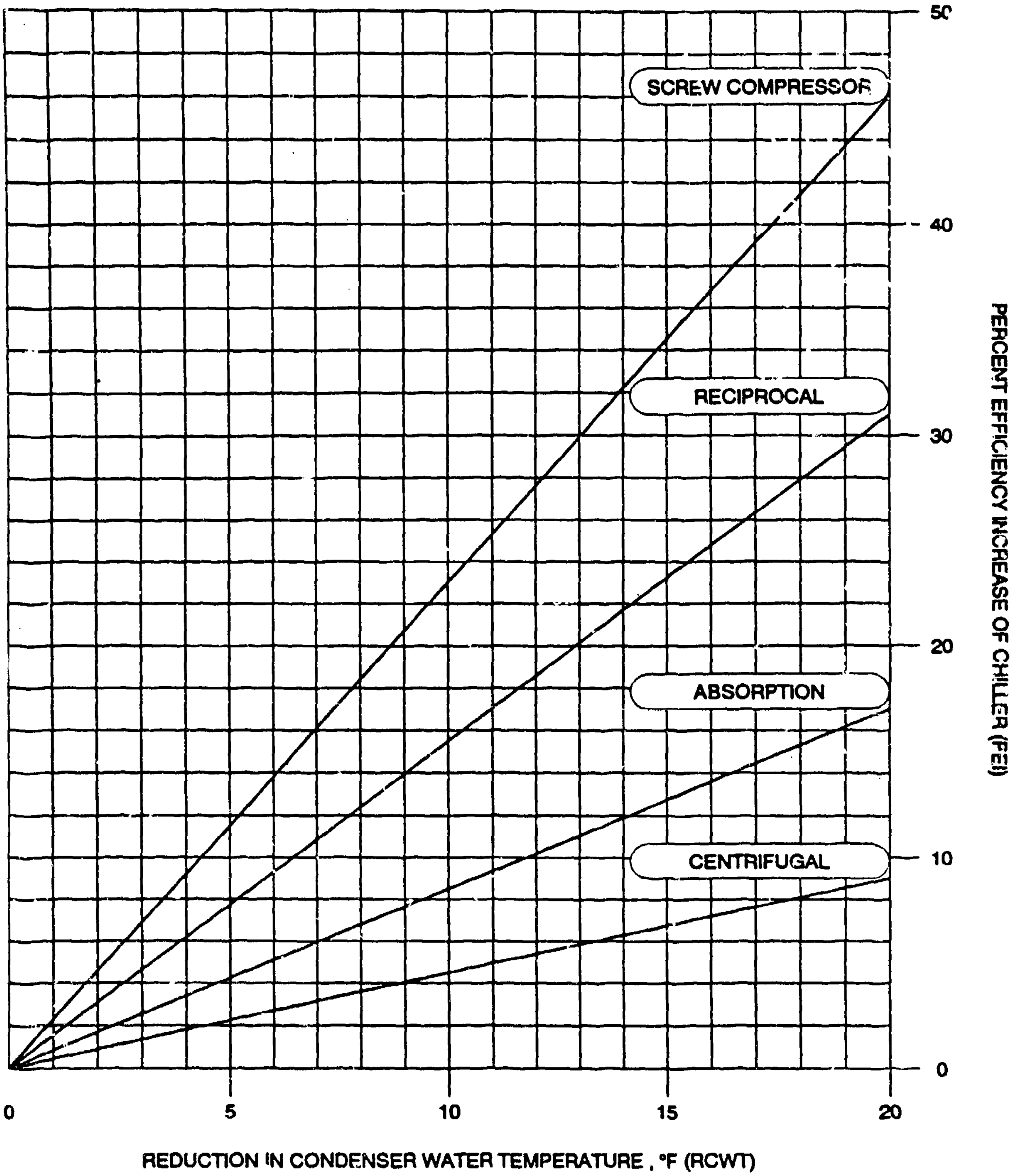


Figure 5-2. Chiller RCWT vs PEI

5-4.15 Chiller Demand Limit

APPLICATION NOTES:

1. Applicable to centrifugal chillers that are equipped with an adjustable control system for limiting the available cooling capacity.

CALCULATIONS:

$$\text{Savings (kW)} = CHP \times CME \times 0.746 \times SDC \times SDT$$

5-4.16 Lighting Control

APPLICATION NOTES:

1. Applicable to relay operated zoned lighting.

2. Assumes one lighting zone..

CALCULATIONS:

$$\text{Savings (kWh/yr)} = TC_L \times (H_L - H_L EMCS) \times 52 \text{ wk/yr}$$

5-4.17 Run Time Recording

APPLICATION NOTES: This savings is based on the assumption that the EMCS is able to save one 2 hour man-visit per year to the system being monitored. This may or may not represent a savings over present facility maintenance procedures.

Labor savings - 2 man-hours/yr

5-4.18 Safety Alarm

APPLICATION NOTES: This savings is based on the assumption that the EMCS is able to save one 2 hour man-visit per year to check alarms and diagnose problems. This may or may not represent a savings over present facility maintenance procedures.

Labor savings - 2 man-hours/yr

Ref	Strategy	Savings			
		MBtu/yr	kWh/yr	kW	Mh/yr
5-4.1	Scheduled Start/Stop				
5-4.2	Optimum Start/Stop				
5-4.3	Duty Cycling				
5-4.4	Demand Limiting				
5-4.5	Day/Night Setback				
5-4.6	OA Dry Bulb Economizer				
5-4.7	Ventilation and Recirculation				
5-4.8	Hot Deck/Cold Deck Temperature Reset				
5-4.9	Reheat Coil Reset				
5-4.10	Boiler Selection				
5-4.11	Hot Water Outside Air Reset				
5-4.12	Chiller Selection				
5-4.13	Chiller Water Temperature Reset				
5-4.14	Condenser Water Temperature Reset				
5-4.15	Chiller Demand Limit				
5-4.16	Lighting Control				
5-4.17	Run Time Recording				
5-4.18	Safety Alarm				
	MBtu Sub Total				
Fuel Type	+ HV (See Appendix A)				
Notes -	TOTALS		kWh/yr	kW	Mh/yr

Figure 5-3. System Savings Summary

Section VI. EXAMPLE SAVINGS CALCULATIONS

6-1 INTRODUCTION and DATA FORMS. This section demonstrates several energy savings calculations for hypothetical Headquarters building 607 which is located on Fort Example, Springfield, Missouri. Building 607 is serviced by the following HVAC and lighting systems:

1.	AHU 1	Multi-zone AHU
2.	AHU 2	Single Zone AHU
3.	HW 1	Hot Water Boiler
4.	CH 2	Water Cooled Chiller
5.	LT 1	Lighting Circuit
6.	LT 2	Lighting Circuit

The savings calculation procedure consists of:

- Completing a physical survey of the building.
- Determining the climate and building factors using the procedures outlined in Section IV.
- Determining which EMCS savings calculations to apply considering the systems and operating conditions (refer to Figure 5-1).
- Using the survey data and factors to calculate EMCS savings.

Input data is included for all systems. Calculations and summary sheets are provided for AHU 1 as an example of methodology. A detailed printout from the ESA program is enclosed which shows the input and output data for AHU 1 and the remaining systems.

GROUP 3 North

NOTE - UNITS OF MEASURE: Area = ft², Temperature = °F

See Appendix A for explanation of terms.

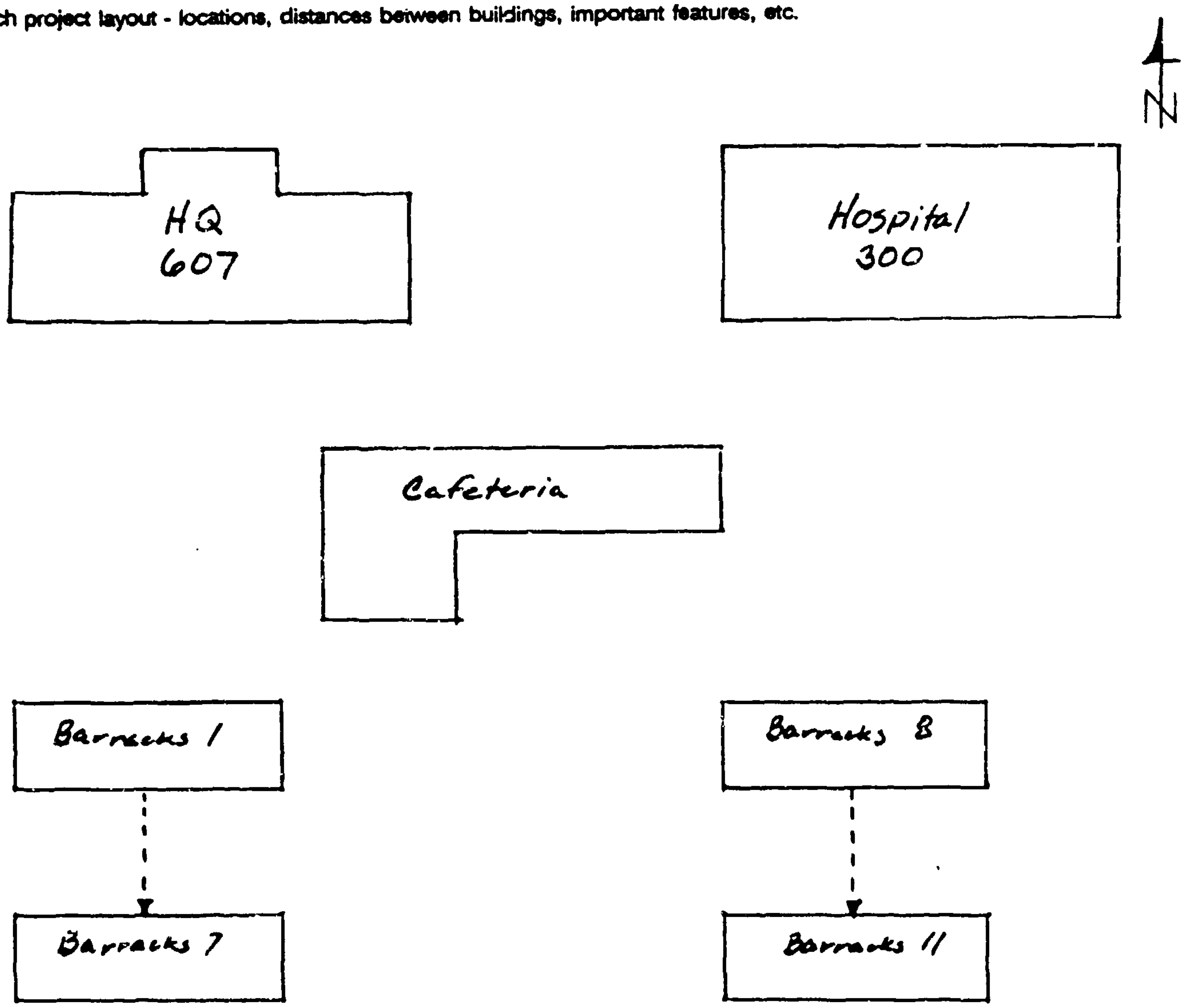
GROUP DATA

Group Desc 408th Division

Location West of James Lake - Fort Example

Buildings in Group 14

Sketch project layout - locations, distances between buildings, important features, etc.



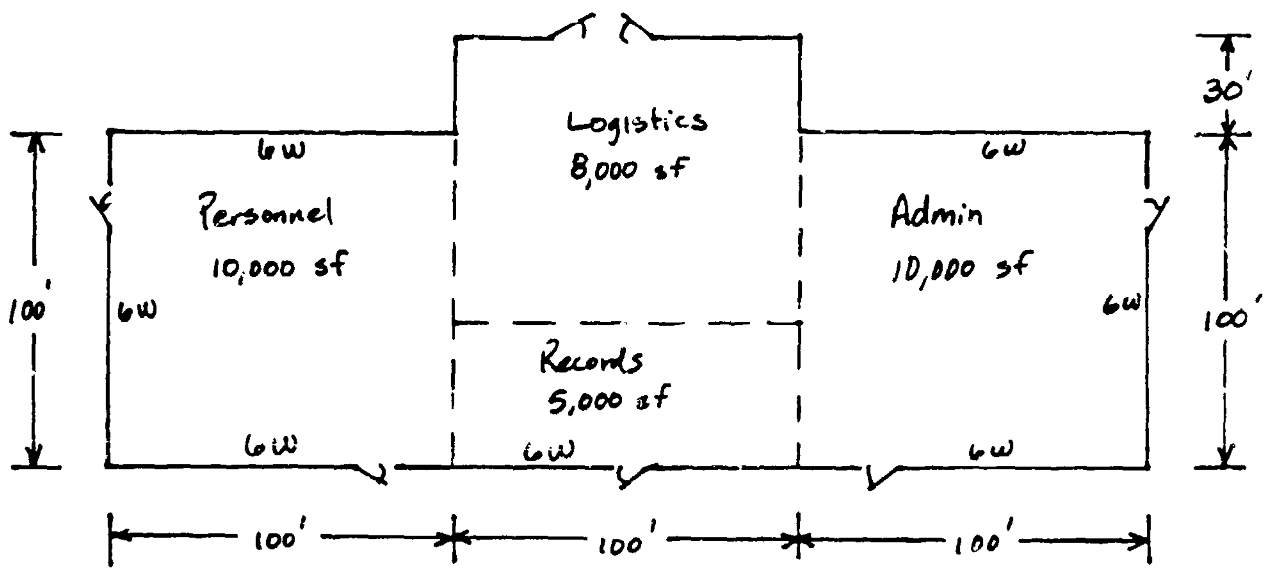
GROUP 3 North	BUILDING 607

BUILDING DATA (1/3)

Building Hours of Operation: 0100-0800 0900-1600 1700-2400 Other ________

Heating Fuel Type: Natural Gas

Sketch Building - Locate Zones, Windows, Doors, etc.



Doors: Main 8' x 7' Qty 1 swinging, glass

Personnel 4' x 6' Qty 5 solid wood, 2¼" t

Windows: 3' x 5' Qty 42 Aluminum frame, non-opening

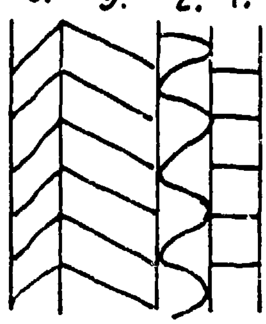
Af = 33,000 sf
One story
No basement

GROUP 3 North	BUILDING 607

BUILDING DATA (2/3)

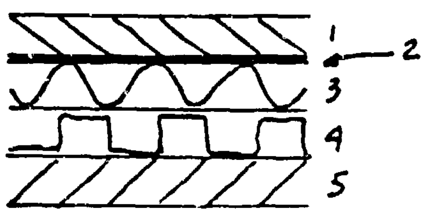
WALLS, EXTERIOR COMPONENTS	R-VALUES
Outside Air Film	0.17
1. 4" common brick	0.92
2. 1" cellular glass	2.86
3. 8" perlite filled	
4. concrete block	2.10
5. ½" gypsum board	0.45
6.	
7.	
Inside Air Film	0.68
TOTAL R VALUE	7.18
$1/R = \langle U_{wall} \rangle =$	0.1393

SKETCH CROSS SECTION



ROOF COMPONENTS	R-VALUES
Outside Air Film	0.17
1. ½" slate	0.05
2. mopped felt	0.12
3. 2" fiber board	5.88
4. steel decking	0.01
5. ½" acoustic tile	1.25
6.	
7.	
Inside Air Film	0.68
TOTAL R VALUE	8.16
$1/R = \langle U_{roof} \rangle =$	0.1225

SKETCH CROSS SECTION



No. of Floors (above ground) 1	Calculated Total Areas (above ground):
Avg. Floor to Floor Height 13'	Walls, gross 11,180 sf
No. of Basement Levels 0	Windows $\langle A_{window} \rangle$ 630 sf
Gross Floor Area <Af> 33,000	Doors $\langle A_{door} \rangle$ 176 sf (56+120)
Roof Area $\langle A_{roof} \rangle$ 33,000	Other
Estimated total bldg. air infiltration (cfm) <I> 750	Walls, net $\langle A_{wall, net} \rangle$ 10,374 sf

GROUP 3 North	BUILDING 607

BUILDING DATA (3/3)

WINDOW TYPE Fixed, Al frame, Single	R-VALUE 1.75	$\langle U_{window} \rangle$ 0.5714
WINDOW TYPE	R-VALUE	$\langle U_{window} \rangle$
WINDOW TYPE	R-VALUE	$\langle U_{window} \rangle$
DOOR TYPE Single pane glass, swinging, 2x	R-VALUE 2.16	$\langle U_{door} \rangle$ 0.4630
DOOR TYPE Wood, solid	R-VALUE 4.55	$\langle U_{door} \rangle$ 0.2198
DOOR TYPE	R-VALUE	$\langle U_{door} \rangle$
OTHER	R-VALUE	$\langle U_{other} \rangle$
OTHER	R-VALUE	$\langle U_{other} \rangle$
OTHER	R-VALUE	$\langle U_{other} \rangle$

$$U_oA_o = U_{wall} \times A_{wall,\,net} + U_{window} \times A_{window} + U_{door} \times A_{door} + U_{roof} \times A_{roof}$$

$$(0.1393 \times 10{,}374) + (0.5714 \times 630) + (0.4630 \times 56) + (0.2198 \times 120) + (0.1225 \times 33{,}000) = 5899.9$$

Remarks - Note air leaks, structural damage, broken/defective windows, fit of windows and doors, vents that remain open, etc.

GROUP 3 North	BUILDING 607

ZONE DATA

ZONE ID 1	Systems Serving Zone AHU1, HW1, CH2, LT1
Location West wing	Nominal hours/week occupied <OH> 45
Function Personnel	Warmup time before occupancy (hr) <WU> 2
Floor Area 10,000	Low Temperature Limit <LTL> 55
Occupied Summer Setpoint <SSP> 75	Summer Setpoint Reset <SSPR> 0
Occupied Winter Setpoint <WSP> 68	(SSPR ≤ AST-SSP)
Days/Week Heating Equipment Operation <Dh> 5	Winter Setpoint Reset <WSPR> 0
Days/Week Cooling Equipment Operation <Dc> 5	(WSPR ≤ WSP-AWT, ≤ WSP-LTL)

SPECIAL REQUIREMENTS

Can ventilation be shut down for duty cycling? (Y/N) Y For what % time? <DCST> 25

Can ventilation be shut down for demand limiting? (Y/N) Y For what % time? <DLST> 25

Can ventilation be shut down during unoccupied hours? (Y/N) Y

If yes, what is the required OA purge time before occupancy? <PT> 15 min

REMARKS

ZONE DATA

ZONE ID 2	Systems Serving Zone AHU1, HW1, CH2, LT1
Location North center	Nominal hours/week occupied <OH> 53
Function Logistics	Warmup time before occupancy (hr) <WU> 2
Floor Area 8,000	Low Temperature Limit <LTL> 55
Occupied Summer Setpoint <SSP> 75	Summer Setpoint Reset <SSPR> 0
Occupied Winter Setpoint <WSP> 68	(SSPR ≤ AST-SSP)
Days/Week Heating Equipment Operation <Dh> 6	Winter Setpoint Reset <WSPR> 8°
Days/Week Cooling Equipment Operation <Dc> 6	(WSPR ≤ WSP-AWT, ≤ WSP-LTL)

SPECIAL REQUIREMENTS

Can ventilation be shut down for duty cycling? (Y/N) Y For what % time? <DCST> 25

Can ventilation be shut down for demand limiting? (Y/N) Y For what % time? <DLST> 25

Can ventilation be shut down during unoccupied hours? (Y/N) Y

If yes, what is the required OA purge time before occupancy? <PT> 15 min

REMARKS

Page ______ of ______

GROUP 3 North	BUILDING 607

ZONE DATA

ZONE ID 3	Systems Serving Zone AHU2, HW1, CH2, LT2
Location South center	Nominal hours/week occupied <OH> 30
Function Records	Warmup time before occupancy (hr) <WU> 1
Floor Area 5,000	Low Temperature Limit <LTL> 55
Occupied Summer Setpoint <SSP> 70	Summer Setpoint Reset <SSPR> 0
Occupied Winter Setpoint <WSP>	(SSPR ≤ AST-SSP)
Days/Week Heating Equipment Operation <Dh> 5	Winter Setpoint Reset <WSPR> 10
Days/Week Cooling Equipment Operation <Dc> 5	(WSPR ≤ WSP-AWT, ≤ WSP-LTL)

SPECIAL REQUIREMENTS

Can ventilation be shut down for duty cycling? (Y/N) Y For what % time? <DCST> 25

Can ventilation be shut down for demand limiting? (Y/N) Y For what % time? <DLST> 25

Can ventilation be shut down during unoccupied hours? (Y/N) Y

If yes, what is the required OA purge time before occupancy? <PT> 15 min

REMARKS

ZONE DATA

ZONE ID 4	Systems Serving Zone AHU1, HW1, CH2, LT1
Location East Wing	Nominal hours/week occupied <OH> 45
Function Administration	Warmup time before occupancy (hr) <WU> 2
Floor Area 10,000	Low Temperature Limit <LTL> 55
Occupied Summer Setpoint <SSP> 75	Summer Setpoint Reset <SSPR> 0
Occupied Winter Setpoint <WSP> 68	(SSPR ≤ AST-SSP)
Days/Week Heating Equipment Operation <Dh> 5	Winter Setpoint Reset <WSPR> 0
Days/Week Cooling Equipment Operation <Dc> 5	(WSPR ≤ WSP-AWT, ≤ WSP-LTL)

SPECIAL REQUIREMENTS

Can ventilation be shut down for duty cycling? (Y/N) Y For what % time? <DCST> 25

Can ventilation be shut down for demand limiting? (Y/N) Y For what % time? <DLST> 25

Can ventilation be shut down during unoccupied hours? (Y/N) Y

If yes, what is the required OA purge time before occupancy? <PT> 15 min

REMARKS

GROUP 3 North	BUILDING 607	SYSTEM AHU1

Applicable Systems

A. Single Zone AHU	D. Multi-zone AHU	G. Two Pipe Fan Coil Unit
B. Terminal Reheat AHU	E. Single Zone DX-A/C	H. Four Pipe Fan Coil Unit
C. Variable Volume AHU	F. Multi-zone DX-A/C	

System Desc Carrier package unit	Zones Served 1-2-4
Location NW roof	Total Area Served <Az> 28,000
System Efficiency <HSE> 0.6	Unit Supplying Heating Energy HW1
Reheat Coil Reset <RHR> —	Heating Energy Fuel Source Nat Gas
Present percent of OA used (decimal) <POA> 0.2	Unit Supplying Cooling Energy CH2
Energy Used/Ton Refrigeration <CPT> 1.5	Cooling Energy Fuel Source Elec.

CURRENT OPERATING SCHEDULE	PROPOSED OPERATING SCHEDULE
Hours/Week Heating System <Hh> 80	Hours/Week Heating System <HhEMCS> 63
Hours/Week at WSP <Hwsp> 80	Hours/Week Cooling System <HcEMCS> 63
Hours/Week Cooling System <Hc> 80	Can system be shut down when
Hours/Week at SSP <Hssp> 80	zone(s) unoccupied? (Y/N) Y

FAN DATA Function	<CFM>	<HP>	PUMP DATA Function	<HP>	AUX DATA Function	<HP>
Supply Air	300	4				
Return Air	300	4				

MULTI-ZONE DATA	
Percent of air passing through Hot Deck <Phd> 50	Summer Hot Deck Reset <SHDR> 4
Percent of air passing through Cold Deck <Pcd> 50	Winter Hot Deck Reset <WHDR> 4
Operating Hours/Week Dual Deck <Hhc> 80	Summer Cold Deck Reset <SCDR> 4

MAX/MIN ZONE DATA			
	<WSP> 68	<SSP> 75	<WU> 2
	<LTL> 55	<WSPR> 8	<Dh> 6
	<OH> 53	<SSPR> 0	<Dc> 6
	<DCST> 25	<DLST> 25	<PT> 15 min

GROUP 3 North	BUILDING 607	SYSTEM AHU 2

Applicable Systems

A. Single Zone AHU	D. Multi-zone AHU	G. Two Pipe Fan Coil Unit
B. Terminal Reheat AHU	E. Single Zone DX-A/C	H. Four Pipe Fan Coil Unit
C. Variable Volume AHU	F. Multi-zone DX-A/C	

System Desc Bowden component

Location South roof

System Efficiency <HSE> 0.70

Reheat Coil Reset <RHR> –

Present percent of OA used (decimal) <POA> 0.1

Energy Used/Ton Refrigeration <CPT> 1.5

Zones Served 3

Total Area Served <Az> 5,000

Unit Supplying Heating Energy HWI

Heating Energy Fuel Source Nat Gas

Unit Supplying Cooling Energy CH2

Cooling Energy Fuel Source Elec.

CURRENT OPERATING SCHEDULE

Hours/Week Heating System <Hh> 80

Hours/Week at WSP <Hwso> 80

Hours/Week Cooling System <Hc> 80

Hours/Week at SSP <Hssp> 80

PROPOSED OPERATING SCHEDULE

Hours/Week Heating System <HhEMCS> 35

Hours/Week Cooling System <HcEMCS> 35

Can system be shut down when zone(s) unoccupied? (Y/N) Y

FAN DATA Function	<CFM>	<HP>	PUMP DATA Function	<HP>	AUX DATA Function	<HP>
Supply Air	200	3				
Return Air	200	3				

MULTI-ZONE DATA

Percent of air passing through Hot Deck <Phd>

Percent of air passing through Cold Deck <Pcd>

Operating Hours/Week Dual Deck <Hhc>

Summer Hot Deck Reset <SHDR>

Winter Hot Deck Reset <WHDR>

Summer Cold Deck Reset <SCDR>

MAX/MIN ZONE DATA			
	<WSP> 68	<SSP> 70	<WU> 1
	<LTL> 55	<WSPR> 10	<Dh> 5
	<OH> 30	<SSPR> 0	<Dc> 5
	<DCST> 25	<DLST> 25	<PT> 15 min

GROUP 3 North	BUILDING 607	SYSTEM HW1

Applicable Systems

R. Steam Boiler	S. Hot Water Boiler

System Desc McGee 1K unit

Zones Served 1-2-3-4

Location West end bldg 300

Heating Energy Fuel Type Nat Gas

Efficiency Increase

Max Total Capacity (Btu/hr) <CAP> 12,500

when Changing Boilers <BCEI> 1

Heating system Efficiency Increase <OAEI> 3

System Availability (days/year) 180

System Efficiency <HSE> 0.6

REMARKS

GROUP 3 North	BUILDING 607	SYSTEM CH2

Applicable Systems

W. Water Cooled DX Compressor
X. Air Cooled DX Compressor
Y. Air Cooled Chiller
Z. Water Cooled Chiller

System Desc Old Peterson unit

Location East end of Bldg 607

Chiller Type: (1) Centrifugal (2) Absorption (3) Reciprocal (4) Screw Comp

Centrifugal Chiller Motor HP <CHP> 60

Centrifugal Chiller Motor Efficiency <CME> 0.85

System Availability (days/year) 180

Zones Served 1-2-3-4

Energy Used/Ton Refrigeration <CPT> 1.5

Chiller Capacity (tons) <TON> 45

Present Condenser Water Temperature <PCWT> 83

Is the condenser fan continuous or cycling? Cont

Chiller water temperature reset <CWTR> 2

Efficiency increase when changing chillers <CSEI> /

Can the centrifugal chiller be shut down for demand limiting? (Y/N) Y For what % time? <SDT> 25

Can the centrifugal chiller capacity be stepped down for demand limiting? (Y/N) Y By what %? <SDC> 20

CURRENT OPERATING SCHEDULE

Hours/Week Cooling System <Hc> ______

PROPOSED OPERATING SCHEDULE

Hours/Week Cooling System <HcEMCS> ______

FAN DATA Function	<HP>	PUMP DATA Function	<HP>
Condenser	/		

REMARKS

Page ______ of ______

GROUP 3 North	BUILDING 607	SYSTEM LT1

Applicable Systems

(AA) Lighting Control

System Desc LT1

Zones Served 1-2-4

Location NE wall

Total Wattage $<TC_L>$ 56,000

CURRENT OPERATING SCHEDULE

Hours/Week Lighting System $<H_L>$ 80

PROPOSED OPERATING SCHEDULE

Hours/Week Lighting System $<H_L EMCS>$ 55

REMARKS

GROUP 3 North	BUILDING 607	SYSTEM LT2

Applicable Systems

AA. Lighting Control

System Desc LT2

Zones Served 3

Location South Wall

Total Wattage $<TC_L>$ 5,000

CURRENT OPERATING SCHEDULE

Hours/Week Lighting System $<H_L>$ 80

PROPOSED OPERATING SCHEDULE

Hours/Week Lighting System $<H_L EMCS>$ 32

REMARKS

Page ________ of ________

GROUP 3 North	BUILDING 607

Factor Summary

Ref	Factor	Calculated Value	
4-4.1	ACWT	= 75.6	°F
4-4.2	ANDW	= 264	days/year
4-4.3	AST	= 76.9	°F
4-4.4	AWT	= 43.5	°F
4-4.5	CFLH	= 760	hrs/year
4-4.6	HFLH	= 525	hrs/year
4-4.7	WKH	= 31.7	weeks/year
4-4.7	WKC	= 15.1	weeks/year
4-4.8	OAE	= 32.14	Btu/lb
4-4.9	PRT	= 14.7	%
4-4.10	UoAo I Af BTT	= 5899.9 = 750 = 33,000 = 0.203	Btu/hr·°F cfm ft^2 Btu/hr·ft^2·°F

Page ________ of ________

6-2 CALCULATIONS.

6-2.1 Climate Factors. See example calculations in Section IV. Results are summarized on page 6-14.

6-2.2 Building Factors.

From page 6-3, Heating Fuel Type is Natural Gas
From calculation on page 6-5, UoAo = 5899.9 Btu/(hr•°F)
From page 6-4, I = 750 cfm, Af = 33,000 ft²
From page 4-16,

$$BTT = \frac{5899.9 + (750 \times 1.08)}{33{,}000} = 0.2033303 \text{ Btu/(hr}\cdot\text{ft}^2\cdot{}^\circ\text{F)}$$

6-2.3 System 1, AHU 1, Multi-zone AHU.

Data from page 6-8, Climate Factors, and Building Factors.

ANDW=264	AST=76.9	AWT=43.5	Az=28,000	BTT=0.203
CFM=300	CPT=1.5	Hc=80	HcEMCS=63	Hh=80
Hhc=80	HhEMCS=63	HP=8	LTL=55	OAE=32.14
Pcd=0.5	Phd=0.5	POA=0.2	PRT=14.7	PT=15
SCDR=4	SHDR=4	SSP=75	WHDR=4	WKC=15.1
WKH=31.7	WSP=68	WU=2		

System may be shut down when building unoccupied.

Using defaults RAE=29.91 and L=0.80

Scheduled Start/Stop Strategy

1. Heat loss/gain through the structure

Heating savings (MBtu/yr):

$$\frac{BTT \times Az \times (WSP-LTL) \times (Hh-HhEMCS) \times WKH}{HSE \times 10^6}$$

$$\frac{0.203 \times 28{,}000 \times (68 - 55) \times (80 - 63) \times 31.7}{0.6 \times 10^6} = 66.37$$

Cooling savings with electrically driven chiller (kWh/yr with CPT in kW/ton):

$$\frac{BTT \times Az \times (AST-SSP) \times (Hc-HcEMCS) \times WKC \times CPT}{12{,}000}$$

$$\frac{0.203 \times 28{,}000 \times (76.9 - 75) \times (80 - 63) \times 15.1 \times 1.5}{12{,}000} = 346.5$$

2. Heat loss/gain through ventilation air

Heating savings (MBtu/yr):

$$\frac{CFM \times POA \times 1.08 \times (WSP\text{-}AWT) \times (Hh\text{-}HhEMCS) \times WKH}{HSE \times 10^6}$$

$$\frac{300 \times 0.2 \times 1.08 \times (68 - 43.5) \times (80 - 63) \times 31.7}{0.6 \times 10^6} = 1.43$$

Cooling savings with electrically driven chiller (kWh/yr with CPT in kW/ton):

$$\frac{CFM \times POA \times 4.5 \times (OAE\text{-}RAE) \times (Hc\text{-}HcEMCS) \times WKC \times CPT}{12{,}000}$$

$$\frac{300 \times 0.2 \times 4.5 \times (32.14 - 29.91) \times (80 - 63) \times 15.1 \times 1.5}{12{,}000} = 19.3$$

3. Auxiliary equipment operation

Heating auxiliary savings (kWh/yr):

$$HP \times L \times 0.746 \times (Hh\text{-}HhEMCS) \times WKH \times (1\text{-}PRT)$$

$$8 \times 0.8 \times 0.746 \times (80 - 63) \times 31.7 \times (1 - .147) = 2194.7$$

Cooling auxiliary savings (kWh/yr):

$$HP \times L \times 0.746 \times (Hc\text{-}HcEMCS) \times WKC$$

$$8 \times 0.8 \times 0.746 \times (80 - 63) \times 15.1 = 1225.6$$

Total savings for Scheduled Start/Stop:

MBtu/yr = 66.37 + 1.43 + = 67.80

kWh/yr = 346.5 + 19.3 + 2194.7 + 1225.6 = 3786.1

Note: These numbers will differ slightly from the ESA program output due to rounding.

Ventilation and Recirculation

Heating savings (MBtu/yr) =

$$\frac{CFM \times FOA \times 1.08 \times (WSP-AWT) \times ANDW \times [WU-(PT/60)]}{HSE \times 10^6}$$

$$\frac{300 \times 0.2 \times 1.08 \times (68 - 43.5) \times 264 \times [2 - (15/60)]}{0.6 \times 10^6} = 1.222$$

Hot Deck/Cold Deck Temperature Reset

Heating savings (MBtu/yr) =

$$\frac{CFM \times Phd \times 1.08 \times Hhc \times [(WKC \times SHDR) + (WKH \times WHDR)]}{HSE \times 10^6}$$

$$\frac{300 \times 0.5 \times 1.08 \times 80 \times [(15.1 \times 4) + (31.7 \times 4)]}{0.6 \times 10^6} = 4.044$$

The following equation assumes that a 1°F change in cold deck temperature is equivalent to a 0.6 Btu/lb change in enthalpy.

Cooling savings with electrically driven chiller, no economizer (kWh/yr with CPT in kW/ton):

$$\frac{CFM \times Pcd \times 4.5 \times Hhc \times WKC \times SCDR \times 0.6 \times CPT}{12{,}000}$$

$$\frac{300 \times 0.5 \times 4.5 \times 80 \times 15.1 \times 4 \times 0.6 \times 1.5}{12{,}000} = 245$$

Refer to the ESA program detailed output for savings results from additional systems.

GROUP 3 North	BUILDING 607	SYSTEM AHU 1

System Savings Summary

Ref	Strategy	Savings MBtu/yr	kWh/yr	kW	Mh/yr
5-4.1	Scheduled Start/Stop	67.80	3786.1		
5-4.2	Optimum Start/Stop				
5-4.3	Duty Cycling				
5-4.4	Demand Limiting				
5-4.5	Day/Night Setback				
5-4.6	OA Dry Bulb Economizer				
5-4.7	Ventilation and Recirculation	1.22			
5-4.8	Hot Deck/Cold Deck Temperature Reset	4.044	245		
5-4.9	Reheat Coil Reset				
5-4.10	Boiler Selection				
5-4.11	Hot Water Outside Air Reset				
5-4.12	Chiller Selection				
5-4.13	Chiller Water Temperature Reset				
5-4.14	Condenser Water Temperature Reset				
5-4.15	Chiller Demand Limit				
5-4.16	Lighting Control				
5-4.17	Run Time Recording				
5-4.18	Safety Alarm				
	MBtu Sub Total	73.064			
Fuel Type Nat Gas	1,025 (See Appendix A) + HV	1,025			
Notes -	TOTALS	71,282 cf/yr	4,031 kWh/yr	kW	Mh/yr

EMCS Annual Energy Savings Detailed Report

Base:	3-NORTH
Building:	607
Case:	1
Description:	Section 6 Example Calculation
Fuel Type:	Natural gas (methane)
Heating Value:	1,025 Btu/cf

Caution

The ESA program makes no attempt to exclude incompatible strategies. It is the user's responsibility to select all appropriate strategies.

Note

The scheduled start/stop and day/night setback strategies are affected by the following data values:

- If PRT is zero, then AWT will be used in place of LTL.
- If AWT > LTL, then AWT will be used in place of LTL.
- If WSPR > WSP-LTL, then WSP-LTL will be used in place of WSPR.
- If SSPR > AST-SSP, then AST-SSP will be used in place of SSPR.

Building Data Table

Variable Description	Symbol	Value	Units
Mod Comb Thermal Transmittance	UoAo	5,899.9	Btu/hr*F
Total Air Infiltration	I	750	cfm
Gross Floor Area	Af	33,000	sq ft
Building Thermal Transmission	BTT	0.203	Btu/hr*sq ft*F

Climate Data Table for MO, Springfield MAP (9-16)

Variable Description	Symbol	Value	Units
Avg Entering Condenser Water Temperature	ACWT	75.6	degrees F
Annual Number of Days for Morning Warmup	ANDW	264	days/year
Average Summer Temperature	AST	76.9	degrees F
Average Winter Temperature	AWT	43.5	degrees F
Cooling Full-Load Hours	CFLH	760	hours/year
Heating Full-Load Hours	HFLH	525	hours/year
Weeks of Cooling	WKC	15.1	weeks/year
Weeks of Heating	WKH	31.7	weeks/year
Average Outside Air Enthalpy	OAE	32.14	Btu/lb
Percent Run Time	PRT	14.7	percent

Input Data Table for Single Zone AHU

System Description: AHU 2 - Bowden component unit on S roof

Variable Description	Symbol	Value	Units
Area of zone	Az	5,000	sq ft
Winter thermostat setpoint, occupied	WSP	68.0	degrees F
Low temperature limit	LTL	55.0	degrees F
Heating operation without EMCS	Hh	80	hours/week
Heating operation with EMCS	HhEMCS	35	hours/week
Heating system efficiency	HSE	0.70	decimal
Summer thermostat setpoint, occupied	SSP	70.0	degrees F
Return air enthalpy when unoccupied	RAE	29.91	Btu/lb
Cooling operation without EMCS	Hc	80	hours/week
Cooling operation with EMCS	HcEMCS	35	hours/week
Cooling energy consumption per ton	CPT	1.5	kW/ton
Supply air capacity	CFM	200	cfm
Present fraction of outside air used	POA	0.10	decimal
Equipment motor horsepower	HP	6.00	hp
Equipment motor load factor	L	0.80	decimal
Zone occupied hours	OH	30	hours/week
Duty cycling shutdown time	DCST	25.0	percent
Demand limiting shed time	DLST	25.0	percent
Winter thermostat setpoint reset	WSPR	10.0	degrees F
Winter setpoint equipment operation	Hwsp	80	hours/week
Summer thermostat setpoint reset	SSPR	0.0	degrees F
Summer setpoint equipment operation	Hssp	80	hours/week
Shutdown system when bldg unoccupied?		Y	Y or N
Present warmup time before occupancy	WU	1.0	hours/day
Heating equipment operating schedule	Dh	5	days/week
Cooling equipment operating schedule	Dc	5	days/week
Purge time before occupancy	PT	15.0	minutes
Optimum start/stop heating savings		0.0	MBtu
Optimum start/stop htg-vent savings		0.0	MBtu
Optimum start/stop htg aux savings		0.0	kWh
Optimum start/stop cooling savings		0.0	kWh
Optimum start/stop clg-vent savings		0.0	kWh
Optimum start/stop clg aux savings		0.0	kWh
Economizer cooling savings		0.0	kWh
Scheduled start/stop labor savings		0	mh
Optimum start/stop labor savings		0	mh
Duty cycling labor savings		0	mh
Demand limiting labor savings		0	mh
Day/night setback labor savings		0	mh
Economizer labor savings		0	mh
Vent/recirc labor savings		0	mh
Run time recording labor savings		2	mh
Safety alarm labor savings		2	mh

Annual Energy Savings Table for Single Zone AHU

Description: AHU 2 - Bowden component unit on S roof				
Strategy	MBtu/yr	kWh/yr	kW	mh/yr
Scheduled Start/Stop	28.012	7,403	0.0	0
Duty Cycling	0.000	1,397	0.0	0
Demand Limiting	0.000	0	0.9	0
Subtotals	28.012	8,800	0.9	0
Heating Value +	1,025 Btu/cf			
Totals	27,328 cf/yr	8,800 kWh/yr	0.9 kW	0 mh/yr

Input Data Table for Multi-zone AHU

System Description: AHU 1 - Carrier package unit on NW roof			
Variable Description	Symbol	Value	Units
Area of zone	Az	28,000	sq ft
Winter thermostat setpoint, occupied	WSP	68.0	degrees F
Low temperature limit	LTL	55.0	degrees F
Heating operation without EMCS	Hh	80	hours/week
Heating operation with EMCS	HhEMCS	63	hours/week
Heating system efficiency	HSE	0.60	decimal
Summer thermostat setpoint, occupied	SSP	75.0	degrees F
Return air enthalpy when unoccupied	RAE	29.91	Btu/lb
Cooling operation without EMCS	Hc	80	hours/week
Cooling operation with EMCS	HcEMCS	63	hours/week
Cooling energy consumption per ton	CPT	1.5	kW/ton
Supply air capacity	CFM	300	cfm
Present fraction of outside air used	POA	0.20	decimal
Equipment motor horsepower	HP	8.00	hp
Equipment motor load factor	L	0.80	decimal
Zone occupied hours	OH	45	hours/week
Duty cycling shutdown time	DCST	25.0	percent
Demand limiting shed time	DLST	25.0	percent
Winter thermostat setpoint reset	WSPR	0.0	degrees F
Winter setpoint equipment operation	Hwsp	80	hours/week
Summer thermostat setpoint reset	SSPR	0.0	degrees F
Summer setpoint equipment operation	Hssp	80	hours/week
Shutdown system when bldg unoccupied?		Y	Y or N
Present warmup time before occupancy	WU	2.0	hours/day
Heating equipment operating schedule	Dh	6	days/week
Cooling equipment operating schedule	Dc	6	days/week
Purge time before occupancy	PT	15.0	minutes
Fraction of total air thru hot deck	Phd	0.50	decimal
Hot/cold deck equipment operation	Hhc	80	hours/week
Summer hot deck reset	SHDR	4.0	degrees F
Winter hot deck reset	WHDR	4.0	degrees F
Fraction of total air thru cold deck	Pcd	0.50	decimal

Summer cold deck reset	SCDR	4.0	degrees F
Optimum start/stop heating savings		0.0	MBtu
Optimum start/stop htg-vent savings		0.0	MBtu
Optimum start/stop htg aux savings		0.0	kWh
Optimum start/stop cooling savings		0.0	kWh
Optimum start/stop clg-vent savings		0.0	kWh
Optimum start/stop clg aux savings		0.0	kWh
Economizer cooling savings		0.0	kWh
Scheduled start/stop labor savings		0	mh
Optimum start/stop labor savings		0	mh
Duty cycling labor savings		0	mh
Demand limiting labor savings		0	mh
Day/night setback labor savings		0	mh
Economizer labor savings		0	mh
Vent/recirc labor savings		0	mh
Hot deck/cold deck labor savings		0	mh
Run time recording labor savings		2	mh
Safety alarm labor savings		2	mh

Annual Energy Savings Table for Multi-zone AHU

Description: AHU 1 - Carrier package unit on NW roof				
Strategy	MBtu/yr	kWh/yr	kW	mh/yr
Scheduled Start/Stop	67.901	3,787	0.0	0
Vent/Recirculation	1.222	0	0.0	0
Hot/Cold Deck Reset	4.044	245	0.0	0
Subtotals	73.167	4,031	0.0	0
Heating Value +	1,025 Btu/cf			
Totals	71,383 cf/yr	4,031 kWh/yr	0.0 kW	0 mh/yr

Input Data Table for Hot Water Boiler

System Description: HW 1 - McGee 1K unit/bldg 300			
Variable Description	Symbol	Value	Units
Heating system efficiency	HSE	0.60	decimal
Total input rating of boilers	CAP	12,500	Btu/hr
Boiler conversion efficiency increase	BCEI	1.0	percent
Heating system efficiency increase	OAEI	3.0	percent
HW boiler selection labor savings		0	mh
HW outside air reset labor savings		0	mh
Run time recording labor savings		2	mh
Safety alarm labor savings		2	mh

Annual Energy Savings Table for Hot Water Boiler

Description: HW 1 - McGee 1K unit/bldg 300				
Strategy	MBtu/yr	kWh/yr	kW	mh/yr
HW Boiler Selection	0.109	0	0.0	0
Hot Water OA Reset	0.328	0	0.0	0
Run Time Recording	0.000	0	0.0	2
Safety Alarm	0.000	0	0.0	2
Subtotals	0.438	0	0.0	4
Heating Value +	1,025 Btu/cf			
Totals	427	0	0.0	4
	cf/yr	kWh/yr	kW	mh/yr

Input Data Table for Water Cooled Chiller

System Description: CH 2 - Old Peterson unit/ E end of bldg 607			
Variable Description	Symbol	Value	Units
Cooling energy consumption per ton	CPT	1.7	kW/ton
Total capacity of chillers	TON	45	tons
Chiller selection efficiency increase	CSEI	1.0	percent
Chiller water temperature reset	CWTR	2.0	degrees F
Chiller type		1	choice list
Present condenser water temperature	PCWT	83.0	degrees F
Present fan operation		0	choice list
Centrifugal chiller motor horsepower	CHP	60.00	hp
Centrifugal chiller motor efficiency	CME	0.85	decimal
Step down percent of capacity	SDC	20.0	percent
Step down percent of time	SDT	25.0	percent
Chiller selection labor savings		0	mh
Chiller water reset labor savings		0	mh
Condenser water reset labor savings		0	mh
Chiller demand limit labor savings		0	mh
Run time recording labor savings		2	mh
Safety alarm labor savings		2	mh

Annual Energy Savings Table for Water Cooled Chiller

Description: CH 2 - Old Peterson unit/ E end of bldg 607				
Strategy	MBtu/yr	kWh/yr	kW	mh/yr
Chiller Selection	0.000	581	0.0	0
Chiller Water Reset	0.000	1,977	0.0	0
Condenser Water Reset	0.000	5,134	0.0	0
Chiller Demand Limit	0.000	0	1.9	0
Run Time Recording	0.000	0	0.0	2
Totals	0.000 MBtu/yr	7,692 kWh/yr	1.9 kW	2 mh/yr

Input Data Table for Lighting Control

System Description: LT 2 - LT2			
Variable Description	Symbol	Value	Units
Total power consumption of lights	TC1	15	kW
Lighting operation without EMCS	H1	80	hours/week
Lighting operation with EMCS	H1EMCS	32	hours/week
Lighting control labor savings		0	mh
Run time recording labor savings		2	mh
Safety alarm labor savings		2	mh

Annual Energy Savings Table for Lighting Control

Description: LT 2 - LT2				
Strategy	MBtu/yr	kWh/yr	kW	mh/yr
Lighting Control	0.000	37,440	0.0	0
Totals	0.000 MBtu/yr	37,440 kWh/yr	0.0 kW	0 mh/yr

Input Data Table for Lighting Control

System Description: LT 1 - LT1			
Variable Description	Symbol	Value	Units
Total power consumption of lights	TC1	84	kW
Lighting operation without EMCS	H1	80	hours/week
Lighting operation with EMCS	H1EMCS	55	hours/week
Lighting control labor savings		0	mh
Run time recording labor savings		2	mh
Safety alarm labor savings		2	mh

Annual Energy Savings Table for Lighting Control

Description: LT 1 - LT1				
Strategy	MBtu/yr	kWh/yr	kW	mh/yr
Lighting Control	0.000	109,200	0.0	0
Totals	0.000 MBtu/yr	109,200 kWh/yr	0.0 kW	0 mh/yr

EMCS Annual Energy Savings for Building 607

Description	Value	Units
Natural gas (methane)	99,138	cf/yr
Electrical Energy	167,163	kWh/yr
Electrical Demand Reduction	2.8	kW
Labor Savings	6	mh/yr

Appendix A. DEFINITIONS OF VARIABLES

ACWT = Average entering condenser water temperature in °F. ACWT is calculated during normal operating time period of 0900-1600 for temperature ranges above 55°F.

AEI = Adjusted efficiency increase (decimal) of the condenser water reset.

Af = Enter the building's gross floor area in ft².

ANDW = Annual number of days requiring morning warmup. ANDW is calculated during normal start-up time period of 0100 to 0800 for temperature ranges below 55°F. ANDW is limited by boiler availability; use the lesser of ANDW, scheduled days of boiler operation, or WKH x 7 days per week.

AST = Average summer temperature in °F. AST is calculated during normal off-time periods of 0100-0800 and 1700-2400 for temperature ranges above 75°F.

AWT = Average winter temperature in °F. AWT is calculated during 24 hour time period for temperature ranges below 65°F.

Az = Area of the zone being serviced by this system in ft².

BCEI = Percent efficiency increase when changing from one boiler/converter to another. Use actual data or typical value of 1.0.

BTT = Building thermal transmission factor in Btu/hr·ft²·°F.

CAP = Total input rating of boilers/converters in Btu/hr.

CFLH = Annual equivalent full-load hours for cooling in hours per year. CFLH is calculated during 0900 to 1600 time period for temperature ranges equal to or above 65°F. CFLH is limited by chiller availability; use scheduled days of chiller operation if less than CFLH.

CFM = AHU capacity in cfm. Use, in order of preference, manufacturer's name plate data, as-built mechanical plans, catalog data, or a cfm value equal to the square feet of the area being served (Az).

CHP = Centrifugal chiller motor horsepower.

CME = Centrifugal chiller motor efficiency.

CPT = Energy consumption per ton of refrigeration in kW/ton (electrical) or lb/ton-hr (steam). Use nameplate data, value from manufacturer's catalog, typical values listed below, or approximate electrical power inputs for compressors listed in the latest ASHRAE Handbook--Equipment. Table 2, page 12.7, of the ASHRAE 1983 Handbook--Equipment is reproduced in Appendix C of the EMCS Savings Manual. To convert tons/hp to kW/ton,

$$\text{kW/ton} = (0.746 \text{ kW/hp})/(1/\text{xx tons/hp})$$

Typical values for electrically-driven units:

Air Cooled DX unit (old) = 1.5 kW/ton
Air Cooled DX unit (new) = 1.3 kW/ton
Chiller w/o pump (old) = 0.8 kW/ton
Chiller w/o pump (new) = 0.7 kW/ton

Typical values for steam-driven refrigeration machines:

Steam absorption machine = 18 lb/ton-hr
Steam turbine driven machine = 40 lb/ton-hr

CPT will be the same for all air handling systems using chilled water from the same central chiller. Direct expansion units or package units will be exceptions.

CSEI = The percent efficiency increase due to the EMCS selecting a more efficient chiller.

CWTR = Chiller water temperature reset in °F. The value generally ranges between 2° and 5°F.

Dc = Present days per week of cooling equipment operation.

DCST = The amount of time, in percent, that the system can be shut down for duty cycling.

Dh = Present days per week of heating equipment operation.

DLST = The amount of time, in percent, that the system can be shut down for demand limiting.

Hc = Present hours of cooling equipment operation per week.

HcEMCS= Proposed hours of cooling equipment operation per week with EMCS.

HFLH = Annual equivalent full-load hours for heating in hours per year. HFLH is calculated during 0900-1600 time period for temperature ranges below 65°F. HFLH is limited by boiler availability; use scheduled days of boiler operation if less than HFLH.

Hh = Present hours of heating equipment operation per week. Include warmup (WU) time.

Hhc = Hours of operation per week for the hot deck/cold deck. Use actual data or occupied hours (OH) plus one hour per occupied day.

HhEMCS= Proposed hours of heating equipment operation per week with EMCS. Include warmup (WU) time.

H_L = Present hours of lighting equipment operation per week. Use actual hours of operation or hours of occupancy.

H_LEMCS= Proposed hours of lighting equipment operation per week with EMCS.

HP = Total motor horsepower for all fans, cooling, and heating pumps associated with this system. EXCEPTION: For packaged units such as Air Cooled Chillers and Air Cooled DX units, include HP as a component of the CPT factor.

If horsepower is not listed on the motor name plate it may be calculated as follows:

$$\text{Design HP} = \frac{V \times A \times \sqrt{\phi} \times 1.34 \text{ hp/kW} \times pf}{1000 \text{ watts/kW}}$$

where, V = voltage, A = full load or rated amperage, ϕ = number of phases, pf = power factor (use actual data or typical value of 0.90)

For motors 25 hp or greater, it is preferable to measure the electrical consumption. Use total system HP for auxiliary equipment applications if required.

HSE = Heating system efficiency. Use manufacturer's data or the following average values:

Oil or gas fired boiler and hot water heating system	0.6-0.7
Coal fired boilers	0.6
Electrical resistance duct heaters	1.0

All systems - Use actual data for heat exchanger efficiency (HEE), boiler efficiency (BE), and distribution efficiency (DE) or use typical values of HEE = 0.90, DE = 0.90. Calculate overall efficiency as follows:

$$HSE = HEE \text{ (if any)} \times BE \times DE$$

Hssp = The time, in hours per week, during which the system is operated at the SSP.

HV = Heating value of fuel. Use actual data or the following average values:

Electricity (at the meter)	3413 Btu/kWh
Electricity (at point of generation)	11,600 Btu/kWh
Fuel oil, distillate #2	138,690 Btu/gallon
Fuel oil, residual #6	149,690 Btu/gallon
Natural gas (methane)[1,3]	1,025 Btu/cf
Propane, gas[1,3]	2500 Btu/cf
Propane, liquid[1,3]	91,500 Btu/gallon
Bituminous coal[2,3]	26,260,000 Btu/short ton
Steam (at point of consumption)	1000 Btu/lb
Steam (at point of generation)	1390 Btu/lb

Hwsp = The time, in hours per week, during which the system is operated at the WSP.

I = Total air infiltration for the building in cfm. This value may be calculated using methods discussed in Chapter 23 of the ASHRAE Handbook--Fundamentals.

L = Load factor for the motor(s). Use actual data or typical value of 0.80.

LTL = Low temperature limit in °F. LTL is the lowest allowable temperature for the zone. Use AWT in place of LTL if AWT > LTL. If no LTL is desired, use AWT in place of LTL and set PRT=0.

OAE = Average outside air enthalpy in Btu/lb. OAE is calculated during the normally unoccupied time periods of 0100-0800 and 1700-2400 for dry bulb temperatures above 75°F.

OAEI = Percent efficiency increase in the heating system. Increased outside air temperature will reduce demand thus allowing water/steam temperature to be decreased resulting in decreased system losses. Use actual data or typical value of 1.0.

OH = Zone occupied hours per week.

Pcd = The portion (decimal) of total air passing through the cold deck. Use actual data or typical value of 0.50.

PCWT = Present condenser water temperature in °F.

PEI = Percent efficiency increase of the chiller.

Phd = The portion (decimal) of total air passing through the hot deck. Use actual data or typical value of 0.50.

POA = Decimal fraction of outside air which is inducted into the system.

PRT = Fan percent run time to maintain 55° Low Temperature Limit (LTL). The percent run time is the percentage of scheduled off time during unoccupied periods when the fans and pumps must come back on in order to maintain a 55°F low temperature limit. Use the actual equipment schedule if available. If no LTL is desired, set PRT=0.

PT = The outside air purge time, in minutes, which is required prior to occupancy for a system which has been shut down by the scheduled start/stop strategy.

PWR = Kilowatt power rating for electric heating devices.

RAE = Return air enthalpy during unoccupied hours. Use 29.91 Btu/lb for 78°F and 50% humidity. For other conditions obtain value from psychrometric chart (Appendix C).

RCWT = Potential reduction in condenser water temperature in °F.

REI = Rate of efficiency increase per °F increase in chilled water temperature. Typical values are:

Screw compressor machine	.024 per °F
Centrifugal machine	.017 per °F
Reciprocal machine	.012 per °F
Absorption machine	.006 per °F

RHR = Reheat system cooling coil discharge reset in °F. Typical increment 3°F. Maximum value typically 6°F.

SCDR = Summer cold deck reset in °F. The average reset that will result from this function is dependent upon the air handler capacity relative to loads in the space that it serves. A typical increment is 4°F.

SDC = The percent of maximum cooling capacity that the centrifugal chiller can be stepped down for demand limiting.

SDDDBT= Summer design data 2.5% dry bulb temperature in °F. This is the dry bulb temperature which was equaled or exceeded 2.5 % of the time, on average, during the warmest 4 consecutive months (standardized as June, July, August, September).

SDT = The amount of time, in percent, that the centrifugal chiller can be shut down for demand limiting.

SHDR = Summer hot deck reset in °F. The average reset that will result from this function is dependent upon the air handler capacity relative to loads in the space that it serves. A typical increment is 4°F.

SSP = Summer thermostat setpoint for occupied periods in °F. Typical value 75°F.

SSPR = Summer setpoint reset is the number of °F that the thermostat is raised during cooling season unoccupied periods. SSPR ≤ (AST-SSP). SSPR is used (infrequently) for the Day/Night Setback strategy.

TC_L = The total kW power consumption of lights in zone.

TON = Chiller capacity in tons of refrigeration.

U = Thermal transmittance factor for specific exterior surfaces in Btu/hr·ft²·°F.

UoAo = Modified Combined Thermal Transmittance Factor. This modified combined U factor is for all exterior surfaces (walls, windows, doors, roof) and may be calculated using methods discussed below and in Chapter 22 of the ASHRAE Handbook--Fundamentals (ref Appendix C).

Repeat the U x A calculation for each different type of wall, window, door, or roofing material.

UoAo = (U wall x A wall) + (U window x A window) + (U door x A door) + (U roof x A roof)

WDDDBT= Winter design data 97.5% dry bulb temperature in °F. This is the dry bulb temperature which was equaled or exceeded 97.5 % of the time, on average, during the coldest 3 consecutive months (standardized as December, January, February).

WHDR = Winter hot deck reset in °F. The average reset that will result from this function is dependent upon the air handler capacity relative to loads in the space that it serves. A typical increment is 4°F.

WKC = Length of cooling season in weeks per year. WKC is calculated using all annual total hours above 55° F. WKC is less than or equal to chiller operating period.

WKH = Length of heating season in weeks per year. WKH is calculated using all annual total hours below 55° F. WKH is less than or equal to boiler operating period.

WSP = Winter thermostat setpoint in °F for the zone being serviced by this system.

WSPR = The number of °F that the thermostat is lowered during heating season unoccupied periods. WSPR is less than or equal to the smaller value of (WSP-LTL) or (WSP-AWT). WSPR is used for the Day/Night Setback strategy.

WU = Present warmup time before occupancy in hours per day. Use currently scheduled time or 2 hours per day.

Notes: 1. Heating values for these materials are averages based on the following conditions:

Dry gas at 60°F, 30" Hg., Specific volume at 32°F, 29.92" Hg.

More precise data may be used if available.

2. This is an average value for low, medium, and high volatile (A, B, C) bituminous coal.

3. Reference 1989 ASHRAE Handbook--Fundamentals.

Appendix B. CONSTANTS and CONVERSION FACTORS

1.08 Btu/cfm·hr·°F =>
nominal air density x nominal specific heat x conversion factor
0.075 lb/ft^3 x 0.24 Btu/lb·°F x 60 min/hr

4.5 min·lb/hr·ft^3 =>
nominal air density x conversion factor
0.075 lb/ft^3 x 60 min/hr

12,000 Btu/hr = ton of refrigeration

1000 Btu/lb nominal heat content of steam

0.746 kW/hp

Tons of cooling (chiller) = (GPM x delta °F inlet to outlet)/24

Condenser GPM = (Tons of chiller capacity x 30)/delta °F inlet to outlet

168 = hours/wk

52 = wks/yr

Appendix C. ASHRAE DATA and METHODOLOGY

Chapters 22 and 23 in this section are reprinted by permission of ASHRAE from the 1989 ASHRAE Handbook--Fundamentals. These sections, including handwritten corrections, were received from ASHRAE on March 11, 1992.

The psychrometric chart and "Table 2" have credits as noted.

CHAPTER 22

THERMAL AND WATER VAPOR TRANSMISSION DATA

Building Envelopes 22.1
Calculating Overall Thermal Resistances 22.2
Mechanical and Industrial Systems 22.15
Calculating Heat Flow for Buried Pipelines 22.21

THIS chapter presents thermal and water vapor transmission data based on steady-state or equilibrium conditions. Chapter 3 covers heat transfer under transient or changing temperature conditions. Chapter 20 discusses selection of insulation materials and procedures for determining overall thermal resistances by simplified methods.

BUILDING ENVELOPES

Thermal Transmission Data for Building Components

The steady-state thermal resistances (R-values) of building components (walls, floors, windows, roof systems, etc.) can be calculated from the thermal properties of the materials in the component; or the heat flow through the assembled component can be measured directly with laboratory equipment such as the guarded hot box or the calibrated hot box.

Tables 1 through 6 list thermal values, which may be used to calculate thermal resistances of building walls, floors, and ceilings. The values shown in these tables were developed under ideal conditions. In practice, overall thermal performance can be reduced significantly by such factors as improper installation and shrinkage, settling, or compression of the insulation (Tye and Desjarlais 1983, Tye 1985, 1986).

Most values in these tables were obtained by accepted ASTM test methods described in ASTM Standards C 177 and C 518 for materials and ASTM Standards C 236 and C 976 for building envelope components. Because commercially available materials vary, not all values apply to specific products. Previous editions of the handbook can be consulted for data on materials no longer commercially available.

The most accurate method of determining the overall thermal resistance for a combination of building materials assembled as a building envelope component is to test a representative sample by a hot box method. However, all combinations may not be conveniently or economically tested in this manner. For many simple constructions, calculated R-values agree reasonably well with values determined by hot box measurement.

The performance of materials fabricated in the field is especially subject to the quality of workmanship during construction and installation. Good workmanship becomes increasingly important as the insulation requirement becomes greater. Therefore, some engineers include additional insulation or other safety factors based on experience in their design.

Figure 1 shows how convection affects surface conductance of several materials. Other tests on smooth surfaces show the average value of the convection part of conductance decreases as the length of the surface increases.

Vapor retarders, outlined in Chapters 20 and 21, require special attention. Moisture from condensation or other sources may reduce the thermal resistance of insulation, but the effect of moisture must be determined for each material. For example, some materials with large airspaces are not affected significantly if the moisture content is less than 10% by weight, while the effect of moisture on other materials is approximately linear.

Ideal conditions of components and installations are assumed in calculating overall R-values (*i.e.*, insulating materials are of uniform nominal thickness and thermal resistance, airspaces are of uniform thickness and surface temperature, moisture effects are not involved, and installation details are in accordance with design). The National Bureau of Standards Building Materials and Structures Report BMS 151 shows that measured values differ from calculated values for certain insulated constructions. For this reason, some engineers decrease the calculated R-values a moderate amount to account for departures of constructions from requirements and practices.

Tables 2 and 3 give values for well-sealed systems constructed with care. Field applications can differ substantially from

The preparation of this chapter is assigned to TC 4.4, Thermal Insulation and Moisture Retarders.

laboratory test conditions. Air gaps in these types of insulation systems can seriously degrade thermal performance as a result of air movement due to both natural and forced convection. Sabine *et al.* (1975) found the tabular values are not necessarily additive for multiple-layer, low-emittance airspaces, and tests on actual constructions should be conducted to accurately determine thermal resistance values.

Values for foil insulation products supplied by manufacturers must also be used with caution because they apply only to systems that are identical to the configuration in which the product was tested. In addition, surface oxidation, dust accumulation, and other factors that change the condition of the low-emittance surface can reduce the thermal effectiveness of these insulation systems. Deterioration results from contact with several types of solutions, either acidic or basic (*e.g.*, wet cement mortar or the preservatives found in decay-resistant lumber). Polluted environments may cause rapid and severe material degradation. However, site inspections show a predominance of well-preserved installations and only a small number of cases in which rapid and severe deterioration has occurred.

CALCULATING OVERALL THERMAL RESISTANCES

Relatively small conductive elements within an insulating layer or thermal bridges can substantially reduce the average thermal resistance of a component. Examples include wood and metal studs in frame walls, concrete webs in concrete masonry walls, and metal ties or other elements in insulated wall panels. The following examples illustrate how to calculate R-values and U-factors for components containing thermal bridges.

The following conditions are assumed in calculating the design R-values:

(1) Equilibrium or steady-state heat transfer, disregarding effects of heat storage;

(2) Surrounding surfaces at ambient air temperature;

(3) Exterior wind velocity of 15 mph for winter (surface with R = 0.17 °F · ft² · h/Btu) and 7.5 mph for summer (surface with R = 0.25 °F · ft² · h/Btu); and

(4) Surface emittance of ordinary building materials is 0.90.

Table 1 Surface Conductances, Btu/h · ft² · °F, and Resistances, °F · ft² · h/Btu, for Air[a,b,c,d]

Position of Surface	Direction of Heat Flow	Surface Emittance, ε[e]: Non-reflective ε = 0.90, h_i	R	Reflective ε = 0.20, h_i	R	Reflective ε = 0.05, h_i	R
STILL AIR							
Horizontal	Upward	1.63	0.61	0.91	1.10	0.76	1.32
Sloping—45°	Upward	1.60	0.62	0.88	1.14	0.73	1.37
Vertical	Horizontal	1.46	0.68	0.74	1.35	0.59	1.70
Sloping—45°	Downward	1.32	0.76	0.60	1.67	0.45	2.22
Horizontal	Downward	1.08	0.92	0.37	2.70	0.22	4.55
MOVING AIR	(Any Position)	h_o	R	h_o	R	h_o	R
15-mph Wind (for winter)	Any	6.00	0.17	—		—	
7.5-mph Wind (for summer)	Any	4.00	0.25	—		—	

[a]No surface has both an airspace resistance value and a surface resistance value. No airspace value exists for any surface facing an airspace of less than 0.5 in.
[b]For ventilated attics or spaces above ceilings under summer conditions (heat flow down), see Table 5.
[c]Conductances are for surfaces of the stated emittance facing virtual blackbody surroundings at the same temperature as the ambient air. Values are based on a surface-air temperature difference of 10°F and for surface temperature of 70°F.
[d]See Chapter 3 for more detailed information, especially Tables 5 and 6, and see Figure 1 for additional data.
[e]Condensate can have a significant impact on surface emittance (see Table 3).

Table 2 Thermal Resistances of Plane Airspaces[a,b,c], °F · ft² · h/Btu

Position of Airspace	Direction of Heat Flow	Airspace Mean Temp.[d], °F	Airspace Temp. Diff.[d], °F	0.5-in. Airspace[c] Effective Emittance, E[d,e] 0.03	0.05	0.2	0.5	0.82	0.75-in. Airspace[c] Effective Emittance, E[d,e] 0.03	0.05	0.2	0.5	0.82
Horiz.	Up	90	10	2.13	2.03	1.51	0.99	0.73	2.34	2.22	1.61	1.04	0.75
		50	30	1.62	1.57	1.29	0.96	0.75	1.71	1.66	1.35	0.99	0.77
		50	10	2.13	2.05	1.60	1.11	0.84	2.30	2.21	1.70	1.16	0.87
		0	20	1.73	1.70	1.45	1.12	0.91	1.83	1.79	1.52	1.16	0.93
		0	10	2.10	2.04	1.70	1.27	1.00	2.23	2.16	1.78	1.31	1.02
		−50	20	1.69	1.66	1.49	1.23	1.04	1.77	1.74	1.55	1.27	1.07
		−50	10	2.04	2.00	1.75	1.40	1.16	2.16	2.11	1.84	1.46	1.20
45° Slope	Up	90	10	2.44	2.31	1.65	1.06	0.76	2.96	2.78	1.88	1.15	0.81
		50	30	2.06	1.98	1.56	1.10	0.83	1.99	1.92	1.52	1.08	0.82
		50	10	2.55	2.44	1.83	1.22	0.90	2.90	2.75	2.00	1.29	0.94
		0	20	2.20	2.14	1.76	1.30	1.02	2.13	2.07	1.72	1.28	1.00
		0	10	2.63	2.54	2.03	1.44	1.10	2.72	2.62	2.08	1.47	1.12
		−50	20	2.08	2.04	1.78	1.42	1.17	2.05	2.01	1.76	1.41	1.16
		−50	10	2.62	2.56	2.17	1.66	1.33	2.53	2.47	2.10	1.62	1.30
Vertical	Horiz.	90	10	2.47	2.34	1.67	1.06	0.77	3.50	3.24	2.08	1.22	0.84
		50	30	2.57	2.46	1.84	1.23	0.90	2.91	2.77	2.01	1.30	0.94
		50	10	2.66	2.54	1.88	1.24	0.91	3.70	3.46	2.35	1.43	1.01
		0	20	2.82	2.72	2.14	1.50	1.13	3.14	3.02	2.32	1.58	1.18
		0	10	2.93	2.82	2.20	1.53	1.15	3.77	3.59	2.64	1.73	1.26
		−50	20	2.90	2.82	2.35	1.76	1.39	2.90	2.83	2.36	1.77	1.39
		−50	10	3.20	3.10	2.54	1.87	1.46	3.72	3.60	2.87	2.04	1.56
45° Slope	Down	90	10	2.48	2.34	1.67	1.06	0.77	3.53	3.27	2.10	1.22	0.84
		50	30	2.64	2.52	1.87	1.24	0.91	3.43	3.23	2.24	1.39	0.99
		50	10	2.67	2.55	1.89	1.25	0.92	3.81	3.57	2.40	1.45	1.02
		0	20	2.91	2.80	2.19	1.52	1.15	3.75	3.57	2.63	1.72	1.26
		0	10	2.94	2.83	2.21	1.53	1.15	4.12	3.91	2.81	1.80	1.30
		−50	20	3.16	3.07	2.52	1.86	1.45	3.78	3.65	2.90	2.05	1.57
		−50	10	3.26	3.16	2.58	1.89	1.47	4.35	4.18	3.22	2.21	1.66
Horiz.	Down	90	10	2.48	2.34	1.67	1.06	0.77	3.55	3.29	2.10	1.22	0.85
		50	30	2.66	2.54	1.88	1.24	0.91	3.77	3.52	2.38	1.44	1.02
		50	10	2.67	2.55	1.89	1.25	0.92	3.84	3.59	2.41	1.45	1.02
		0	20	2.94	2.83	2.20	1.53	1.15	4.18	3.96	2.83	1.81	1.30
		0	10	2.96	2.85	2.22	1.53	1.16	4.25	4.02	2.87	1.82	1.31
		−50	20	3.25	3.15	2.58	1.89	1.47	4.60	4.41	3.36	2.28	1.69
		−50	10	3.28	3.18	2.60	1.90	1.47	4.71	4.51	3.42	2.30	1.71

Table 2 Thermal Resistances of Plane Airspaces[a,b,c], °F·ft²·h/Btu (*Concluded*)

Position of Airspace	Direction of Heat Flow	Airspace Mean Temp.[d], °F	Airspace Temp. Diff.[d], °F	1.5-in. Airspace[c] Effective Emittance, E[d,e] 0.03	0.05	0.2	0.5	0.82	3.5-in. Airspace[c] Effective Emittance, E[d,e] 0.03	0.05	0.2	0.5	0.82
Horiz.	Up ↑	90	10	2.55	2.41	1.71	1.08	0.77	2.84	2.66	1.83	1.13	0.80
		50	30	1.87	1.81	1.45	1.04	0.80	2.09	2.01	1.58	1.10	0.84
		50	10	2.50	2.40	1.81	1.21	0.89	2.80	2.66	1.95	1.28	0.93
		0	20	2.01	1.95	1.63	1.23	0.97	2.25	2.18	1.79	1.32	1.03
		0	10	2.43	2.35	1.90	1.38	1.06	2.71	2.62	2.07	1.47	1.12
		−50	20	1.94	1.91	1.68	1.36	1.13	2.19	2.14	1.86	1.47	1.20
		−50	10	2.37	2.31	1.99	1.55	1.26	2.65	2.58	2.18	1.67	1.33
45° Slope	Up ↗	90	10	2.92	2.73	1.86	1.14	0.80	3.18	2.96	1.97	1.18	0.82
		50	30	2.14	2.06	1.61	1.12	0.84	2.36	2.17	1.67	1.15	0.86
		50	10	2.88	2.74	1.99	1.29	0.94	3.12	2.95	2.10	1.34	0.96
		0	20	2.30	2.23	1.82	1.34	1.04	2.42	2.35	1.90	1.38	1.06
		0	10	2.79	2.69	2.12	1.49	1.13	2.98	2.87	2.23	1.54	1.16
		−50	20	2.22	2.17	1.88	1.49	1.21	2.34	2.29	1.97	1.54	1.25
		−50	10	2.71	2.64	2.23	1.69	1.35	2.87	2.79	2.33	1.75	1.39
Vertical	Horiz. →	90	10	3.99	3.66	2.25	1.27	0.87	3.69	3.40	2.15	1.24	0.85
		50	30	2.58	2.46	1.84	1.23	0.90	2.67	2.55	1.89	1.25	0.91
		50	10	3.79	3.55	2.39	1.45	1.02	3.63	3.40	2.32	1.42	1.01
		0	20	2.76	2.66	2.10	1.48	1.12	2.88	2.78	2.17	1.51	1.14
		0	10	3.51	3.35	2.51	1.67	1.23	3.49	3.33	2.50	1.67	1.23
		−50	20	2.64	2.58	2.18	1.66	1.33	2.82	2.75	2.30	1.73	1.37
		−50	10	3.31	3.21	2.62	1.91	1.48	3.40	3.30	2.67	1.94	1.50
45° Slope	Down ↘	90	10	5.07	4.55	2.56	1.36	0.91	4.81	4.33	2.49	1.34	0.90
		50	30	3.58	3.36	2.31	1.42	1.00	3.51	3.30	2.28	1.40	1.00
		50	10	5.10	4.66	2.85	1.60	1.09	4.74	4.36	2.73	1.57	1.08
		0	20	3.85	3.66	2.68	1.74	1.27	3.81	3.63	2.66	1.74	1.27
		0	10	4.92	4.62	3.16	1.94	1.37	4.59	4.32	3.02	1.88	1.34
		−50	20	3.62	3.50	2.90	2.01	1.54	3.77	3.64	2.90	2.05	1.57
		−50	10	4.67	4.47	3.40	2.29	1.70	4.50	4.32	3.31	2.25	1.68
Horiz.	Down ↓	90	10	6.09	5.35	2.79	1.43	0.94	10.07	8.19	3.41	1.57	1.00
		50	30	6.27	5.63	3.18	1.70	1.14	9.60	8.17	3.86	1.88	1.22
		50	10	6.61	5.90	3.27	1.73	1.15	11.15	9.27	4.09	1.93	1.24
		0	20	7.03	6.43	3.91	2.19	1.49	10.90	9.52	4.87	2.47	1.62
		0	10	7.31	6.66	4.00	2.22	1.51	11.97	10.32	5.08	2.52	1.64
		−50	20	7.73	7.20	4.77	2.85	1.99	11.64	10.49	6.02	3.25	2.18
		−50	10	8.09	7.52	4.91	2.89	2.01	12.98	11.56	6.36	3.34	2.22

[a]See Chapter 20, section on "Factors Affecting Heat Transfer Across Airspaces." Thermal resistance values were determined from the relation, $R = 1/C$, where $C = h_c + Eh_r$; h_c is the conduction-convection coefficient, Eh_r is the radiation coefficient $\approx 0.00686E[(t_m + 460)/100]^3$, and t_m is the mean temperature of the airspace. Values for h_c were determined from data developed by Robinson *et al.* (1954). Equations 5 through 7 in Yarbrough (1983) show the data in Table 2 in analytic form. For extrapolation from Table 2 to airspaces less than 0.5 in. (as in insulating window glass), assume

$$h_c = 0.159(1 + 0.0016\, t_m)/l$$

where l is the airspace thickness in in., and h_c is heat transfer through the airspace only.

[b]Values are based on data presented by Robinson *et al.* (1954). (Also see Chapter 3, Tables 3 and 4, and Chapter 39). Values apply for ideal conditions, *i.e.*, airspaces of uniform thickness bounded by plane, smooth, parallel surfaces with no air leakage to or from the space. When accurate values are required, use overall U-factors determined through calibrated hot box (ASTM C 976) or guarded hot box (ASTM C 236) testing. Thermal resistance values for multiple airspaces must be based on careful estimates of mean temperature differences for each airspace.

[c]A single resistance value cannot account for multiple airspaces; each airspace requires a separate resistance calculation that applies only for the established boundary conditions. Resistances of horizontal spaces with heat flow downward are substantially independent of temperature difference.

[d]Interpolation is permissible for other values of mean temperature, temperature difference, and effective emittance E. Interpolation and moderate extrapolation for airspaces greater than 3.5 in. are also permissible. Calculation as

[e]Effective emittance E of the airspace is given by $1/E = 1/e_1 + 1/e_2 - 1$, where e_1 and e_2 are the emittances of the surfaces of the airspace (see Table 3).

facing

Wood Frame Walls

The average overall R-values and U-factors of wood frame walls can be calculated by assuming parallel heat flow paths through areas with different thermal resistances. Equations (1) through (5) from Chapter 20 are used.

For simple stud walls 16 in. on center (OC), the fraction of framing is assumed to be approximately 0.15; for studs 24 in. OC, approximately 0.12. These fractions contain an allowance for multiple studs, plates, sills, and extra framing around windows and doors but do not allow for headers or band joists.

Example 1. Calculate the U-factor of the 2 by 4 stud wall shown in Figure 2. The studs are at 16 in. OC. There is a 3.5-in. mineral fiber batt insulation (R-11) in the stud space. The inside finish is 0.5-in. gypsum board; the outside is finished with 0.5-in. vegetable fiber board sheathing and 0.5-in. by 8-in. wood lapped siding. The framing occupies approximately 15% of the transmission area.

Solution: Obtain the R-value of the various building elements from Tables 1 and 4.

Element	R(Insulation)	R(Framing)
1. Outside surface (15 mph wind)	0.17	0.17
2. Wood bevel lapped siding	0.81	0.81
3. 0.5-in. sheathing	1.32	1.32
4. 3.5-in. mineral fiber batt insulation	11	—
5. Nominal 2 by 4 wood stud	—	4.38
6. 0.5-in. gypsum wallboard	0.45	0.45
7. Inside surface (still air)	0.68	0.68
	R_1 = 14.43	R_2 = 7.81

Therefore $U_1 = 0.069$; $U_2 = 0.128$ Btu/h·ft²·°F.

If the wood framing (*i.e.*, thermal bridging) is not included, Equation (3) from Chapter 20 may be used to calculate the U-factor of the wall as follows:

$$U_{av} = U_1 = 1/R_1 = 0.069 \text{ Btu/h·ft}^2\text{·°F}$$

If the wood framing is accounted for using the parallel flow method, the U-factor of the wall is determined using Equation (5) from Chapter 20 as follows:

$$U_{av} = (0.85 \times 0.069) + (0.15 \times 0.128) = 0.078 \text{ Btu/h·ft}^2\text{·°F}$$

If the wood framing is included using the isothermal planes method, the U-factor of the wall is determined using Equations (2) and (3) from Chapter 20 as follows:

$$R_{T(av)} = 2.30 + 1/[(0.85/11.00) + (0.15/4.38)] + 1.13$$
$$= 12.44\ °F \cdot ft^2 \cdot h/Btu$$
$$U_{av} = 0.080\ Btu/h \cdot ft^2 \cdot °F$$

For a frame wall with a 24 in. OC stud space, the average overall R-value becomes 13.16 °F·ft²·h/Btu. Similar calculation procedures can be used to evaluate other wall designs.

Masonry Walls

The average overall R-values of masonry walls can be estimated by assuming a combination of layers in series, one or more of which provides parallel paths. This method is used because heat flows laterally through block face shells so that transverse isothermal planes result. Average total resistance $R_{T(av)}$ is the sum of the resistances of the layers between such planes, each layer calculated as shown in Example 2.

Example 2. Calculate the overall thermal resistance and average U-factor of the 7-5/8-in. thick insulated concrete block wall shown in Figure 3. The two-core block has an average web thickness of 1-in. and a face shell thickness of 1-1/4-in. Overall block dimensions are 7-5/8 by 7-5/8 by 15-5/8 in. Thermal resistances of 112 lb/ft³ concrete and 5 lb/ft³ expanded perlite insulation are 0.10 and 2.90 °F·ft²·h/Btu per in., respectively.

Solution: The equation used to determine the overall thermal resistance of the insulated concrete block wall is derived from Equations (2) and (5) from Chapter 20 and is given below:

$$R_{T(av)} = R_i + R_f + \frac{R_w R_c}{a_c R_w + a_w R_c} + R_o$$

where

$R_{T(av)}$ = overall thermal resistance based on the assumption of isothermal planes
R_i = thermal resistance of inside air surface film (still air)
R_o = thermal resistance of outside air surface film (15 mph wind)
R_f = total thermal resistance of face shells
R_c = thermal resistance of cores between face shells
R_w = thermal resistance of webs between face shells
a_w = fraction of total area transverse to heat flow represented by webs of blocks
a_c = fraction of total area transverse to heat flow represented by cores of blocks

From the information given and the data in Table 1, determine the values needed to compute the overall thermal resistance.

R_i = 0.68
R_o = 0.17
R_f = (2)(1.25)(0.10) = 0.25
R_c = (5.125)(2.90) = 14.86
R_w = (5.125)(0.10) = 0.51
a_w = 3/15.625 = 0.192
a_c = 12.625/15.625 = 0.808

Using the equation given, the overall thermal resistance and average U-factor are calculated as follows:

$$R_{T(av)} = 0.68 + 0.25 + (0.51)(14.86)/[(0.808)(0.51) + (0.192)(14.86)] + 0.17$$
$$= 0.68 + 0.25 + 2.33 + 0.17 = 3.43\ °F \cdot ft^2 \cdot h/Btu$$
$$U_{av} = 1/3.43 = 0.292\ Btu/h \cdot ft^2 \cdot °F$$

Based on guarded hot box tests, Van Geem (1985) measured the average R-value for this insulated concrete block wall as 3.13 °F·ft²·h/Btu.

Assuming parallel heat flow only, the calculated resistance is usually higher than that calculated on the assumption of isothermal planes. The actual resistance generally is some value between the two calculated values. In the absence of test values, examination of the construction usually reveals whether a value closer to the higher or lower calculated R-value should be used. Generally, if the construction contains a layer in which lateral conduction is high compared with transmittance through the construction, the calculation with isothermal planes should be used. If the construction has no layer of high lateral conductance, the parallel heat flow calculation should be used.

Hot box tests of insulated and uninsulated masonry walls constructed with block of conventional configuration show that thermal resistances calculated using the isothermal planes heat flow

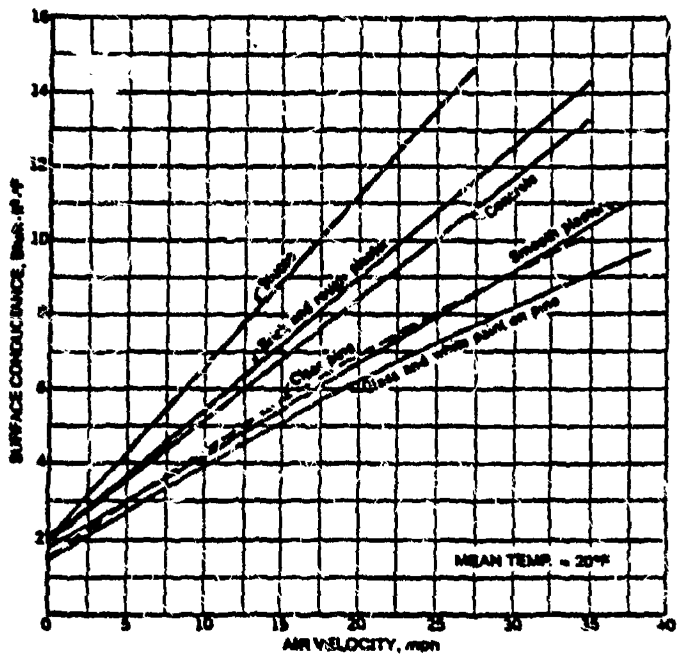
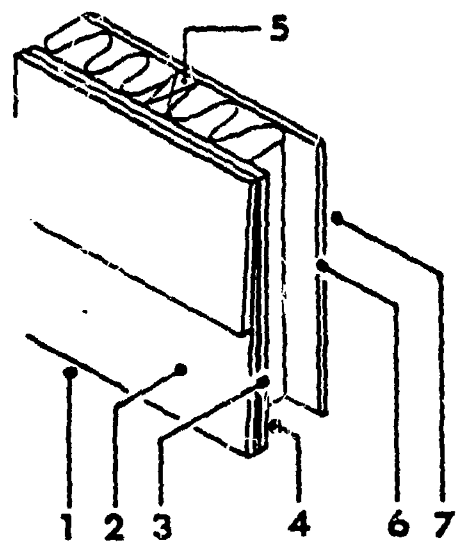


Fig. 1 Surface Conductance for Different 12-Inch-Square Surfaces as Affected by Air Movement



1. Outside surface (15 mph wind)
2. Wood siding, 0.5 in. by 8 in. lapped
3. Sheathing, 0.5 in. vegetable fiber board
4. Mineral fiber batt insulation, 3.5 in.
5. Nominal 2 by 4 wood stud
6. Gypsum wallboard, 0.5 in.
7. Inside surface (still air)

Fig. 2 Insulated Wood Frame Wall (Example 1)

method agree well with measured values (see Van Geem 1985, Valore 1980, Shu *et al.* 1979). Neglecting horizontal mortar joints can result in thermal transmittance values up to 16% lower than actual, depending on the density and thermal properties of the masonry, and 1 to 6% lower depending on the core insulation material (Van Geem 1985, McIntyre 1984). Horizontal mortar joints usually found in concrete block wall construction are neglected in Example 2.

Panels Containing Metal

Curtain wall constructions often include metallic and other thermal bridges. Thermal resistance of panels can be significantly reduced by metallic thermal bridges. However, the capacity of the adjacent facing materials to transmit heat transversely to the metal is limited, and some contact resistance between all materials in contact limits the reduction. Contact resistances in building structures are only 0.06 to 0.6 °F·ft²·h/Btu which are too small to be of concern in many cases. However, the contact resistances of steel framing members are important to consider. Also, in many cases (as illustrated in Example 3) the area of metal in contact with the facing greatly exceeds the thickness of the metal which mitigates the influence.

Thermal characteristics for panels of sandwich construction can be computed by combining the thermal resistances of the various layers. However, few panels are true sandwich constructions; many have ribs and stiffeners that create complicated heat flow paths. R-values for the assembled sections should be determined on a representative sample by using a hot box method. If the sample is a wall section with air cavities on both sides of fibrous insulation, the sample must be of representative height since convective airflow can contribute significantly to heat flow through the test section. Computer modeling can also be useful, but all heat transfer mechanisms must be considered.

In Example 3, the metal member is only 0.020 in. thick, but it is in contact with adjacent facings over a 1.25 in.-wide area. The steel member is 3.50 in. deep, has a thermal resistance of approximately 0.011 °F·ft²·h/Btu, and is virtually isothermal. The calculation involves careful selection of the appropriate thickness for the steel member. If the member is assumed to be 0.020 in. thick, the fact that the flange transmits heat to the adjacent facing is ignored. If the member is assumed to be 1.25 in. thick, the heat flow through the steel is overestimated. In Example 3, the steel member behaves in much the same way as a rectangular member 1.25 in. thick and 3.50 in. deep with a thermal resistance of 0.69 °F·ft²·h/Btu [(1.25/0.020) × 0.011] does. The Building Research Association of New Zealand (BRANZ) commonly uses this approximation.

Table 3 Emittance Values of Various Surfaces and Effective Emittances of Airspaces[a]

Surface	Average Emittance ϵ	Effective Emittance, E of Airspace: One surface emittance ϵ; the other 0.9	Effective Emittance, E of Airspace: Both surfaces emittance ϵ
Aluminum foil, bright	0.05	0.05	0.03
Aluminum foil, with condensate just visible (> 0.7 gr/ft²)	0.30[b]	0.29	—
Aluminum foil, with condensate clearly visible (> 2.9 gr/ft²)	0.70[b]	0.65	—
Aluminum sheet	0.12	0.12	0.06
Aluminum coated paper, polished	0.20	0.20	0.11
Steel, galvanized, bright	0.25	0.24	0.15
Aluminum paint	0.50	0.47	0.35
Building materials: wood, paper, masonry, nonmetallic paints	0.90	0.82	0.82
Regular glass	0.84	0.77	0.72

[a]These values apply in the 4 to 40 μm range of the electromagnetic spectrum.
[b]Values are based on data presented by Bassett and Trethowen (1984).

Example 3. Calculate the C-factor of the insulated steel frame wall shown in Figure 4. Assume that the steel member has an R-value of 0.69 °F·ft²·h/Btu and that the framing behaves as though it occupies approximately 8% of the transmission area.

Solution: Obtain the R-values of the various building elements from Table 4.

Element	R(Insulation)	R(Framing)
1. 0.5-in. gypsum wallboard	0.45	0.45
2. 3.5-in. mineral fiber batt insulation	11	—
3. Steel framing member	—	0.69
4. 0.5-in. gypsum wallboard	0.45	0.45
	R_1 = 11.90	R_2 = 1.59

Therefore, $C_1 = 0.084$; $C_2 = 0.629$ Btu/h·ft²·°F.

If the steel framing (*i.e.*, thermal bridging) is not considered, the C-factor of the wall is calculated using Equation (3) from Chapter 20 as follows:

$$C_{av} = C_1 = 1/R_1 = 0.084 \text{ Btu/h·ft}^2\text{·°F}$$

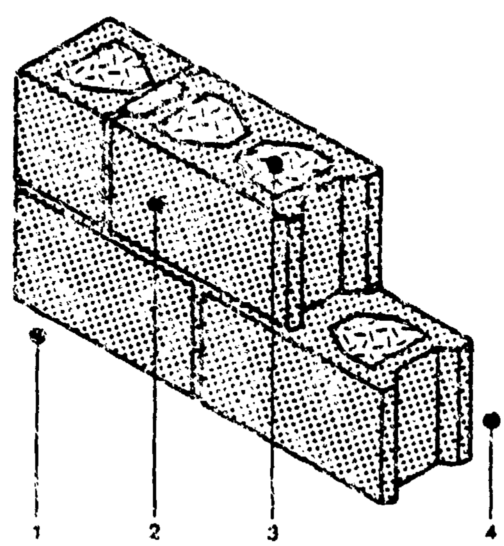
If the steel framing is accounted for using the parallel flow method, the C-factor of the wall is determined using Equation (5) from Chapter 20 as follows:

$$C_{av} = (0.92 \times 0.084) + (0.08 \times 0.629)$$
$$= 0.128 \text{ Btu/h·ft}^2\text{·°F}$$
$$R_{T(av)} = 7.81 \text{ °F·ft}^2\text{·h/Btu}$$

If the steel framing is included using the isothermal planes method, the C-factor of the wall is determined using Equations (2) and (3) from Chapter 20 as follows:

$$R_{T(av)} = 0.45 + 1/[(0.92/11.00) + (0.08/0.69)] + 0.45$$
$$= 5.91 \text{ °F·ft}^2\text{·h/Btu}$$
$$C_{av} = 0.169 \text{ Btu/h·ft}^2\text{·°F}$$

Farouk and Larson (1983) measured an average R-value of 6.61 °F·ft²·h/Btu for this insulated steel frame wall.



1. Outside surface (15 mph wind)
2. Concrete block
3. Expanded perlite insulation
4. Inside surface (still air)

Fig. 3 Insulated Concrete Block Wall (Example 2)

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values[a]

Description	Density, lb/ft^3	Conductivity[b] (k), $\frac{Btu \cdot in.}{h \cdot ft^2 \cdot °F}$	Conductance (C), $\frac{Btu}{h \cdot ft^2 \cdot °F}$	Resistance[c] (R): Per inch thickness (1/k), $\frac{°F \cdot ft^2 \cdot h}{Btu \cdot in.}$	Resistance[c] (R): For thickness listed (1/C), $\frac{°F \cdot ft^2 \cdot h}{Btu}$	Specific Heat, $\frac{Btu}{lb \cdot °F}$
BUILDING BOARD						
Asbestos-cement board	120	4.0	—	0.25	—	0.24
Asbestos-cement board ......0.125 in.	120	—	33.00	—	0.03	
Asbestos-cement board ......0.25 in.	120	—	16.50	—	0.06	
Gypsum or plaster board ......0.375 in.	50	—	3.10	—	0.32	0.26
Gypsum or plaster board ......0.5 in.	50	—	2.22	—	0.45	
Gypsum or plaster board ......0.625 in.	50	—	1.78	—	0.56	
Plywood (Douglas Fir)[d]	34	0.80	—	1.25	—	0.29
Plywood (Douglas Fir) ......0.25 in.	34	—	3.20	—	0.31	
Plywood (Douglas Fir) ......0.375 in.	34	—	2.13	—	0.47	
Plywood (Douglas Fir) ......0.5 in.	34	—	1.60	—	0.62	
Plywood (Douglas Fir) ......0.625 in.	34	—	1.29	—	0.77	
Plywood or wood panels ......0.75 in.	34	—	1.07	—	0.93	0.29
Vegetable Fiber Board						
Sheathing, regular density[e] ......0.5 in.	18	—	0.76	—	1.32	0.31
......0.78125 in.	18	—	0.49	—	2.06	
Sheathing intermediate density[e] ......0.5 in.	22	—	0.92	—	1.09	0.31
Nail-base sheathing[e] ......0.5 in.	25	—	0.94	—	1.06	0.31
Shingle backer ......0.375 in.	18	—	1.06	—	0.94	0.31
Shingle backer ......0.3125 in.	18	—	1.28	—	0.78	
Sound deadening board ......0.5 in.	15	—	0.74	—	1.35	0.30
Tile and lay-in panels, plain or acoustic	18	0.40	—	2.50	—	0.14
......0.5 in.	18	—	0.80	—	1.25	
......0.75 in.	18	—	0.53	—	1.89	
Laminated paperboard	30	0.50	—	2.00	—	0.33
Homogeneous board from repulped paper	30	0.50	—	2.00	—	0.28
Hardboard[e]						
Medium density	50	0.73	—	1.37	—	0.31
High density, service temp. service underlay	55	0.82	—	1.22	—	0.32
High density, std. tempered	63	1.00	—	1.00	—	0.32
Particleboard[e]						
Low density	37	0.71	—	1.41	—	0.31
Medium density	50	0.94	—	1.06	—	0.31
High density	62.5	1.18	—	0.85	—	0.31
Underlayment ......0.625 in.	40	—	1.22	—	0.82	0.29
Waferboard	37	0.63	—	1.59	—	—
Wood subfloor ......0.75 in.	—	—	1.06	—	0.94	0.33
BUILDING MEMBRANE						
Vapor—permeable felt	—	—	16.70	—	0.06	
Vapor—seal, 2 layers of mopped 15-lb felt	—	—	8.35	—	0.12	
Vapor—seal, plastic film	—	—	—	—	Negl.	
FINISH FLOORING MATERIALS						
Carpet and fibrous pad	—	—	0.48	—	2.08	0.34
Carpet and rubber pad	—	—	0.81	—	1.23	0.33
Cork tile ......0.125 in.	—	—	3.60	—	0.28	0.48
Terrazzo ......1 in.	—	—	12.50	—	0.08	0.19
Tile—asphalt, linoleum, vinyl, rubber	—	—	20.00	—	0.05	0.30
vinyl asbestos						0.24
ceramic						0.19
Wood, hardwood finish ......0.75 in.	—	—	1.47	—	0.68	
INSULATING MATERIALS						
Blanket and Batt[f,g]						
Mineral Fiber, fibrous form processed from rock, slag, or glass						
approx. 3–4 in.	0.3–2.0	—	0.091	—	11	
approx. 3.5 in.	0.3–2.0	—	0.077	—	13	
approx. 5.5–6.5 in.	0.3–2.0	—	0.053	—	19	
approx. 6–7.5 in.	0.3–2.0	—	0.045	—	22	
approx. 9–10 in.	0.3–2.0	—	0.033	—	30	
approx. 12–13 in.	0.3–2.0	—	0.026	—	38	
Board and Slabs						
Cellular glass	8.5	0.35	—	2.86	—	0.18
Glass fiber, organic bonded	4.0–9.0	0.25	—	4.00	—	0.23
Expanded perlite, organic bonded	1.0	0.36	—	2.78	—	0.30
Expanded rubber (rigid)	4.5	0.22	—	4.55	—	0.40

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values[a] (*Continued*)

Description	Density, lb/ft^3	Conductivity[b] (*k*), $\frac{Btu \cdot in.}{h \cdot ft^2 \cdot °F}$	Conductance (*C*), $\frac{Btu}{h \cdot ft^2 \cdot °F}$	Resistance[c] (*R*): Per inch thickness (1/*k*), $\frac{°F \cdot ft^2 \cdot h}{Btu \cdot in.}$	Resistance[c] (*R*): For thickness listed (1/*C*), $\frac{°F \cdot ft^2 \cdot h}{Btu}$	Specific Heat, $\frac{Btu}{lb \cdot °F}$
Expanded polystyrene, extruded (smooth skin surface) (CFC-[illegible] exp.)	1.8–3.5	0.20	—	5.00	—	0.29
Expanded polystyrene, molded beads	1.0	0.26	—	3.85	—	—
	1.25	0.25	—	4.00	—	—
	1.5	0.24	—	4.17	—	—
	1.75	0.24	—	4.17	—	—
	2.0	0.23	—	4.35	—	—
Cellular polyurethane/polyisocyanurate[h] (CFC-11 exp.)(unfaced)	1.5	0.16–0.18	—	6.25–5.56	—	0.38
Cellular polyisocyanurate[h] (CFC-11 exp.)(gas-permeable facers)	1.5–2.5	0.16–0.18	—	6.25–5.56	—	0.22
Cellular polyisocyanurate[i] (CFC-11 exp.)(gas-impermeable facers)	2.0	0.14	—	~~7.20~~ 7.04	—	0.22 Set
Cellular phenolic (closed cell)(CFC-11, CFC-113 exp.)	3.0	0.12	—	8.20	—	—
Cellular phenolic (open cell)	1.8–2.2	0.23	—	4.40	—	—
Mineral fiber with resin binder	15.0	0.29	—	3.45	—	0.17
Mineral fiberboard, wet felted						
Core or roof insulation	16–17	0.34	—	2.94	—	
Acoustical tile	18.0	0.35	—	2.86	—	0.19
Acoustical tile	21.0	0.37	—	2.70	—	
Mineral fiberboard, wet molded						
Acoustical tile[j]	23.0	0.42	—	2.38	—	0.14
Wood or cane fiberboard						
Acoustical tile[j] 0.5 in.	—	—	0.80	—	1.25	0.31
Acoustical tile[j] 0.75 in.	—	—	0.53	—	1.89	
Interior finish (plank, tile)	15.0	0.35	—	2.86	—	0.32
Cement fiber slabs (shredded wood with Portland cement binder	25–27.0	0.50–0.53	—	2.0–1.89	—	—
Cement fiber slabs (shredded wood with magnesia oxysulfide binder)	22.0	0.57	—	1.75	—	0.31
Loose Fill						
Cellulosic insulation (milled paper or wood pulp)	2.3–3.2	0.27–0.32	—	3.70–3.13	—	0.33
Perlite, expanded	2.0–4.1	0.27–0.31	—	3.7–3.3	—	0.26
	4.1–7.4	0.31–0.36	—	3.3–2.8	—	
	7.4–11.0	0.36–0.42	—	2.8–2.4	—	
Mineral fiber (rock, slag, or glass)[g]						
approx. 3.75–5 in.	0.6–2.0	—	—		11.0	0.17
approx. 6.5–6.75 in.	0.6–2.0	—	—		19.0	
approx. 7.5–10 in.	0.6–2.0	—	—		22.0	
approx. 10.25–13.75 in.	0.6–2.0	—	—		30.0	
Mineral fiber (rock, slag, or glass)[g] approx. 3.5 in. (closed sidewall application)	2.0–3.5	—	—	—	12.0–14.0	
Vermiculite, exfoliated	7.0–8.2	0.47	—	2.13	—	0.32
	4.0–6.0	0.44	—	2.27	—	
Masonry Units						
Brick, common	80	2.2–3.2	—	0.45–0.31	—	—
	90	2.7–3.7	—	0.37–0.27	—	—
	100	3.3–4.3	—	0.30–0.23	—	—
	110	3.5–5.5	—	0.29–0.18	—	—
	120	4.4–6.4	—	0.23–0.16	—	0.19
	130	5.4–9.0	—	0.19–0.11	—	—
Clay tile, hollow						
1 cell deep 3 in.	—	—	1.25	—	0.80	0.21
1 cell deep 4 in.	—	—	0.90	—	1.11	—
2 cells deep 6 in.	—	—	0.66	—	1.52	—
2 cells deep 8 in.	—	—	0.54	—	1.85	—
2 cells deep 10 in.	—	—	0.45	—	2.22	—
3 cells deep 12 in.	—	—	0.40	—	2.50	—
Concrete blocks[k]						
Limestone aggregate						
8 in., 36 lb, 138 lb/ft^3 concrete, 2 cores	—	—	—	—	—	—
Same with perlite filled cores	—	—	0.48	—	2.1	—
12 in., 55 lb, 138 lb/ft^3 concrete, 2 cores	—	—	—	—	—	—
Same with perlite filled cores	—	—	0.27	—	3.7	—

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values[a] (*Continued*)

Description	Density, lb/ft^3	Conductivity[b] (k), Btu·in./h·ft^2·°F	Conductance (C), Btu/h·ft^2·°F	Resistance[c] (R) Per inch thickness ($1/k$), °F·ft^2·h/Btu·in.	Resistance[c] (R) For thickness listed ($1/C$), °F·ft^2·h/Btu	Specific Heat, Btu/lb·°F
Normal weight aggregate (sand and gravel)						
8 in., 33-36 lb, 126-136 lb/ft^3 concrete, 2 or 3 cores	—	—	0.90-1.03	—	1.11-0.97	0.22
Same with perlite filled cores	—	—	0.50	—	2.0	—
Same with verm. filled cores	—	—	0.52-0.73	—	1.92-1.37	—
12 in., 50 lb, 125 lb/ft^3 concrete, 2 cores	—	—	0.81	—	1.23	0.22
Medium weight aggregate (combinations of normal weight and lightweight aggregate)						
8 in., 26-29 lb, 97-112 lb/ft^3 concrete, 2 or 3 cores	—	—	0.58-0.78	—	1.71-1.28	—
Same with perlite filled cores	—	—	0.27-0.44	—	3.7-2.3	—
Same with verm. filled cores	—	—	0.30	—	3.3	—
Same with molded EPS (beads) filled cores	—	—	0.32	—	3.2	—
Same with molded EPS inserts in cores	—	—	0.37	—	2.7	—
Lightweight aggregate (expanded shale, clay, slate or slag, pumice)						
6 in., 16-17 lb 85-87 lb/ft^3 concrete, 2 or 3 cores	—	—	0.52-0.61	—	1.93-1.65	—
Same with perlite filled cores	—	—	0.24	—	4.2	—
Same with verm. filled cores	—	—	0.33	—	3.0	—
8 in., 19-22 lb, 72-86 lb/ft^3 concrete	—	—	0.32-0.54	—	3.2-1.90	0.21
Same with perlite filled cores	—	—	0.15-0.23	—	6.8-4.4	—
Same with verm. filled cores	—	—	0.19-0.26	—	5.3-3.9	—
Same with molded EPS (beads) filled cores	—	—	0.21	—	4.8	—
Same with UF foam filled cores	—	—	0.22	—	4.5	—
Same with molded EPS inserts in cores	—	—	0.29	—	3.5	—
12 in., 32-36 lb, 80-90 lb/ft^3 concrete, 2 or 3 cores	—	—	0.38-0.44	—	2.6-2.3	—
Same with perlite filled cores	—	—	0.11-0.16	—	9.2-6.3	—
Same with verm. filled cores	—	—	0.17	—	5.8	—
Stone, lime, or sand	—	12.50	—	0.08	—	0.19
Gypsum partition tile						
3 by 12 by 30 in., solid	—	—	0.79	—	1.26	0.19
3 by 12 by 30 in., 4 cells	—	—	0.74	—	1.35	
4 by 12 by 30 in., 3 cells	—	—	0.60	—	1.67	
METALS (See Chapter 37, Table 3)						
ROOFING						
Asbestos-cement shingles	120	—	4.76	—	0.21	0.24
Asphalt roll roofing	70	—	6.50	—	0.15	0.36
Asphalt shingles	70	—	2.27	—	0.44	0.30
Built-up roofing 0.375 in.	70	—	3.00	—	0.33	0.35
Slate 0.5 in.	—	—	20.00	—	0.05	0.30
Wood shingles, plain and plastic film faced	—	—	1.06	—	0.94	0.31
Spray Applied						
Polyurethane foam	1.5-2.5	0.16-0.18	—	6.25-5.56	—	
Ureaformaldehyde foam	0.7-1.6	0.22-0.28	—	4.55-3.57	—	
Cellulosic fiber	3.5-6.0	0.29-0.34	—	3.45-2.94	—	
Glass fiber	3.5-4.5	0.26-0.27	—	3.85-3.70	—	
PLASTERING MATERIALS						
Cement plaster, sand aggregate	116	5.0	—	0.20	—	0.20
Sand aggregate 0.375 in.	—	—	13.3	—	0.08	0.20
Sand aggregate 0.75 in.	—	—	6.66	—	0.15	0.20
Gypsum plaster:						
Lightweight aggregate 0.5 in.	45	—	3.12	—	0.32	
Lightweight aggregate 0.625 in.	45	—	2.67	—	0.39	
Lightweight agg. on metal lath 0.75 in.	—	—	2.13	—	0.47	
Perlite aggregate	45	1.5	—	0.67	—	0.32
Sand aggregate	105	5.6	—	0.18	—	0.20
Sand aggregate 0.5 in.	105	—	11.10	—	0.09	
Sand aggregate 0.625 in.	105	—	9.10	—	0.11	
Sand aggregate on metal lath 0.75 in.	—	—	7.70	—	0.13	
Vermiculite aggregate	45	1.7	—	0.59	—	
MASONRY MATERIALS						
Concretes						
Cement mortar	105-135	5.0-10.5	—	0.20-0.10	—	—
Gypsum-fiber concrete 87.5% gypsum, 12.5% wood chips	51	1.66	—	0.60	—	0.21
Lightweight aggregates including expanded shale, clay or slate; expanded slags; cinders; pumice; vermiculite; also cellular concretes	120	5.5-11.0	—	0.18-0.09	—	—
	100	3.7-5.9	—	0.27-0.17	—	0.20
	80	2.5-3.5	—	0.40-0.29	—	0.20
	60	1.6-1.8	—	0.63-0.56	—	—
	40	0.93-1.11	—	1.08-0.90	—	—

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values[a] (*Concluded*)

Description	Density, lb/ft³	Conductivity[b] (*k*), Btu·in./h·ft²·°F	Conductance (*C*), Btu/h·ft²·°F	Resistance[c] (*R*) Per inch thickness (1/*k*), °F·ft²·h/Btu·in.	Resistance[c] (*R*) For thickness listed (1/*C*), °F·ft²·h/Btu	Specific Heat, Btu/lb·°F
	30	0.75-0.91	—	1.33-1.10	—	0.20
	20	0.63-0.83	—	1.59-1.20	—	—
Perlite, expanded	50	1.4-1.8	—	0.71-0.56	—	—
	40	0.93	—	1.08	—	0.10
	30	0.71	—	1.41	—	—
	20	0.50	—	2.00	—	0.32
Sand and gravel or stone aggregate (oven dried)	140	8.0-16.0	—	0.13-0.06	—	0.18-0.22
Sand and gravel or stone aggregate (not dried)	140	10.0-20.0	—	0.10-0.05	—	0.19-0.24
Stucco	116	5.0	—	0.20	—	—
SIDING MATERIALS (on flat surface)						
Shingles						
Asbestos-cement	120	—	4.75	—	0.21	
Wood, 16 in., 7.5 exposure	—	—	1.15	—	0.87	0.31
Wood, double, 16-in., 12-in. exposure	—	—	0.84	—	1.19	0.28
Wood, plus insul. backer board, 0.3125 in.	—	—	0.71	—	1.40	0.31
Siding						
Asbestos-cement, 0.25 in., lapped	—	—	4.76	—	0.21	0.24
Asphalt roll siding	—	—	6.50	—	0.15	0.35
Asphalt insulating siding (0.5 in. bed.)	—	—	0.69	—	1.46	0.35
Hardboard siding, 0.4375 in.	—	—	~~0.49~~ 1.49	—	0.67	0.28
Wood, drop, 1 by 8 in.	—	—	1.27	—	0.79	0.28
Wood, bevel, 0.5 by 8 in., lapped	—	—	1.23	—	0.81	0.28
Wood, bevel, 0.75 by 10 in., lapped	—	—	0.95	—	1.05	0.28
Wood, plywood, 0.375 in., lapped	—	—	1.59	—	0.59	0.29
Aluminum or Steel[l], over sheathing						
Hollow-backed	—	—	1.61	—	0.61	0.29
Insulating-board backed nominal 0.375 in.	—	—	0.55	—	1.82	0.32
Insulating-board backed nominal 0.375 in., foil backed			0.34		2.96	
Architectural glass	—	—	10.00	—	0.10	0.20
WOODS (12% Moisture Content)[e,m]						
Hardwoods						0.39[n]
Oak	41.2-46.8	1.12-1.25	—	0.89-0.80	—	
Birch	42.6-45.4	1.16-1.22	—	0.87-0.82	—	
Maple	39.8-44.0	1.09-1.19	—	0.92-0.84	—	
Ash	38.4-41.9	1.06-1.14	—	0.94-0.88	—	
Softwoods						0.39[n]
Southern Pine	35.6-41.2	1.00-1.12	—	1.00-0.89	—	
Douglas Fir-Larch	33.5-36.3	0.95-1.01	—	1.06-0.99	—	
Southern Cypress	31.4-32.1	0.90-0.92	—	1.11-1.09	—	
Hem-Fir, Spruce-Pine-Fir	24.5-31.4	0.74-0.90	—	1.35-1.11	—	
West Coast Woods, Cedars	21.7-31.4	0.68-0.90	—	1.48-1.11	—	
California Redwood	24.5-28.0	0.74-0.82	—	1.35-1.22	—	

[a]Values are for a mean temperature of 75°F. Representative values for dry materials are intended as design (not specification) values for materials in normal use. Thermal values of insulating materials may differ from design values depending on their in-situ properties (e.g., density and moisture content, orientation, etc.) and variability experienced during manufacture. For properties of a particular product, use the value supplied by the manufacturer or by unbiased tests.

[b]To obtain thermal conductivities in Btu/h·ft·°F, divide the *k*-factor by 12 in./ft.

[c]Resistance values are the reciprocals of *C* before rounding off *C* to two decimal places.

[d]Lewis (1967).

[e]U.S. Department of Agriculture (1974).

[f]Does not include paper backing and facing, if any. Where insulation forms a boundary (reflective or otherwise) of an airspace, see Tables 2 and 3 for the insulating value of an airspace with the appropriate effective emittance and temperature conditions of the space.

[g]Conductivity varies with fiber diameter. (See Chapter 20, "Factors that Affect Thermal Performance.") Batt, blanket, and loose-fill mineral fiber insulations are manufactured to achieve specified R-values, the most common of which are listed in the table. Due to differences in manufacturing processes and materials, the product thicknesses, densities, and thermal conductivities vary over considerable ranges for a specified R-value.

[h]For additional information, see Society of Plastics Engineers (SPI) *Bulletin* U108. Values are for aged, unfaced board stock. For change in conductivity with age of expanded polyurethane/polyisocyanurate, see Chapter 20, "Factors that Affect Thermal Performance."

[i]Values are for aged products with gas-impermeable facers on the two major surfaces. An aluminum foil facer of 0.001 in. thickness or greater is generally considered impermeable to gases. For change in conductivity with age of expanded polyisocyanurate, see Chapter 20, "Factors that Affect Thermal Performance," and SPI Bulletin U108.

[j]Insulating values of acoustical tile vary, depending on density of the board and on type, size, and depth of perforations.

[k]Values for fully grouted block may be approximated using values for concrete with a similar unit weight.

[l]Values for metal siding applied over flat surfaces vary widely, depending on amount of ventilation of airspace beneath the siding; whether airspace is reflective or nonreflective; and on thickness, type, and application of insulating backing-board used. Values given are averages for use as design guides, and were obtained from several guarded hot box tests (ASTM C236) or calibrated hot box (ASTM C976) on hollow-backed types and types made using backing-boards of wood fiber, foamed plastic, and glass fiber. Departures of ± 50% or more from the values given may occur.

[m]See Adams (1971), MacLean (1941), and Wilkes (1979). The conductivity values listed are for heat transfer across the grain. The thermal conductivity of wood varies linearly with the density and the density ranges listed are those normally found for the wood species given. If the density of the wood species is not known, use the mean conductivity value. For extrapolation to other moisture contents, the following empirical equation developed by Wilkes (1979) may be used:

Table 4 Footnotes (*Concluded*)

$$k = 0.1791 + \frac{(1.874 \times 10^{-2} + 5.753 \times 10^{-4}M)\rho}{1 + 0.01M}$$

where ρ is density based on oven-dry mass in lb/ft^3 and M is the moisture content in percent.

[a]From Adams (1971), an empirical equation for the specific heat of moist wood at 75°F is as follows:

$$c_p = \frac{(0.299 + 0.01M)}{(1 + 0.01M)} + \Delta c_p$$

where Δc_p accounts for the heat of sorption and is denoted by

$$\Delta c_p = M(1.921 \times 10^{-3} - 3.168 \times 10^{-5} M)$$

where M is the moisture content in percent by mass.

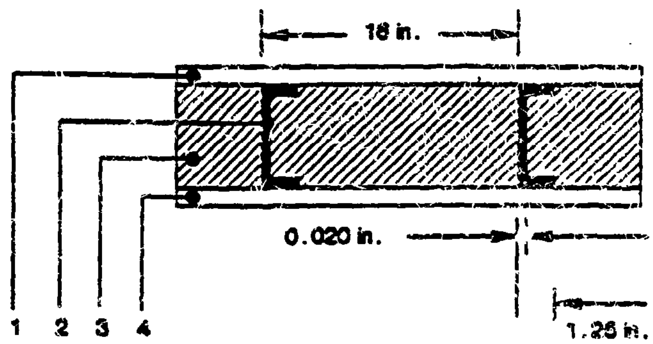


Fig. 4 Insulated Steel Frame Wall (Example 3)

The Zone Method of Calculation

For structures with widely spaced metal members of substantial cross-sectional area, calculation by the isothermal planes method can result in thermal resistance values that are too low. For these constructions, the Zone Method can be used. This method involves two separate computations—one for a chosen limited portion, Zone A, containing the highly conductive element; the other for the remaining portion of simpler construction, Zone B. The two computations are then combined using the parallel flow method, and the average transmittance per unit overall area is calculated. The basic laws of heat transfer are applied by adding the area conductances, CA, of elements in parallel, and adding area resistances, R/A, of elements in series.

The surface shape of Zone A is determined by the metal element. For a metal beam (see Figure 5), the Zone A surface is a strip of width W that is centered on the beam. For a rod perpendicular to panel surfaces, it is a circle of diameter W. The value of W is calculated from Equation (1), which is empirical. The value of d should not be less than 0.5 in. for still air.

$$W = m + 2d \qquad (1)$$

where

m = width or diameter of the metal heat path terminal, in.

d = distance from panel surface to metal, in.

Generally, the value of W should be calculated using Equation (1) for each end of the metal heat path; the larger value, within the limits of the basic area, should be used as illustrated in Example 4.

Example 4. Calculate transmittance of the roof deck shown in Figure 5. Tee-bars at 24 in. OC support glass fiber form boards, gypsum concrete, and built-up roofing. Conductivities of components are: steel, 314.4 Btu·in./h·ft^2·°F; gypsum concrete, 1.66 Btu·in./h·ft^2·°F; and glass fiber form board, 0.25 Btu·in./h·ft^2·°F. Conductance of built-up roofing is 3.00 Btu/h·ft^2·°F.

Solution: The basic area is 2 ft^2 (24 in. by 12 in.) with a tee-bar (12-in. long) across the middle. This area is divided into *Zones A* and *B*.

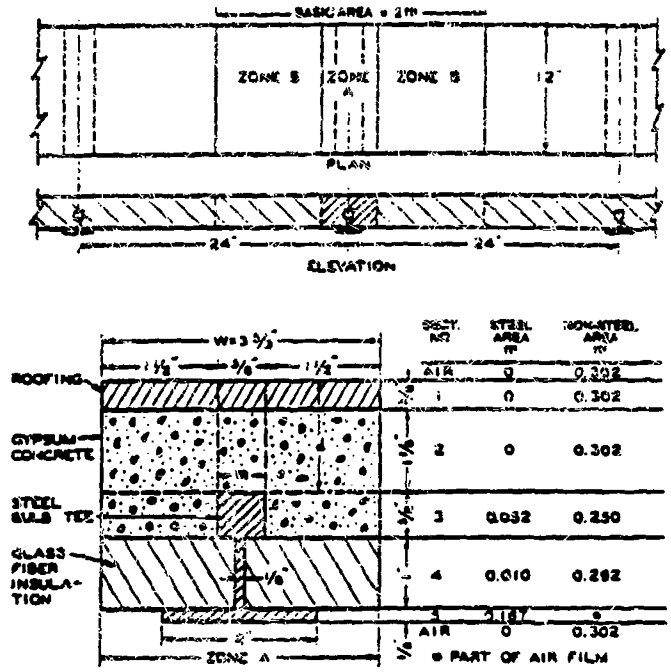


Fig. 5 Gypsum Roof Deck on Bulb Tees (Example 4)

Zone A is determined from Equation 1 as follows:

Top side $W = m + 2d = 0.625 + (2 \times 1.5) = 3.625$ in.
Bottom side $W = m + 2d = 2.0 + (2 \times 0.5) = 3.0$ in.

Using the larger value of W, the area of *Zone A* is $(12 \times 3.625)/144 = 0.302$ ft^2. The area of *Zone B* is $2.0 - 0.302 = 1.698$ ft^2.

To determine area transmittance for *Zone A*, divide the structure within the zone into five sections parallel to the top and bottom surfaces (Figure 5). The area conductance, CA, of each section is calculated by adding the area conductances of its metal and nonmetal paths. Area conductances of the sections are converted to area resistances, R/A, and added to obtain the total resistance of *Zone A*.

Section	Area × Conductance	= CA	$\frac{1}{CA} = \frac{R}{A}$
Air (outside, 15 mph)	0.302 × 6.00	1.81	0.55
No. 1, Roofing	0.302 × 3.00	0.906	1.10
No. 2, Gypsum concrete	0.302 × 1.66/1.125	0.446	2.24
No. 3, Steel	0.052 × 314.4/0.625	26.2	0.04
No. 3, Gypsum concrete	0.250 × 1.66/0.625	0.664	
No. 4, Steel	0.010 × 314.4/1.00	3.14	0.31
No. 4, Glass fiberboard	0.292 × 0.25/1.00	0.073	
No. 5 Steel	0.167 × 314.4/0.125	420.0	0.002
Air (inside)	0.302 × 1.63	0.492	2.03
			Total R/A = 6.27

Area transmittance of *Zone A* = $1/(R/A)$ = 1/6.27 = 0.159.

For *Zone B*, the unit resistances are added and then converted to area transmittance, as shown in the following table.

Section	Resistance, *R*	
Air (outside, 15 mph)	1/6.00	= 0.17
Roofing	1/3.00	= 0.33
Gypsum concrete	1.75/1.66	= 1.05
Glass fiberboard	1.00/0.25	= 4.00
Air (inside)	1/1.63	= 0.61
Total resistance		= 6.16

Since unit transmittance = $1/R$ = 0.162, the total area transmittance, *UA*, is calculated as follows:

$$Zone\ B = 1.698 \times 0.162 = 0.275$$
$$Zone\ A = 0.159$$
$$\text{Total area transmittance of basic area} = 0.434$$
$$\text{Transmittance per ft}^2 = 0.434/2.0 = 0.217$$
$$\text{Resistance per ft}^2 = 4.61$$

Overall R-values of 4.57 and 4.85 °F·ft²·h/Btu have been measured in two guarded hot box tests of a similar construction.

When the steel member represents a relatively large proportion of the total heat flow path, as in Example 4, detailed calculations of resistance in sections 3, 4, and 5 of Zone A are unnecessary; if only the steel member is considered, the final result of Example 4 is the same. However, if the heat flow path represented by the steel member is small, as for a tie rod, detailed calculations for sections 3, 4, and 5 are necessary. A panel with an internal metallic structure and bonded on one or both sides to a metal skin or covering, presents special problems of lateral heat flow not covered in the zone method.

Ceilings and Roofs

The overall R-value for ceilings of wood frame flat roofs can be calculated using Equations (1) through (5) from Chapter 20. Properties of the materials are found in Tables 1, 2, 3, and 4. The fraction of framing is assumed to be 0.10 for joists at 16 in. OC and 0.07 for joists at 24 in. OC. The calculation procedure is similar to that shown in Example l. Note that if the ceiling contains plane airspaces (see Table 2), the resistance depends on the direction of heat flow, *i.e.*, whether the calculation is for a winter (heat flow up) or summer (heat flow down) condition.

For ceilings of pitched roofs under winter conditions, calculate the R-value of the ceiling using the procedure for flat roofs. The heat loss from these ceilings can be obtained using a calculated attic temperature (see Chapter 25). Table 5 can be used to determine the effective resistance of the attic space under summer conditions for varying conditions of ventilation air temperature, airflow direction and rates, ceiling resistance, roof or sol-air temperatures, and surface emittances (Joy 1958).

Table 5 Effective Thermal Resistance of Ventilated Attics[a] (Summer Condition)

		No Ventilation[b]		Natural Ventilation		Power Ventilation[c]					
		Ventilation Rate, cfm/ft²									
		0		0.1[d]		0.5		1.0		1.5	
		Ceiling Resistance, R[e], °F·ft²·h/Btu									
Ventilation Air Temp., °F	Sol-Air[f] Temp., °F	10	20	10	20	10	20	10	20	10	20
PART A. NONREFLECTIVE SURFACES											
80	120	1.9	1.9	2.8	3.4	6.3	9.3	9.6	16	11	20
	140	1.9	1.9	2.8	3.5	6.5	10	9.8	17	12	21
	160	1.9	1.9	2.8	3.6	6.7	11	10	18	13	22
90	120	1.9	1.9	2.5	2.8	4.6	6.7	6.1	10	6.9	13
	140	1.9	1.9	2.6	3.1	5.2	7.9	7.6	12	8.6	15
	160	1.9	1.9	2.7	3.4	5.8	9.0	8.5	14	10	17
100	120	1.9	1.9	2.2	2.3	3.3	4.4	4.0	6.0	4.1	6.9
	140	1.9	1.9	2.4	2.7	4.2	6.1	5.8	8.7	6.5	10
	160	1.9	1.9	2.6	3.2	5.0	7.6	7.2	11	8.3	13
PART B. REFLECTIVE SURFACES[g]											
80	120	6.5	6.5	8.1	8.8	13	17	17	25	19	30
	140	6.5	6.5	8.2	9.0	14	18	18	26	20	31
	160	6.5	6.5	8.3	9.2	15	18	19	27	21	32
90	120	6.5	6.5	7.5	8.0	10	13	12	17	13	19
	140	6.5	6.5	7.7	8.3	12	15	14	20	16	22
	160	6.5	6.5	7.9	8.6	13	16	16	22	18	25
100	120	6.5	6.5	7.0	7.4	8.0	10	8.5	12	8.8	12
	140	6.5	6.5	7.3	7.8	10	12	11	15	12	16
	160	6.5	6.5	7.6	8.2	11	14	13	18	15	20

[a] Although the term effective resistance is commonly used when there is attic ventilation, this table includes values for situations with no ventilation. The effective resistance of the attic, added to the resistance ($1/U$) of the ceiling yields the effective resistance of this combination based on sol-air (see Chapter 26) and room temperatures. These values apply to wood frame construction with a roof deck and roofing that has a conductance of 1.0 Btu/h·ft²·°F.

[b] This condition cannot be achieved in the field unless extreme measures are taken to tightly seal the attic.

[c] Based on air discharging outward from attic.

[d] When attic ventilation meets the requirements stated in Chapter 23, 0.1 cfm/ft² is assumed as the natural summer ventilation rate for design purposes.

[e] When determining ceiling resistance, do not add the effect of a reflective surface facing the attic, as it is accounted for in Table 5, Part B.

[f] Roof surface temperature rather than sol-air temperature (see Chapter 26) can be used if 0.25 is subtracted from the attic resistance shown.

[g] Surfaces with effective emittance *E* of 0.05 between ceiling joists facing the attic space.

Table 6 Transmission Coefficients (U) for Wood and Steel Doors, Btu/h·ft²·°F

Nominal Door Thickness, in.	Description	No Storm Door	Wood Storm Door[c]	Metal Storm Door[d]
Wood Doors[a, b]				
1-3/8	Panel door with 7/16-in. panels[e]	0.57	0.33	0.37
1-3/8	Hollow core flush door	0.47	0.30	0.32
1-3/8	Solid core flush door	0.39	0.26	0.28
1-3/8	Panel door with 7/16-in. panels[e]	0.57	0.33	0.36
1-3/4	Hollow core flush door	0.46	0.29	0.32
1-3/4	Panel door with 1-1/8-in. panels[e]	0.39	0.26	0.28
1-3/4	Solid core flush door	0.33	0.28	0.25
2-1/4	Solid core flush door	0.27	0.20	0.21
Steel Doors[b]				
1-3/4	Fiberglass or mineral wool core with steel stiffeners, no thermal break[f]	0.60	—	—
1-3/4	Paper honeycomb core without thermal break[f]	0.56	—	—
1-3/4	Solid urethane foam core without thermal break[a]	0.40	—	—
1-3/4	Solid fire rated mineral fiberboard core without thermal break[f]	0.38	—	—
1-3/4	Polystyrene core without thermal break (18 gage commercial steel)[f]	0.35	—	—
1-3/4	Polystyrene core without thermal break (18 gage commercial steel)[f]	0.35	—	—
1-3/4	Polyurethane core without thermal break (18 gage commercial steel)[f]	0.29	—	—
1-3/4	Polyurethane core without thermal break (24 gage commercial steel)[f]	0.29	—	—
1-3/4	Polyurethane core with thermal break and wood perimeter (24 gage residential steel)[f]	0.20	—	—
1-3/4	Solid urethane foam core with thermal break[a]	0.19	0.16	0.17

Note: All U-factors for exterior doors in this table are for doors with no glazing, except for the storm doors which are in addition to the main exterior door. Any glazing area in exterior doors should be included with the appropriate glass type and analyzed (see Chapter 27). Interpolation and moderate extrapolation are permitted for door thicknesses other than those specified.

[a]Values are based on a nominal 32 by 80 in. door size with no glazing.

[b]Outside air conditions: 15 mph wind speed, 0°F air temperature; inside air conditions: natural convection, 70°F air temperature.

[c]Values for wood storm door are for approximately 50% glass area.

[d]Values for metal storm door are for any percent glass area.

[e]55% panel area.

[f]ASTM C 236 hotbox data on a nominal 3 by 7 ft door size with no glazing.

The R-value is the total resistance obtained by adding the ceiling and effective attic resistances. The applicable temperature difference is that difference between room air and sol-air temperatures or between room air and roof temperatures (see Table 5, footnote f). Table 5 can be used for pitched and flat residential roofs over attic spaces. When an attic has a floor, the ceiling resistance should account for the complete ceiling-floor construction.

Windows and Doors

The U-factors given in Table 13 of Chapter 27 are for vertical glazing (e.g., windows, glass in exterior doors, glass doors, and skylights). The values were computed using procedures outlined in Chapter 27. The U-factors in Table 6 are for exterior wood and steel doors. The values given for wood doors were calculated, and those for steel doors were taken from hot box tests (Sabine *et al.* 1975; Yellott 1965) or from manufacturers' test reports. An outdoor surface conductance of 6.0 Btu/h·ft²·°F was used, and the indoor surface conductance was taken as 1.46 Btu/h·ft²·°F for vertical surfaces with horizontal heat flow. All values given are for exterior doors without glazing. If an exterior door contains glazing, the glazing should be analyzed as a window, as illustrated in Example 5.

Example 5. Determine the U-factor of a wood frame residential window containing double insulating glass with 0.5-in. airspace for winter conditions.

Solution: From Chapter 27, Table 13, the U-factor of the center of the glass portion only is 0.49 Btu/h·ft²·°F. The wood frame of the window also must be considered when determining the window U-factor. Referring to Table 13 in Chapter 27, for a wood frame window of Product Size R (see Figure 7 in Chapter 27), the U-factor is also given as 0.49 Btu/h·ft²·°F.

All R-values are approximate, since a significant portion of the resistance of a window or door is contained in the air film resistances, and some parameters that may have important effects are not considered. For example, the listed U-factors assume the surface temperatures of surrounding bodies are equal to the ambient air temperature. However, the indoor surface of a window or door in an actual installation may be exposed to nearby radiating surfaces, such as radiant-heating panels, or opposite walls with much higher or lower temperatures than the indoor air. Air movement across the indoor surface of a window or door, such as that caused by nearby heating and cooling outlet grilles, increases the U-factor; and air movement (wind) across the outdoor surface of a window or door also increases the U-factor.

For windows that are sloped or horizontal, Chapter 27 gives a U-factor conversion table (see Table 13 Part B). Values for the vertical (90° slope) orientation, such as those shown in Part A of Table 13, are converted to sloped (45°) and horizontal (0°) orientations. Since data are presented only for vertical, horizontal, and 45-degree-sloped glazing, the orientation that most closely approximates the application condition should be used.

U_o Concept

In Section 4 of ASHRAE *Standard* 90A-1980, "Energy Conservation in New Building Design," requirements are stated in terms of U_o, where U_o is the combined thermal transmittance of the respective areas of gross exterior wall, roof or ceiling or both, and floor assemblies. The U_o equation for a wall is as follows:

$$U_o = (U_{wall}A_{wall} + U_{window}A_{window} + U_{door}A_{door})/A_o \qquad (2)$$

where

U_o = average thermal transmittance of the gross wall area
A_o = gross area of exterior walls
U_{wall} = thermal transmittance of all elements of the opaque wall area
A_{wall} = opaque wall area
U_{window} = thermal transmittance of the window area (including frame)
A_{window} = window area (including frame)
U_{door} = thermal transmittance of the door area
A_{door} = door area

Where more than one type of wall, window, or door is used, the UA term for that exposure should be expanded into its subelements, as shown in Equation (3).

$$\begin{aligned} U_oA_o = \; & U_{wall\,1}A_{wall\,1} + U_{wall\,2}A_{wall\,2} + \cdots + U_{wall\,m}A_{wall\,m} \\ & + U_{window\,1}A_{window\,1} + U_{window\,2}A_{window\,2} + \cdots \\ & + U_{window\,n}A_{window\,n} + U_{door\,1}A_{door\,1} \\ & + U_{door\,2}A_{door\,2} + \cdots + U_{door\,o}A_{door\,o} \end{aligned} \qquad (3)$$

Example 6. Calculate U_o for a wall 30 ft by 8 ft, constructed as in Example 1. The wall contains one window 60 in. by 34 in. and a second window 36 in. by 30 in. Both windows are constructed as in Example 5. The wall also contains a 1.75-in. solid core flush door with a metal storm door 34 in. by 80 in. (U = 0.25 Btu/h·ft²·°F from Table 6).

Solution: The U-factors for the wall and windows were obtained in Examples 1 and 5, respectively. The areas of the different components are:

$$A_{window} = [(60 \times 34) + (36 \times 30)]/144 = 21.7 \text{ ft}^2$$
$$A_{door} = (34 \times 80)/144 = 18.9 \text{ ft}^2$$
$$A_{wall} = (30 \times 8) - (21.7 + 18.9) = 199.4 \text{ ft}^2$$

Therefore, the combined thermal transmittance for the wall is:

$$U_o = \frac{(0.078 \times 199.4) + (0.49 \times 21.7) + (0.25 \times 18.9)}{(30 \times 8)}$$
$$= 0.13 \text{ Btu/h·ft}^2\text{·°F}$$

Slab-on-Grade and Below-Grade Construction

Heat transfer through basement walls and floors to the ground depends on the following factors: (1) the difference between the air temperature within the room and that of the ground and outside air, (2) the material of the walls or floor, and (3) the thermal conductivity of the surrounding earth. The latter varies with local conditions and is usually unknown. Because of the great thermal inertia of the surrounding soil, ground temperature varies with depth, and there is a substantial time lag between changes in outdoor air temperatures and corresponding changes in ground temperatures. As a result, ground-coupled heat transfer is less amenable to steady-state representation than above-grade building elements. However, several simplified procedures for estimating ground-coupled heat transfer have been developed. These fall into two principal categories: (1) those that reduce the ground heat transfer problem to a closed-form solution, and (2) those that use simple regression equations developed from statistically reduced multidimensional transient analyses.

Closed-form solutions, including the ASHRAE arc-length procedure discussed in Chapter 25 by Latta and Boileau (1969), generally reduce the problem to one-dimensional, steady-state heat transfer. These procedures use simple, "effective" U-factors

Table 7 Typical Water Vapor Permeance and Permeability Values for Common Building Materials[a]

Material	Thickness, in.	Permeance, Perm	Resistance[b], Rep	Permeability, Perm-in.	Resistance/in.[b], Rep/in.
Construction Materials					
Concrete (1:2:4 mix)				3.2	0.31
Brick masonry	4	0.8[f]	1.3		
Concrete block (cored, limestone aggregate)	8	2.4[f]	0.4		
Tile masonry, glazed	4	0.12[f]	8.3		
Asbestos cement board	0.12	4-8[d]	0.1-0.2		
With oil-base finishes		0.3-0.5[d]	2-3		
Plaster on metal lath	0.75	15[f]	0.067		
Plaster on wood lath		11[e]	0.091		
Plaster on plain gypsum lath (with studs)		20[f]	0.050		
Gypsum wall board (plain)	0.375	50[f]	0.020		
Gypsum sheathing (asphalt impreg.)	0.5			20[d]	0.050
Structural insulating board (sheathing qual.)				20-50[f]	0.050-0.020
Structural insulating board (interior, uncoated)	0.5	50-90[f]	0.020-0.011		
Hardboard (standard)	0.125	11[f]	0.091		
Hardboard (tempered)	0.125	5[f]	0.2		
Built-up roofing (hot mopped)		0.0			
Wood, sugar pine				0.4-5.4[f,b]	2.5-0.19
Plywood (douglas fir, exterior glue)	0.25	0.7[f]	1.4		
Plywood (douglas fir, interior glue)	0.25	1.9[f]	0.53		
Acrylic, glass fiber reinforced sheet	0.056	0.12[d]	8.3		
Polyester, glass fiber reinforced sheet	0.048	0.05[d]	20		
Thermal Insulations					
Air (still)				120[f]	0.0083
Cellular glass				0.0[d]	∞
Corkboard				2.1-2.6[d]	0.48-0.38
				9.5[e]	0.11
Mineral wool (unprotected)				116[e]	0.0086
Expanded polyurethane (R-11 blown) board stock				0.4-1.6[d]	2.5-0.62
Expanded polystyrene—extruded				1.2[d]	0.83
Expanded polystyrene—bead				2.0-5.8[d]	0.50-0.17
Phenolic foam (covering removed)				26	0.038
Unicellular synthetic flexible rubber foam				0.02-0.15[d]	50-6.7

Table 7 Typical Water Vapor Permeance and Permeability Values for Common Building Materials[a] (*Concluded*)

Material	Weight, lb/100 ft²	Permeance, Perms Dry-Cup	Permeance, Perms Wet-Cup	Permeance, Perms Other	Resistance[h] Rep Dry-Cup	Resistance[h] Rep Wet-Cup	Resistance[h] Rep Other
Plastic and Metal Foils and Films[c]							
Aluminum foil	0.001		0.0[d]		∞		
Aluminum foil	0.00035		0.05[d]		20		
Polyethylene	0.002		0.16[d]		6.3		3100
Polyethylene	0.004		0.08[d]		12.5		3100
Polyethylene	0.006		0.06[d]		17		3100
Polyethylene	0.008		0.04[d]		25		3100
Polyethylene	0.010		0.03[d]		33		3100
Polyvinylchloride, unplasticized	0.002		0.68[d]		1.5		
Polyvinylchloride, plasticized	0.004		0.8-1.4[d]		1.3-0.72		
Polyester	0.001		0.73[d]		1.4		
Polyester	0.0032		0.23[d]		4.3		
Polyester	0.0076		0.08[d]		12.5		
Cellulose acetate	0.01		4.6[d]		0.2		
Cellulose acetate	0.125		0.32[d]		3.1		
Building paper, felts, roofing papers[g]							
Duplex sheet, asphalt laminated, aluminum foil one side	8.6	0.002	0.176		500	5.8	
Saturated and coated roll roofing	65	0.05	0.24		20	4.2	
Kraft paper and asphalt laminated, reinforced 30-120-30	6.8	0.3	1.8		3.3	0.55	
Blanket therm[illegible] insulation back-up paper, asphalt coated	6.2	0.4	0.6-4.2		2.5	1.7-0.24	
Asphalt-saturated and coated vapor retarder paper	8.6	0.2-0.3	0.6		5.0-3.3	1.7	
Ashphal-saturated but not coated sheathing paper	4.4	3.3	20.2		0.3	0.05	
15-lb asphalt felt	14	1.0	5.6		1.0	0.18	
15-lb tar felt	14	4.0	18.2		0.25	0.055	
Single-kraft, double	3.2	31	42		0.032	0.024	
Liquid-Applied Coating Materials	**Thickness, in.**						
Commercial latex paints (dry film thickness)[i]							
Vapor retarder paint	0.0031			0.45			2.22
Primer-sealer	0.0012			6.28			0.16
Vinyl acetate/acrylic primer	0.002			7.42			0.13
Vinyl-acrylic prim[illegible]	0.0016			8.62			0.12
Semi-gloss vin[illegible] enamel	0.0024			6.61			0.15
Exterior acrylic [illegible] and trim	0.0017			5.47			0.18
Paint-2 coats							
Asphalt paint on [illegible]			0.4			2.5	
Aluminum varnish [illegible] wood		0.3-0.5			3.3-2.0		
Enamels on smooth plaster				0.5-1.5			2.0-0.66
Primers and sealers on interior insulation board				0.9-2.1			1.1-0.48
Various primers plus 1 [illegible] flat oil paint on plaster				1.6-3.0			0.63-0.33
Flat paint on interior i[illegible]ation board				4			0.25
Water emulsion on interior insulation board				30-85			0.03-0.012
	Weight, oz/ft²						
Paint-3 coats							
Exterior paint, white lead and oil on wood siding		0.3-1.0			3.3-1.0		
Exterior paint, white lead-zinc oxide and oil on wood		0.9			1.1		
Styrene-butadiene latex coating	2	11			0.09		
Polyvinyl acetate latex coating	4	5.5			0.18		
Chlorosulfonated polyethylene mastic	3.5	1.7			0.59		
	7.0	0.06			16		
Asphalt cut-back mastic, 1/16 in., dry		0.14			7.2		
3/16 in., dry		0.0			—		
Hot melt asphalt	2	0.5			2		
	3.5	0.1			10		

[a]This table permits comparisons of materials; but in the selection of vapor retarder materials, exact values for permeance or permeability should be obtained from the manufacturer or from laboratory tests. The values shown indicate variations among mean values for materials that are similar but of different density, orientation, lot, or source. The values should not be used as design or specification data. Values from dry-cup and wet-cup methods were usually obtained from investigations using ASTM E96 and C355; values shown under others were obtained by two-temperature, special cell, and air velocity methods. Permeance, resistance, permeability, and resistance per unit thickness values are given in the following units:

Permeance	Perm	= gr/h·ft²·in. Hg
Resistance	Rep	= in. Hg·ft²·h/gr
Permeability	Perm-in.	= gr/h·ft²·(in. HG/in.)
Resistance/unit thickness	Rep/in.	= (in. Hg·ft²·h/gr)/in.

[b]Depending on construction and direction of vapor flow.

[c]Usually installed as vapor retarders, although sometimes used as exterior finish and elsewhere near cold side, where special considerations are then required for warm side barrier effectiveness.

[d]Dry-cup method.

[e]Wet-cup method.

[f]Other than dry- or wet-cup method.

[g]Low permeance sheets used as vapor retarders. High permeance used elsewhere in construction.

[h]Resistance and resistance/in. values have been calculated as the reciprocal of the permeance and permeability values.

[i]Cast at 10 mils wet film thickness.

or ground temperatures or both. Methods differ in the various parameters averaged or manipulated to obtain these effective values. Closed-form solutions provide acceptable results in climates that have a single dominant season, because the dominant season persists long enough to permit a reasonable approximation of steady-state conditions at shallow depths. The large errors (percentage) that are likely during transition seasons should not seriously affect building design decisions, since these heat flows are relatively insignificant when compared with those of the principal season.

The ASHRAE arc-length procedure is a reliable method for wall heat losses in cold winter climates. Chapter 25 discusses a slab-on-grade floor model developed by one study. Although both procedures give results comparable to transient computer solutions for cold climates, their results for warmer U.S. climates differ substantially.

Research conducted by Houghten *et al.* (1942) and Dill *et al.* (1945) indicates a heat flow of approximately 2.0 Btu/h·ft² through an uninsulated concrete basement floor with a temperature difference of 20°F between the basement floor and the air 6 in. above the floor. A U-factor of 0.10 Btu/h·ft²·°F is sometimes used for concrete basement floors on the ground. For basement walls below grade, the temperature difference for winter design conditions is greater than for the floor. Test results indicate that at the midheight of the below-grade portion of the basement wall, the unit area heat loss is approximately twice that of the floor.

For concrete slab floors in contact with the ground at grade level, tests indicate that for small floor areas (equal to that of a 25 by 25 ft house) the heat loss can be calculated as proportional to the length of exposed edge rather than total area. This amounts to 0.81 Btu/h per linear ft of exposed edge per °F difference between the indoor air temperature and the average outdoor air temperature. This value can be reduced appreciably by installing insulation under the ground slab and along the edge between the floor and abutting walls. In most calculations, if the perimeter loss is calculated accurately, no other floor losses need to be considered. Chapter 25 contains data for load calculations and heat loss values for below-grade walls and floors at different depths.

The second category of simplified procedures uses transient two-dimensional computer models to generate the ground heat transfer data that are then reduced to compact form by regression analysis (see Mitalas 1982 and 1983, Shipp 1983). These are the most accurate procedures available, but the database is very expensive to generate. In addition, these methods are limited to the range of climates and constructions specifically examined. Extrapolating beyond the outer bounds of the regression surfaces can produce significant errors.

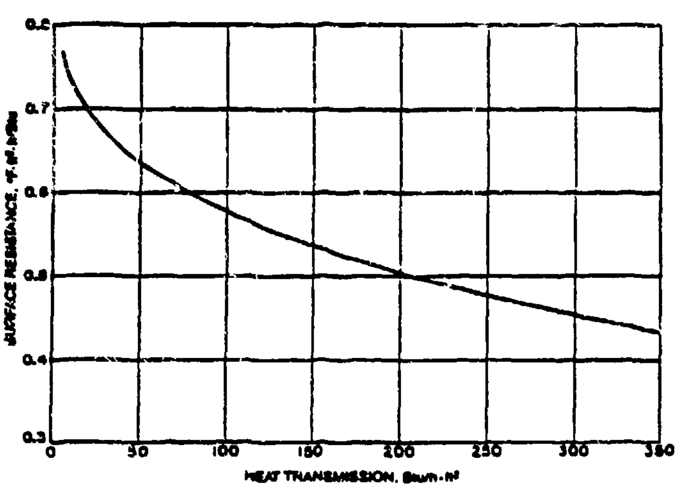


Fig. 6 Surface Resistance as a Function of Heat Transmission for Flat and Cylindrical Surfaces

Water Vapor Transmission Data for Building Components

Table 7 gives typical water vapor permeance and permeability values for common building materials. These values can be used to calculate water vapor flow through building components and assemblies using Equations (2) and (3) in Chapter 21.

MECHANICAL AND INDUSTRIAL SYSTEMS

Thermal Transmission Data

Table 8 lists the thermal conductivities of various materials used as industrial insulations. These values are functions of the arithmetic mean of the temperatures of the inner and outer surfaces for each insulation.

Heat Loss From Pipes and Flat Surfaces

Tables 9A, 9B, and 10 give heat losses from bare steel pipes and flat surfaces and bare copper tubes. These tables were calculated using ASTM *Standard* C 680, "Practice for Determination of Heat Gain or Loss and the Surface Temperature of Insulated Pipe and Equipment Systems by the Use of a Computer Program." User inputs for these programs include operating temperature, ambient temperature, pipe size, insulation type, number of insulation layers, and thickness for each layer. A program option allows the user to input a surface coefficient or surface emittance, surface orientation, and wind speed. The computer uses this information to calculate the heat flow and the surface temperature. The programs calculate the surface coefficients if the user has not already supplied them.

The equations used in ASTM C 680 are:

$$h_{cv} = C\left(\frac{1}{d}\right)^{0.2}\left(\frac{1}{t_{avg}}\right)^{0.181}\Delta t^{0.266}\sqrt{1 + 1.277(\text{Wind})} \quad (4)$$

where

h_{cv} = convection surface coefficient, Btu/h·ft²·°F
d = diameter for cylinder, in. For flat surfaces and large cylinders ($d > 24$), use $d = 24$
t_{avg} = average temperature of air film, °F
Δt = surface to air temperature difference, °F
Wind = air speed, mph
C = constant depending on shape and heat flow condition
= 1.016 for horizontal cylinders
= 1.235 for longer vertical cylinders
= 1.394 for vertical plates
= 1.79 for horizontal plates, warmer than air, facing upward
= 0.89 for horizontal plates, warmer than air, facing downward
= 0.89 for horizontal plates, cooler than air, facing upward
= 1.79 for horizontal plates, cooler than air, facing downward

$$h_{rad} = \frac{\epsilon \times 0.1713 \times 10^{-8}[(t_a + 459.6)^4 - (t_s + 459.6)^4]}{(t_a - t_s)} \quad (5)$$

where

h_{rad} = radiation surface coefficient, Btu/h·ft²·°F
ϵ = surface emittance
t_a = air temperature, °F
t_s = surface temperature, °F

Example 7. Compute total annual heat loss from 165 ft of nominal 2-in. bare pipe in service 4000 h per year. The pipe is carring steam at 10 psi and is exposed to an average air temperature of 80°F.

Solution: The pipe temperature is taken as the steam temperature, which is 239.4°F, obtained by interpolation from Steam Tables. By interpolation in Table 9A between 180 °F and 280 °F, heat loss from a 2-in. pipe is 285.3 Btu/h·ft. Total annual heat loss from the entire line is 285.3 Btu/h·ft × 165 ft × 4000 h = 188 million Btu.

In calculating heat flow, Equations (9) and (10) from Chapter 20 generally are used. For dimensions of standard pipe and fitting sizes refer to the Piping Handbook. For insulation product dimensions refer to ASTM *Standard* C 585, "Recommended Practice for Inner and Outer Diameters of Rigid Thermal Insulation for Nominal Sizes of Pipe and Tubing (NPS) System," or to the insulation manufacturers' literature.

Examples 8 and 9 illustrate how Equations (9) and (10) from Chapter 20 can be used to determine heat loss from both flat and cylindrical surfaces. Figure 6 shows surface resistance as a function of heat transmission for both flat and cylindrical surfaces. The surface emittance is assumed to be 0.85 to 0.90 in still air at 80 °F.

Example 8. Compute heat loss from a boiler wall if the interior insulation surface temperature is 1100 °F and ambient still air temperature is 80 °F. The wall is insulated with 4.5 in. of mineral fiber block and 0.5 in. of mineral fiber insulating and finishing cement.

Solution: Assume that the mean temperature of the mineral fiber block is 700 °F, the mean temperature of the insulating cement is 200 °F and the surface resistance, R_s, is 0.60.

From Table 8, $k_1 = 0.62$ and $k_2 = 0.80$. Using Equation (9) from Chapter 20:

$$q_s = \frac{1100 - 80}{(4.5/0.62) + (0.5/0.80) + 0.60} = \frac{1020}{8.48}$$
$$= 120.2 \text{ Btu/h·ft}^2$$

As a check, from Figure 6, at 120.2 Btu/h·ft², $R_s = 0.56$. The mean temperature of the mineral fiber block is:

$$4.5/0.62 = 7.26;\ 7.26/2 = 3.63$$
$$1100 - [(3.63/8.48)(1020)] = 1100 - 437 = 663\,°F$$

and the mean temperature of the insulating cement is:

$$0.5/0.80 = 0.63;\ 0.63/2 = 0.31;\ 7.26 + 0.31 = 7.57$$
$$1100 - [(7.57/8.48)(1020)] = 1100 - 911 = 189\,°F$$

From Table 8, at 663 °F, $k_1 = 0.60$; at 189 °F, $k_2 = 0.79$. Using these adjusted values to recalculate q_s:

$$q_s = \frac{1020}{(4.5/0.60) + (0.5/0.79) + 0.56} = \frac{1020}{8.69}$$
$$= 117.4 \text{ Btu/h·ft}^2$$

Table 8 Typical Thermal Conductivity (k) for Industrial Insulations at Various Mean Temperatures - Design Values[a]

Material	Accepted Max. Temp. for Use[b], °F	Typical Density, lb/ft³	Typical Conductivity k in Btu·in/h·ft²·°F at Mean Temp, °F													
			−100	−75	−50	−25	0	25	50	75	100	200	300	500	700	900
BLANKETS AND FELTS																
ALUMINOSILICATE FIBER																
7-10µ diameter fiber	1800	4								0.24		0.32		0.54	0.99	1.03
	2000	6-8								0.25		0.30		0.48	0.78	0.95
3µ diameter fiber	2200	4								0.22		0.29		0.45	0.59	0.74
MINERAL FIBER																
(Rock, slag or glass)																
Blanket, metal reinforced	1200	6–12									0.26	0.32	0.39	0.54		
	1000	2.5-6									0.24	0.31	0.40	0.61		
Blanket, flexible, fine-fiber organic bonded	350	<0.75				0.25	0.26	0.28	0.30	0.33	0.36	0.53				
		0.75				0.24	0.25	0.27	0.29	0.32	0.34	0.48				
		1.0				0.23	0.24	0.25	0.27	0.29	0.32	0.43				
		1.5				0.21	0.22	0.23	0.25	0.27	0.28	0.37				
		2.0				0.20	0.21	0.22	0.23	0.25	0.26	0.33				
		3.0				0.19	0.20	0.21	0.22	0.23	0.24	0.31				
Blanket, flexible, textile-fiber organic bonded	350	0.65				0.27	0.28	0.29	0.30	0.31	0.32	0.50	0.68			
		0.75				0.26	0.27	0.28	0.29	0.31	0.32	0.46	0.66			
		1.0				0.24	0.25	0.26	0.27	0.29	0.31	0.45	0.60			
		1.5				0.22	0.23	0.24	0.25	0.27	0.29	0.39	0.51			
		3.0				0.20	0.21	0.22	0.23	0.24	0.25	0.32	0.41			
Felt, semirigid organic bonded	400	3–8						0.24	0.25	0.26	0.27	0.35	0.44			
	850	3	0.16	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.35	0.55			
Laminated and felted without binder	1200	7.5											0.35	0.45	0.60	
BLOCKS, BOARDS, AND PIPE INSULATION																
MAGNESIA	600	11–12									0.35	0.38	0.42			
85% CALCIUM SILICATE	1200	11–12									0.38	0.41	0.44	0.52	0.62	0.72
	1800	12–15												0.63	0.74	0.95
CELLULAR GLASS	900	8.5	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.35	0.36	0.42	0.49	0.70	1.03	
DIATOMACEOUS SILICA	1600	21–22												0.64	0.68	0.72
	1900	23–25												0.70	0.75	0.80
MINERAL FIBER																
Glass,																
Organic bonded, block and boards	400	3–10	0.16	0.17	0.18	0.19	0.20	0.22	0.24	0.25	0.26	0.33	0.40			
Nonpunking binder	1000	3–10									0.26	0.31	0.38	0.52		
Pipe insulation, slag, or glass	350	3–4					0.20	0.21	0.22	0.23	0.24	0.29				
	500	3–10					0.20	0.22	0.24	0.25	0.26	0.33	0.40			
Inorganic bonded block	1000	10–15									0.33	0.38	0.45	0.55		
	1800	15–24									0.32	0.37	0.42	0.52	0.62	0.74
Pipe insulation, slag, or glass	1000	10–15									0.33	0.38	0.45	0.55		
Resin binder		15	0.23	0.24	0.25	0.26	0.28	0.29								

Table 8 Typical Thermal Conductivity (*k*) for Industrial Insulations at Various Mean Temperatures – Design Values[a] (*Concluded*)

Material	Accepted Max. Temp. for Use[b], °F	Typical Density, lb/ft³	Typical Conductivity *k* in Btu·in/h·ft²·°F at Mean Temp., °F: −100	−75	−50	−25	0	25	50	75	100	200	300	500	700	900
RIGID POLYSTYRENE																
Extruded (CFC-12 exp.)																
(smooth skin surface)	165	1.8–3.5	0.16	0.16	0.17	0.16	0.17	0.18	0.19	0.20						
Molded beads	165	1	0.17	0.19	0.20	0.21	0.22	0.24	0.25	0.26	0.28					
		1.25	0.17	0.18	0.19	0.20	0.22	0.23	0.24	0.25	0.27					
		1.5	0.16	0.17	0.19	0.20	0.21	0.22	0.23	0.24	0.26					
		1.75	0.16	0.17	0.18	0.19	0.20	0.22	0.23	0.24	0.25					
		2.0	0.15	0.16	0.18	0.19	0.20	0.21	0.22	0.23	0.24					
RIGID POLYURETHANE/ POLYISOCYANURATE[c,d]																
Unfaced (CFC-11 exp.)	210	1.5–2.5	0.16	0.17	0.18	0.18	0.18	0.17	0.16	0.16	0.17					
RIGID POLYISOCYANURATE[e]																
Gas-impermeable facers (CFC-11 exp.)	250	2.0						0.12	0.13	0.14	0.15					
RIGID PHENOLIC																
Closed cell (CFC-11, CFC-113 exp.)		3.0						0.11	0.115	0.12	0.125					
RUBBER, Rigid Foamed	150	4.5						0.20	0.21	0.22	0.23					
VEGETABLE AND ANIMAL FIBER																
Wool felt (pipe insulation)	180	20						0.28	0.30	0.31	0.33					
INSULATING CEMENTS																
MINERAL FIBER (Rock, slag, or glass)																
With colloidal clay binder	1800	24–30									0.49	0.55	0.61	0.73	0.85	
With hydraulic setting binder	1200	30–40									0.75	0.80	0.85	0.95		
LOOSE FILL																
Cellulose insulation (milled pulverized paper or wood pulp)		2.5–3							0.26	0.27	0.29					
Mineral fiber, slag, rock, or glass		2–5			0.19	0.21	0.23	0.25	0.26	0.28	0.31					
Perlite (expanded)		3–5	0.22	0.24	0.25	0.27	0.28	0.30	0.31	0.33	0.35					
Silica aerogel		7.6			0.13	0.14	0.15	0.15	0.16	0.17	0.18					
Vermiculite (expanded)		7–8.2			0.39	0.40	0.42	0.44	0.45	0.47	0.49					
		4–6			0.34	0.35	0.38	0.40	0.42	0.44	0.46					

[a]Representative values for dry materials, which are intended as design (not specification) values for materials in normal use. Insulation materials in actual service may have thermal values that vary from design values depending on their in-situ properties (e.g., density and moisture content). For properties of a particular product, use the value supplied by the manufacturer or by unbiased tests.

[b]These temperatures are generally accepted as maximum. When operating temperature approaches these limits follow the manufacturer's recommendations.

[c]Some polyurethane foams are formed by means that produce a stable product (with respect to *k*), but most are blown with refrigerant and will change with time.

[d]See Table 4, footnote h.

[e]See Table 4, footnote i.

From Figure 6, at 117.4 Btu/h·ft², R_s = 0.56. The mean temperature of the mineral fiber block is:

$$4.5/0.6 = 7.50;\ 7.50/2 = 3.75$$
$$1100 - [(3.75/8.69)(1020)] = 1100 - 440 = 660°F$$

and the mean temperature of the insulating cement is:

$$0.5/0.79 = 0.63;\ 0.63/2 = 0.31;\ 7.50 + 0.31 = 7.81$$
$$1100 - [(7.81/8.69)(1020)] = 1100 - 917 = 183°F$$

From Table 8, at 660°F, k_1 = 0.60; at 183°F, k_2 = 0.79.

Since R_s, k_1 and k_2 do not change at these values, q_s = 117.4 Btu/h·ft².

Example 9. Compute heat loss per square foot of outer surface of insulation if pipe temperature is 1200°F and ambient still air temperature is 80°F. The pipe is nominal 6-in. steel pipe, insulated with a nominal 3-in. thick diatomaceous silica as the inner layer and a nominal 2-in. thick calcium silicate as the outer layer.

Solution: From Chapter 33 of the 1988 EQUIPMENT Volume, r_o = 3.31 in. A nominal 3-in. thick diatomaceous silica insulation to fit a nominal 6-in. steel pipe is 3.02 in. thick. A nominal 2-in. thick calcium silicate insulation to fit over the 3.02-in. diatomaceous silica is 2.08 in. thick. Therefore, r_i = 6.33 in. and r_s = 8.41 in.

Assume that the mean temperature of the diatomaceous silica is 660°F, the mean temperature of the calcium silicate is 250°F and the surface resistance, R_s is 0.50. From Table 8, k_1 = 0.66; k_2 = 0.42. By Equation (10) from Chapter 20:

$$q_s = \frac{1200 - 80}{[8.41\ln(6.33/3.31)/0.66] + [8.41\ln(8.41/6.33)/0.40] + 0.50}$$

$$= \frac{1120}{(5.45/0.66) + (2.39/0.40) + 0.50} = 76.0\ \text{Btu/h·ft}^2$$

From Figure 6, at 76.0 Btu/h·ft², R_s = 0.60. The mean temperature of the diatomaceous silica is:

$$5.45/0.66 = 8.26;\ 8.26/2 = 4.13$$
$$1200 - [(4.13/14.83)(1120)] = 1200 - 312 = 888°F$$

and the mean temperature of the calcium silicate is:

$$2.39/0.40 = 5.98;\ 5.98/2 = 2.99;\ 8.26 + 2.99 = 11.25$$
$$1200 - [(11.25/14.83)(1120)] = 1200 - 850 = 350°F$$

From Table 8, k_1 = 0.72; k_2 = 0.46. Recalculating:

$$q_s = \frac{1120}{(5.45/0.72) + (2.39/0.46) + 0.60} = 83.8\ \text{Btu/h·ft}^2$$

From Figure 6 at 83.8 Btu/h·ft², R_s = 0.59. The mean temperature of the diatomaceous silica is:

$$5.45/0.72 = 7.57;\ 7.57/2 = 3.78$$
$$1200 - [(3.78/13.36)(1120)] = 1200 - 317 = 883°F$$

and the mean temperature of the calcium silicate is:

$$2.39/0.46 = 5.20;\ 5.20/2 = 2.60;\ 7.57 + 2.60 = 10.17$$
$$1200 - [(10.17/13.36)(1120)] = 1200 - 853 = 347°F$$

From Table 8, k_1 = 0.72; k_2 = 0.46. Recalculating:

$$q_s = \frac{1120}{(5.45/0.72) + (2.39/0.46) + 0.59} = 83.8\ \text{Btu/h·ft}^2$$

Since R_s, k_1, and k_2 do not change at 83.8 Btu/h·ft², this is q_s.

The heat flow per ft² of the inner surface of the insulation is:

$$q_o = q_s(r_s/r_o) = 83.8(8.41/3.31) = 213\ \text{Btu/h·ft}^2$$

Table 9A Heat Loss from Bare Steel Pipe to Still Air at 80°F[a], Btu/h·ft

Nominal Pipe Size[b], in.	Pipe Inside Temperature, °F 180	280	380	480	580	680	780	880	980	1080
0.50	59.3	147.2	263.2	412.3	600.9	836.3	1128.6	1485.6	1918.0	2436.8
0.75	72.5	180.1	322.6	506.2	739.2	1031.2	1392.9	1836.0	2373.5	3018.8
1.00	88.2	220.8	396.1	622.7	910.9	1272.6	1721.2	2271.5	2939.4	3741.6
1.25	109.7	272.7	490.4	772.3	1131.7	1583.8	2145.6	2833.4	3673.4	4680.9
1.50	123.9	308.5	555.1	875.1	1283.8	1798.3	2438.2	3224.6	4180.5	5330.0
2.00	151.8	378.1	681.4	1076.3	1581.5	2218.9	3012.6	3989.2	5177.2	6605.8
2.50	180.5	450.0	811.9	1284.0	1888.8	2652.6	3604.3	4775.3	6199.5	7912.5
3.00	215.9	538.8	973.5	1541.8	2271.4	3194.0	4344.9	5762.2	7486.3	9562.3
3.50	243.9	609.0	1101.4	1746.1	2574.7	3623.6	4933.0	6546.4	8510.4	10874.3
4.00	271.6	678.6	1228.2	1948.7	2875.9	4050.5	5517.5	7326.0	9528.1	12178.9
4.50	299.2	747.7	1354.4	2150.9	3176.8	4477.7	6103.8	8109.5	10533.2	13496.2
5.00	329.8	824.7	1494.8	2375.4	3510.6	4950.7	6751.3	8972.5	11678.4	14936.3
6.00	387.1	968.7	1757.8	2796.8	4138.0	5841.4	7972.7	10603.1	13808.2	17667.6
7.00	440.5	1102.8	2003.0	3189.9	4723.9	6673.5	9114.2	12127.4	15799.4	20220.8
8.00	493.3	1235.7	2246.1	3580.0	5305.5	7500.0	10243.4	13642.2	17778.2	22758.0
9.00	545.9	1368.1	2488.8	3970.2	5888.7	8331.0	11392.1	15174.5	19787.1	25343.6
10.00	604.3	1514.8	2757.2	4400.7	6530.1	9241.1	12638.6	16835.1	21949.2	28104.9
11.00	656.0	1644.8	2995.5	4783.8	7102.1	10054.9	13756.2	18328.4	23900.3	30606.1
12.00	704.0	1762.3	3203.8	5104.9	7557.3	10661.8	14524.9	19256.7	24967.6	31766.8
14.00	771.0	1934.2	3525.9	5636.0	8373.9	11862.4	16235.5	21635.6	28212.3	36120.3
16.00	872.2	2189.0	3993.2	6387.4	9495.9	13458.0	18424.8	24556.6	32021.1	40990.7
18.00	972.5	2441.7	4456.7	7132.9	10609.4	15041.3	20596.7	27453.2	35793.6	45813.1
20.00	1072.1	2692.4	4916.8	7873.2	11715.1	16613.4	22752.5	30326.8	39537.6	50590.0
24.00	1269.3	3188.9	5828.3	9339.9	13905.5	19726.9	27019.7	36010.1	46930.3	60014.7

Table 9B Heat Loss from Flat Surfaces to Still Air at 80°F[a], Btu/h·ft²

	Surface Inside Temperature, °F 180	280	380	480	580	680	780	880	980	1080
Vertical Surface	212.2	533.1	973.3	1558.6	2321.2	3298.0	4530.1	6062.8	7945.5	10231.3
Horizontal Surface Facing Up	234.7	586.4	1061.1	1683.5	2484.9	3501.9	4775.4	6350.4	8276.3	10606.1
Horizontal Surface Facing Down	183.6	465.3	861.4	1399.6	2112.8	3038.4	4217.8	5696.7	7524.5	9754.7

Table 10 Heat Loss from Bare Copper Tube to Still Air at 80°F[a], Btu/h·ft

Nominal Tube Size, in.	Tube Inside Temperature, °F 120	150	180	210	240	270	300	330	
0.250	7.1	14.1	21.9	30.6	49.9	270.0	60.6	71.9	
0.375	9.1	18.0	28.1	39.1	51.1	63.9	77.6	92.2	
0.500	11.0	21.8	34.0	47.4	61.9	77.5	94.1	111.5	
0.750	14.7	29.1	45.4	63.3	82.7	103.6	126.0	149.8	
1.000	18.3	36.2	56.4	78.7	102.8	128.9	156.7	186.5	
1.250	21.8	43.1	67.2	93.6	122.4	153.4	186.7	222.2	
1.500	25.2	49.8	77.6	108.3	141.5	177.4	216.0	257.1	
2.000	31.8	62.9	98.0	136.7	178.8	224.3	273.1	325.4	
2.500	38.3	75.6	117.9	164.4	215.1	269.8	328.7	391.8	Dull ε = 0.44
3.000	44.6	88.1	137.2	191.5	250.5	314.0	383.2	456.9	
3.500	50.8	100.3	156.3	218.0	285.4	358.2	436.7	520.8	
4.000	57.0	112.3	175.0	244.2	319.7	401.4	489.4	583.9	
5.000	69.0	135.9	211.7	295.5	386.9	486.0	592.8	707.6	
6.000	80.7	159.0	247.7	345.7	452.8	568.9	694.2	829.0	
8.000	103.7	204.1	317.8	443.7	581.3	730.7	892.1	1066.0	
10.000	126.1	247.9	386.1	539.1	706.5	888.4	1085.2	1297.4	
12.000	148.0	290.9	453.0	632.5	829.2	1043.2	1274.6	1524.4	
0.250	5.4	10.8	16.9	23.5	30.5	37.9	45.5	53.5	
0.375	6.8	13.7	21.4	29.7	38.6	47.9	57.6	67.6	
0.500	8.2	16.4	25.7	35.7	46.3	57.4	69.1	81.2	
0.750	10.7	21.6	33.8	46.9	60.9	75.6	90.9	106.8	
1.000	13.2	26.5	41.4	57.6	74.7	92.8	111.6	131.2	
1.250	15.5	31.3	48.8	67.8	88.0	109.3	131.6	154.7	
1.500	17.8	35.8	56.0	77.3	100.9	125.3	150.8	177.4	
2.000	22.2	44.6	69.7	96.8	125.7	156.1	187.9	221.1	
2.500	26.4	53.0	82.8	115.1	149.5	185.6	223.5	263.0	Bright ε = 0.08
3.000	30.5	61.2	95.6	132.8	172.4	214.2	257.9	303.5	
3.500	34.4	69.1	107.9	150.0	194.8	242.0	291.4	342.9	
4.000	38.3	76.8	120.0	166.8	216.6	269.1	324.1	381.4	
5.000	45.7	91.8	143.4	195.3	258.8	321.6	387.4	456.1	
6.000	53.0	106.3	166.0	230.7	299.7	372.5	448.7	528.3	
8.000	66.8	134.1	209.4	291.1	378.2	470.1	566.5	667.2	
10.000	80.2	160.8	251.0	349.0	453.4	563.7	679.5	800.4	
12.000	93.0	186.5	291.3	404.9	526.1	654.2	788.7	929.3	

[a]Calculations from ASTM C680-82; for copper: $k = 2784$ Btu·in/h·ft²·°F.

Table 11 Recommended Thicknesses for Pipe and Equipment Insulation[a]

Nominal Pipe Size, in.		MINERAL FIBER (Fiberglass and Rock Wool) Process Temperature, °F 150	250	350	450	550	650	750	850	950	1050	CALCIUM 150	250	350
½	Thickness	1	1½	2	2½	3	3½	4	4	4½	3½	1	1½	2
	Heat Loss	8	16	24	33	43	54	66	84	100	114	13	24	34
	Surface Temperature	72	75	76	78	79	81	82	86	87	87	75	78	80
1	Thickness	1	1½	2	2½	3½	4	4	4½	5	5½	1	2	2½
	Heat Loss	11	21	30	41	49	61	79	96	114	135	16	26	38
	Surface Temperature	73	76	78	80	79	81	84	86	88	89	76	76	79
1½	Thickness	1	2	2½	3	4	4	4	5½	5½	6	1½	2½	3
	Heat Loss	14	22	33	45	54	73	94	103	128	152	17	29	42
	Surface Temperature	73	74	77	79	79	82	86	84	88	90	73	75	78
2	Thickness	1½	2	3	3½	4	4	4	5½	6	6	1½	2½	3
	Heat Loss	13	25	24	47	61	81	105	114	137	168	19	32	47
	Surface Temperature	71	75	75	77	79	83	87	85	87	91	74	76	79
3	Thickness	1½	2½	3½	4	4	4½	4½	6	5½	7	2	3	3½
	Heat Loss	16	28	39	54	75	94	122	133	154	184	21	37	54
	Surface Temperature	72	74	75	77	81	83	87	86	87	90	73	75	78
4	Thickness	1½	3	4	4	4	5	5½	6	7	7½	2	3	4
	Heat Loss	19	29	42	63	88	102	126	152	174	206	25	43	58
	Surface Temperature	72	73	74	78	82	86	85	87	88	90	70	76	77
6	Thickness	2	3	4	4	4½	5	5½	6½	7½	8	2	3½	4
	Heat Loss	21	38	54	81	104	130	159	181	208	246	33	51	75
	Surface Temperature	71	74	75	79	82	84	87	88	89	91	74	75	79
8	Thickness	2	3½	4	4	5	5	5½	7	8	8½	2½	3½	4
	Heat Loss	26	42	65	97	116	155	189	204	234	277	35	62	90
	Surface Temperature	71	73	76	80	81	86	89	88	89	92	73	76	79
10	Thickness	2	3½	4	4	5	5½	5½	7½	8½	9	2½	4	4
	Heat Loss	32	50	77	115	136	170	220	226	259	307	43	66	106
	Surface Temperature	72	74	77	81	82	85	90	87	89	91	73	75	80
12	Thickness	2	3½	4	4	5	5½	5½	7½	8½	9½	2½	4	4
	Heat Loss	36	57	87	131	154	192	249	252	290	331	47	75	121
	Surface Temperature	72	74	77	82	82	86	91	88	89	91	73	76	81
14	Thickness	2	3½	4	4	5	5½	6½	7½	9	9½	2½	4	4
	Heat Loss	40	61	94	141	165	206	236	271	297	352	51	81	130
	Surface Temperature	72	74	77	82	83	86	87	89	89	91	73	76	81
16	Thickness	2½	3½	4	4	5½	5½	7	8	9	10	3	4	4
	Heat Loss	37	68	105	157	171	228	247	284	326	372	50	90	144
	Surface Temperature	71	74	78	83	82	87	86	88	89	91	72	76	82
18	Thickness	2½	3½	4	4	5½	5½	7	8	9	10	3	4	4
	Heat Loss	41	75	115	173	187	250	270	310	354	404	55	99	159
	Surface Temperature	71	74	78	83	83	87	87	88	90	91	73	76	82
20	Thickness	2½	3½	4	4	5½	5½	7	8	9	10	3	4	4
	Heat Loss	45	82	126	189	204	272	292	335	383	436	60	108	174
	Surface Temperature	71	75	78	83	83	87	87	89	90	92	73	77	82
24	Thickness	2½	4	4	4	5½	6	7½	8	9	10	3	4	4
	Heat Loss	53	86	147	221	237	295	320	386	439	498	71	127	203
	Surface Temperature	71	74	78	83	83	86	86	89	91	93	73	77	82
30	Thickness	2½	4	4	4	5½	6½	7½	8½	10	10	3	4	4
	Heat Loss	65	105	179	268	286	332	383	439	481	591	86	154	247
	Surface Temperature	71	74	79	84	84	85	87	89	89	94	73	77	83
36	Thickness	2½	4	4	4	5½	7	8	9	10	10	2½	4	4
	Heat Loss	77	123	211	316	335	364	422	486	556	683	119	181	291
	Surface Temperature	71	74	79	84	84	84	86	88	90	94	74	77	83
Flat	Thickness	2	3½	4	4½	5½	8½	9½	10	10	10	2½	3½	4
	Heat Loss	10	14	20	27	31	27	31	38	47	58	12	20	28
	Surface Temperature	72	74	77	80	82	80	82	85	89	93	73	77	81

[a]Consult manufacturer's literature for product temperature limitations. Table is based on typical operating conditions, e.g., 65°F ambient temperature and 7.5 mph wind speed, and may not represent actual conditions of use. Units for thickness, heat loss, and surface temperature are in inches, Btu/h·ft, and °F, respectively.

Table 11 Recommended Thicknesses for Pipe and Equipment Insulation* (*Concluded*)

SILICATE							CELLULAR GLASS						
Process Temperature, °F							Process Temperature, °F						
450	550	650	750	850	950	1050	150	250	350	450	550	650	750
2½	3	3½	4	4	4	4	1	1½	2	2½	3	3½	4
42	53	63	75	90	108	128	13	26	38	51	63	75	89
81	82	83	84	87	91	94	75	79	82	83	85	86	87
3	3½	4	4	4	4	4	1	2	2½	3	3½	4	4
49	60	72	89	109	130	154	17	29	43	57	71	86	106
80	82	83	86	90	94	98	76	77	80	82	84	86	89
3½	4	4	4	4	5	5	1½	2½	3	4	4	4	4
54	68	86	105	128	139	164	18	32	48	60	80	102	126
80	81	85	88	92	91	94	74	76	79	80	84	88	92
3½	4	4½	5	5½	6	6	1½	2½	3	4	4	4	4½
61	75	90	106	123	142	167	15	36	53	67	89	114	133
81	82	84	85	87	88	91	71	77	80	81	85	89	90
4	4½	5	5½	6	6	6	1½	3	3½	4	4	4½	5
71	87	105	123	143	71	202	26	41	62	82	110	132	154
80	82	84	85	87	90	94	75	76	79	82	87	89	91
4	4½	5	5½	6	6½	7	2	3	4	4	4	4½	5
82	101	121	142	164	187	213	26	48	67	96	128	153	177
81	83	85	87	89	90	92	73	77	79	83	85	90	92
4	4½	5	5½	6	7	8	2	3½	4	4	4½	5½	6
105	129	153	178	205	224	245	35	56	85	123	153	172	201
83	85	87	89	91	91	91	74	76	80	85	88	88	91
4½	5	5	6	7	8	8½	2½	3½	4	4	5	5½	6½
117	144	183	200	220	243	277	37	68	103	148	170	204	226
82	85	89	89	89	90	92	73	77	81	87	87	90	91
4	5	5½	6	7½	8½	9	2½	4	4	4	5½	5½	7
149	168	200	233	243	269	306	46	73	[illegible]	174	186	238	249
85	86	88	90	89	89	91	73	76	82	88	87	91	90
4	5	5½	7	8	8½	9½	2½	4	4	4	5½	5½	7½
170	191	266	236	262	300	330	50	83	138	199	211	268	258
86	85	89	88	88	90	91	74	77	83	89	88	93	89
4	5	5½	7	8	9	9½	2½	4	4	4	5½	5½	8
183	205	242	252	262	308	352	55	90	148	214	226	288	273
86	87	89	88	88	89	91	74	77	83	89	88	93	88
4	5½	6½	7½	8	9	10	2½	4	4	4	5½	5½	8
204	211	237	265	307	338	372	61	100	165	238	250	319	300
87	85	86	87	89	90	91	74	77	83	90	88	94	89
4	5½	6½	7½	8½	9	10	2½	4	4	4	5½	5½	8
225	232	259	289	320	367	403	68	110	182	262	274	350	327
87	86	87	87	88	90	91	74	77	84	90	88	94	89
4	5½	6½	7½	8½	9½	10	2½	4	4	4½	5½	5½	8
245	252	281	312	346	381	435	74	120	199	261	298	380	354
87	86	87	88	89	90	92	74	78	84	88	89	94	90
4	5½	6½	7½	8½	9½	10	2½	4	4	5	5½	5½	8
287	293	325	360	397	437	497	87	140	232	279	346	442	407
88	87	88	88	89	90	93	74	78	84	86	90	95	90
4	5½	7	8	9	10	10	2½	4	4	5½	5½	5½	8
349	353	368	409	452	498	589	107	171	232	312	418	533	486
88	87	87	88	89	90	94	73	78	85	85	90	96	91
4	6½	7½	8	9	10	10	2½	4	4	5½	5½	5½	8
410	359	406	475	524	576	681	127	201	332	366	489	624	565
89	84	86	88	89	91	94	75	78	85	85	91	96	92
5½	6½	7½	8½	9½	10	10	2½	4	4	5½	5½	7½	8½
29	33	36	39	43	49	58	13	20	32	34	46	43	47
81	83	84	85	87	89	93	73	77	82	83	88	87	89

Table 12 Apparent Thermal Conductivity (*k*) for Various Soils[a], Btu·in./h·ft²·°F

Soil Designation	Mechanical Analysis % by Weight				Moisture Content, %						
	Gravel	Sand	Silt	Clay	4			10		20	
					Dry Density, lb/ft³						
	Over 0.079 in.	0.020 to 0.079 in.	0.0002 to 0.002 in.	Under 0.0002 in.	100	110	120	90	110	90	100
Fine Crushed Quartz	0.0	100.0	0.0	0.0	12.0	16.0					
Crushed Quartz	15.5	79.0	5.5		11.5	16.0	22.0				
Graded Ottawa Sand	0.0	99.9	0.1		10.0	14.0					
Fairbanks Sand	27.5	70.0	2.5		8.5±	10.5	13.5		15.0		
Lowell Sand	0.0	100.0	0.0	0.0	8.5	11.0			13.5		
Chena River Gravel	80.0	19.4	0.6			9.0±	13.0				
Crushed Feldspar	25.5	70.3	4.2		6.0	7.5	9.5				
Crushed Granite	16.2	77.0	6.8		5.5	7.5	10.0				
Dakota Sandy Loam	10.9	57.9	21.2	10.0		6.5	9.5		13±		
Crushed Trap Rock	27.0	63.0	10.0		5.0	6.0	7.0				
Ramsey Sandy Loam	0.4	53.6	27.5	18.5	4.5	6.5			10.0		
Northway Fine Sand	0.0	97.0	3.0	0.0	4.5	5.5			8.5		
Northway Sand	3.0	97.0	0.0	0.0	4.5	6.0			7.5±		
Healy Clay	0.0	1.9	20.1	78.0	4.0±			5.5	9.0±	8.0	10.0
Fairbanks Silt Loam	0.0	7.6	80.9	11.5				5.0	9.0±	7.5	10.0
Fairbanks Silty Clay Loam	0.0	9.2	63.8	27.0				5.0	9.0±	7.5	9.5
Northway Silt Loam	1.0	21.0	64.4	13.6				4.0±	7.0±	6.0±	7.0±

[a]Measured at a mean temperature of 40°F.

Because trial and error techniques are tedious, the computer programs previously described should be used to estimate heat flows per unit area of flat surfaces or per unit length of piping, and interface temperatures including surface temperatures.

Several methods can be used to determine the most effective thickness of insulation for piping and equipment. Table 11 shows the recommended insulation thicknesses for three different pipe and equipment insulations. Installed cost data can be developed using procedures described by the Federal Energy Administration (1976). Computer programs capable of calculating thickness information are available from several sources. Also, manufacturers of insulations offer computerized analysis programs for designers and owners to evaluate insulation requirements. For more information on determining economic insulation thickness, see Chapter 20.

Chapters 3 and 20 give guidance concerning process control, personnel protection, condensation control, and economics. For specific information on sizes of commercially available pipe insulation, see ASTM *Standard* C 585 and consult with the Thermal Insulation Manufacturers Association (TIMA) and its member companies.

CALCULATING HEAT FLOW FOR BURIED PIPELINES

In calculating heat flow to or from buried pipelines, the thermal properties of the soil must be assumed. Table 12 gives the apparent thermal conductivity values of various soils. These values can be used as a guide when calculating heat flow for buried lines. Because most soil or earth contains moisture, thermal conductivity can vary widely from the values given in Table 12. Kernsten (1949) discusses thermal properties of soils. Carslaw and Jaeger (1959) give methods for calculating the heat flow taking place between one or more buried cylinders and the surroundings.

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CHAPTER 23

INFILTRATION AND VENTILATION

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OUTDOOR air that flows through a building either intentionally as ventilation air or unintentionally as infiltration (and exfiltration) is important for two reasons. Outdoor air is often used to dilute indoor air contaminants, and the energy associated with heating or cooling this outdoor air is a significant space-conditioning load. The magnitude of these airflow rates should be known at maximum load to properly size equipment and at average conditions, to properly estimate average or seasonal energy consumption. Minimum air exchange rates need to be known to assure proper control of indoor contaminant levels. In large buildings, the effect of infiltration and ventilation on distribution and interzone airflow patterns, which include smoke circulation patterns in the event of fire, should be determined (see Chapter 58 of the 1987 HVAC Volume).

Air exchange between indoors and out is divided into ventilation (intentional and ideally controlled) and infiltration (unintentional and uncontrolled). Ventilation can be natural and forced. Natural ventilation is unpowered airflow through open windows, doors, and other intentional openings in the building envelope. Forced ventilation is intentional, powered air exchange by a fan or blower and intake and/or exhaust vents that are specifically designed and installed for ventilation.

Infiltration is uncontrolled airflow through cracks, interstices, and other unintentional openings. Infiltration, exfiltration, and natural ventilation airflows are caused by pressure differences due to wind, indoor-outdoor temperature differences, and appliance operation.

This chapter focuses on residences and small commercial buildings in which air exchange is due primarily to envelope infiltration. The physical principles are also discussed in relation to large buildings in which air exchange depends more on mechanical ventilation than it does on building envelope performance.

TYPES OF AIR EXCHANGE

Buildings have three different modes of air exchange: (1) forced ventilation, (2) natural ventilation, and (3) infiltration. These modes differ significantly in how they affect energy, air quality, and thermal comfort. They also differ in their ability to maintain a desired air exchange rate. The air exchange rate in a building at any given time generally includes all three modes, and they all must be considered even when only one is expected to dominate.

The air exchange rate associated with a forced air ventilation system depends on the airflow rates through the system fans, the airflow resistance associated with the air distribution system, the airflow resistance between the zones of the building, and the airtightness of the building envelope. If any of these factors is not at the design level or not properly accounted for, the building air exchange rate can be quite different from its design value.

Forced ventilation affords the greatest potential for control of air exchange rate and air distribution within a building through the proper design, installation, operation, and maintenance of the ventilation system. Forced or mechanical ventilation equipment and systems are described in Chapers 1, 2, and 10 of the 1987 HVAC Volume. An ideal forced ventilation system has a sufficient ventilation rate to control indoor contaminant levels and, at the same time, avoids overventilation and the associated energy penalty. In addition, it maintains good thermal comfort (see Chapters 8 and 32).

Forced ventilation is generally mandatory in larger buildings, where a minimum amount of outdoor air is required for occupant health and comfort, and where a mechanical exhaust system is advisable or necessary. Forced ventilation has generally not been used in residential and other envelope-dominated structures. However, tighter, more energy-conserving buildings require ventilation systems to assure an adequate amount of outdoor air for maintaining acceptable indoor air quality.

Natural ventilation through intentional openings is caused by pressures from wind and indoor-outdoor temperature differences. Airflow through open windows and doors and other design openings can be used to provide adequate ventilation for contaminant dilution and temperature control. Unintentional openings in the building envelope and the associated infiltration can interfere with desired natural ventilation air distribution patterns and lead to larger than design airflow rates. Natural ventilation is sometimes defined to include infiltration, but in this chapter it does not.

Infiltration is the uncontrolled flow of air through unintentional openings driven by wind, temperature difference, and appliance-induced presures. Infiltration is least reliable in providing adequate ventilation and distribution, because it depends on weather conditions and the location of unintentional openings. It is the main source of ventilation in envelope-dominated buildings and is also an important factor in mechanically ventilated buildings.

VENTILATION AND THERMAL LOADS

Outdoor air introduced into a building constitutes part of the space-conditioning load, which is one reason to limit air exchange rates in buildings to the minimum required. Air exchange typically represents 20 to 40% of the building's thermal load. Chapters 25 and 26 cover thermal loads in more detail.

The preparation of this Chapter is assigned to TC 4.3, Ventilation Requirements and Infiltration.

Air exchange increases a building's thermal load in three ways. First, the incoming air must be heated or cooled from the outdoor air temperature to the indoor air temperature. The rate of energy consumption is given by:

$$q_s = 60\, Q\, \varrho\, c_p \Delta t \qquad (1)$$

where

q_s = sensible heat load, Btu/h
Q = airflow rate, cfm
ϱ = air density, lb_m/ft^3 (about 0.075)
c_p = specific heat of air, Btu/lb·°F (about 0.24)
Δt = indoor-outdoor temperature difference, °F

Second, air exchange increases a building's moisture content, particularly in the summer in some areas when humid outdoor air must be dehumidified. The rate of energy consumption associated with these latent loads is given by:

$$q_l = 60\, Q\, h_{fg}\, \Delta W \qquad (2)$$

where

q_l = latent heat loads, Btu/h
h_{fg} = latent heat of vapor at the appropriate air temperature, Btu/lb_m (about 1000)
ΔW = humidity ratio of indoor air minus humidity ratio of outdoor air, lb_m water/lb_m dry air

Finally, air exchange can increase a building's thermal loads by decreasing the performance of the envelope insulation system. Air flowing around and through the insulation can increase heat transfer rates above design rates. The effect of such airflow on insulation system performance is difficult to quantify, but should be considered. Airflow within the insulation system can also decrease the system's performance due to moisture condensing in and on the insulation.

VENTILATION AND AIR QUALITY

Outdoor air requirements have been debated for over a century, and different rationales have produced radically different ventilation standards (Klauss *et al.* 1970, Yaglou 1936, 1937). Considerations have included the amount of air required to remove exhaled air and to control interior moisture, carbon dioxide (CO_2), and odor (see Chapter 12).

The maintenance of carbon dioxide (CO_2) levels is a common criteria for determining ventilation rates. A representative value of CO_2 production by a sedentary individual who eats a normal diet is 0.011 cfm. When steady state is reached in a ventilated space in which no removal mechanisms for CO_2 exist other than ventilation, the concentration of CO_2 is given by:

$$C_i = C_o + F/Q \qquad (3)$$

where

C_i = concentration of CO_2 inside the space
C_o = concentration of CO_2 outside the space
F = generation rate of CO_2, cfm
Q = ventilation rate (outdoor air only), cfm

The ventilation rate per person required to maintain the indoor CO_2 level at some prescribed limit C_L is given by:

$$Q = (0.011 \times 100) / [C_L(\%) - C_o(\%)] \qquad (4)$$

A typical outdoor concentration for CO_2 is 0.03%.

ASHRAE *Standard* 62 specifies ventilation rates required to maintain acceptable indoor air quality for a variety of space uses. The standard contains a basic requirement of 15 cfm of outdoor air per person, based on a CO_2 concentration limit of 0.1%. While normal healthy people tolerate 0.5% CO_2 without undesirable symptoms (McHattie 1960) and submarines sometimes operate with 1% CO_2 in the atmosphere, a level of 0.1% provides a safety factor for increased activity, unusual occupancy load, reduced ventilation, and control of odors.

Alternatively, *Standard* 62 can be complied with by maintaining the concentrations of certain contaminants within limits prescribed by the standard through some combination of source control, air treatment, and ventilation. Table 1 lists some contaminants of concern, classified according to source type (Berk *et al.* 1979).

In cases of large contaminant source strengths, impractically high levels of ventilation are required to control contaminant levels, and other methods of control are more effective. Removal or reduction of contaminant sources is a very effective means of control. Construction materials with low contaminant emission rates should be specified when possible. Sealants can be used in some situations to prevent outgassing. Spot ventilation, such as range hoods or bathroom exhausts, for controlling a localized source is also effective.

Particles can be removed with various types of air filters. Gaseous contaminants with higher molecular weight can be controlled with activated carbon or alumina pellets impregnated with substances such as potassium permanganate. Chapter 10 of the 1988 HVAC Volume has information on air cleaning. Standard 62 allows adequately cleansed air to be substituted for outdoor air. The circulation rate must increase, but energy may be saved in conditioning outdoor air. Each contaminant, and an appropriate cleansing method, needs to be considered.

Source control and local exhaust, as opposed to dilution with ventilation air, is the method of choice in industrial environments. The practice of industrial ventilation is well developed, and is discussed in Chapters 41 and 43 of the 1987 HVAC Volume, and the ACGIH Industrial Ventilation Manual (1986).

Table 1 Indoor Air Pollutants in Residential Buildings

Sources	Pollutant Types
OUTDOOR	
Ambient air	SO_2, NO, NO_2, O_3, hydrocarbons, CO, particulates
Motor vehicles	CO, Pb, hydrocarbons, particulates
Soil	Radon
INDOOR	
Building construction materials	
Concrete, stone	Radon
Particleboard, plywood	Formaldehyde
Insulation	Formaldehyde, fiber glass
Fire retardant	Asbestos
Adhesives	Organics
Paint	Mercury, organics
Building Contents	
Heating and cooking combustion appliances	CO, NO, NO_2, formaldehyde, particulates
Furnishings	Organics
Water service; natural gas	Radon
Human occupants	
Metabolic activity	H_2O, CO_2, NH_3, odors
Human activities	
Tobacco smoke	CO, NO_2, organics, particulates, odors
Aerosol spray devices	Fluorocarbons, vinyl chloride
Cleaning and cooking products	Organics, NH_3, odors
Hobbies and crafts	Organics

DRIVING MECHANISMS

Natural ventilation and infiltration are driven by pressure differences caused by wind, temperature differences between indoor and outdoor air (stack effect), and the operation of appliances, such as combustion devices and mechanical ventilation systems. The pressure difference at a location depends on the magnitude of these driving mechanisms as well as on the characteristics of the openings in the building envelope, *i.e.*, their locations and the relationship between pressure difference and airflow for each opening.

Pressure differences across the building envelope are based on the requirement that the mass flow of air into the building equals the mass flow out. In general, density differences between indoors and outdoors can be neglected, so the volumetric airflow rate into the building equals the volumetric airflow rate out. Based on this assumption, the envelope pressure differences can be determined; however, such a determination requires a great deal of detailed information that is essentially impossible to obtain.

When wind impinges on a building, it creates a distribution of static pressures on the building's exterior surface, which depends on the wind direction and the location on the building exterior. This pressure distribution is independent of the pressure inside the building, p_i. If no other forces act on the building, if no indoor-outdoor temperature difference exists, and if no appliance forces air through the building, the pressure differences, in constant units, are determined by the interior static pressure, according to:

$$\Delta p = p_o + p_w - p_i \qquad (5)$$

where

Δp = pressure difference between outdoors and indoors at the location
p_o = static pressure at reference height in the undisturbed flow
p_w = wind pressure at the location
p_i = interior pressure at the height of the location

If no indoor-outdoor temperature difference exists, the interior static pressure p_i decreases linearly with height at a rate dependent on the interior temperature. This rate of pressure decrease equals $-\varrho_i g$ where ϱ_i is the interior air density and g is the acceleration of gravity. The interior static pressure assumes a value such that the total airflow into the building equals the total airflow out of the building. The interior static pressure may be determined by calculating the airflow through each opening as a function of the interior pressure, adding all of these airflow rates together, setting this sum equal to zero, and solving for the interior pressure. However, to solve for the interior pressure in this way, the location of each opening in the building envelope, the value of p_w at each opening, and the relationship between airflow rate and pressure difference for each opening must be known.

When an indoor-outdoor temperature difference exists, it imposes a gradient in the pressure difference. This pressure difference Δp_s is a function of height and temperature difference and may be added to the pressure difference due to wind in Equation (5). The pressure difference is now expressed as:

$$\Delta p = p_o + p_w - p_{i,r} + \Delta p_s \qquad (6)$$

The parameter $p_{i,r}$ is the interior static pressure at some reference height, and this pressure again assumes a value such that the total inflow equals the total outflow. A summation of all the airflows through these openings can be set up, set equal to zero, and solved for the interior pressure at the reference height.

When an appliance such as a combustion device or a ventilation fan operates, an additional airflow is imposed on the building. The pressure difference is still calculated using Equation (6), but the interior pressure $p_{i,r}$ changes so that the balance between inflow and outflow is maintained. This balance necessarily includes the airflow rate(s) associated with the appliance(s).

To determine the pressure differences across the building envelope and the corresponding air exchange rates, the exterior pressure distribution due to wind and the location and airflow rate/pressure difference relationship for every opening in the building envelope are needed. These inputs are difficult to obtain for any given building, making such a determination unrealistic.

Wind Pressure

Wind pressures are generally positive with respect to the static pressure in the undisturbed airstream on the windward side of a building, and negative on the leeward side. Pressures on the other sides are negative or positive, depending on wind angle and building shape. Static pressures over building surfaces are almost proportional to the velocity head of the undisturbed airstream. The wind pressure or velocity head is given by Bernoulli's equation, assuming no height change or head losses:

$$p_v = C_1 C_p \varrho v^2/2 \qquad (7)$$

where

p_v = surface pressure relative to the static pressure in the undisturbed fl , in. of water
ϱ = air density, lb_m/ft^3 (about 0.075)
v = wind speed, mph
C_p = surface pressure coefficient
C_1 = unit conversion factor = 0.0129

Therefore Equation (5) can be rewritten as

$$\Delta p = p_o + C_1 C_p \varrho v^2/2 - p_i \qquad (8)$$

C_p is a function of location on the building envelope and wind direction. Chapter 14 (Airflow Around Buildings) provides additional information on the values of C_p. Although standard conditions are frequently used, the air density and consequently the wind pressure can vary for a given wind speed with changes in temperature and/or elevation. For example, for an elevation rise from sea level to 5000 ft, or an air temperature change from −20° to 70°F, the air density will drop about 20%. If these elevation and temperature changes occur simultaneously, the air density will drop by about 45%. Therefore, the effects of local air density cannot be ignored.

The wind speed incident on a building is generally lower than the average meteorological wind speed for a region, and meteorological data usually overestimates wind pressures on a building. Building wind speeds are lower because of effects of height, terrain, and shielding (Lee *et al.* 1980). The wind speed is zero at the ground surface and increases with height up to an altitude of about 2000 ft above ground level. Meteorological measurements typically are made at a height of 33 ft in open areas. Residential building heights are generally less than 33 ft and are therefore subject to lower wind pressures. Tall buildings are subject to a range in wind speed over the height of the building, exposing the exterior to wind pressures that are both lower and higher than estimates based on Equation (7).

The shielding effects of trees, shrubbery, and other buildings, within several building heights of a particular building, produce large-scale turbulence that not only reduces effective wind speed but also alters wind direction. Thus, meteorological wind speed data must be reduced carefully when applied to low buildings. Chapter 14 provides additional guidance on estimating wind pressures.

The magnitude of the pressure differences found on the surfaces of buildings varies rapidly with time because of turbulent fluctuations in the wind (Grimsrud *et al.* 1979, Etheridge and Nolan 1979). However, the use of average wind pressures to calculate pressure differences is usually sufficient. In residential buildings the magnitude of wind pressure differences averaged over 20 min seldom exceeds ±0.02 in. of water under typical conditions. In many cases the averages are less than ±0.01 in. of water. For tall buildings or buildings completely exposed to open terrain, the pressure on the windward side is much closer to those calculated from average wind speeds for the site (Tamura and Wilson 1968). In the latter cases, for example, if $v = 6.7$ mph, $p_v \cong 0.02$ in. of water; if $v = 15.7$ mph, $p_v \cong 0.12$ in. of water (assuming $C_p = 1$).

Stack Pressures

Temperature differences between indoors and outdoors cause density differences, and therefore pressure differences, that drive infiltration. During the heating season, the warmer inside air rises and flows out of the building near its top. It is replaced by colder outdoor air that enters the building near its base. During the cooling season, the flow directions are reversed and generally lower, because the indoor-outdoor temperature differences are smaller. Qualitatively, the pressure distribution over the building in the heating season takes the form shown in Figure 1.

The height at which the interior and exterior pressures are equal is called the Neutral Pressure Level (NPL) (Tamura and Wilson 1966 and 1967a). Above this point (during the heating season), the interior pressure is greater than the exterior; below this point, the greater exterior pressure causes airflow into the building.

The pressure difference due to the stack effect at height h is:

$$\begin{aligned} \Delta p_s &= C_2(\varrho_o - \varrho_i)g(h - h_{NPL}) \\ &= C_2\varrho_i g(h - h_{NPL})(T_i - T_o)/T_o \end{aligned} \tag{9}$$

where

Δp_s = pressure difference due to stack effect, in. of water
ϱ = air density, lb_m/ft^3 (about 0.075)
g = gravitational constant, 32.2 ft/s^2
h = height of observation, ft
h_{NPL} = height of neutral pressure level, ft
T = absolute temperature, °R
C_2 = unit conversion factor = 0.00598

Subscripts

i = inside
o = outside

A useful estimate of the magnitude of the stack effect on a building is that the pressure difference induced by the stack effect is 2.7×10^{-5} in. of water/ft · °R. This estimate neglects any

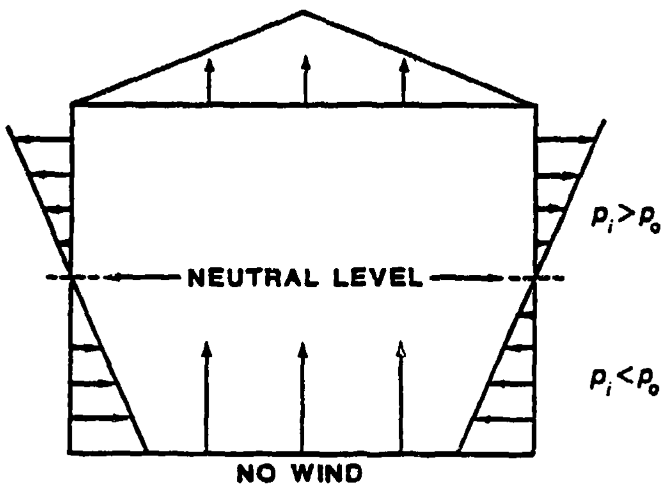

Fig. 1 Pressure Differences Caused by Stack Effect for a Typical Structure (Heating). (Arrows indicate magnitude and direction of pressure difference.)

resistance to airflow within the structure. Therefore, in a one-story house with an 8 ft ceiling, an NPL of one-half the building height, and a temperature difference of 45 °R, the stack pressure will be only 0.005 in. of water at the ceiling and floor. In a tall building (*e.g.*, 20 stories of 13 ft each) with no internal resistance to airflow, the stack pressure under these same conditions will be 0.18 in. of water.

The location of the NPL at zero wind speed depends on the vertical distribution of openings in the shell, the resistance of the openings to airflow, and the resistance to vertical airflow within the building. If the openings are uniformly distributed vertically and there is no internal airflow resistance, the NPL is at the midheight of the building (Figure 1). If there is only one opening, or an extremely large opening relative to any others, the NPL is at or near the center of this opening. Foster and Downs (1987) studied the location of the NPL as it relates to natural ventilation in a building with only two openings.

Internal partitions, stairwells, elevator shafts, utility ducts, chimneys, vents, and mechanical supply and exhaust systems, complicate the analysis of NPL locations. Chimneys and openings at or above roof height, raise the NPL in small buildings. Exhaust systems increase the height of the NPL; outdoor air supply systems lower it.

Available data on the NPL in various kinds of buildings is limited. The NPL in tall buildings varies from 0.3 to 0.7 of total building height (Tamura and Wilson 1966 and 1967a). For houses, especially houses with chimneys, the NPL is usually above midheight. Operating a combustion heat source with a flue raises the NPL further, sometimes above the ceiling (Shaw and Brown 1982).

Equation (9) provides a maximum stack pressure difference, given no internal airflow resistance. The sum of the pressure differences across the exterior wall at the bottom and top of the building, as calculated by Equation (9), equals the total theoretical draft for the building. The sum of the actual top and bottom pressure differences, divided by the total theoretical draft, equals the *thermal draft coefficient*. The value of the thermal draft coefficient depends on the airflow resistance of the exterior walls relative to the airflow resistance between floors. For a building without internal partitions, the total theoretical draft is achieved across the exterior walls (Figure 2A), and the thermal draft coefficient equals 1. In a building with airtight separations at each floor, each story acts independently, its own stack effect being unaffected by that of any other floor (Figure 2B). The ratio of the actual to the theoretical draft is minimized in this case.

Real multistory buildings are neither open inside (Figure 2A), nor airtight between stories (Figure 2B). Vertical air passages, stairwells, elevators, and other service shafts allow airflow between floors. Figure 2C represents a heated building with uniform openings in the exterior wall, through each floor, and into the vertical shaft at each story. Between floors, the slope of the line representing the inside pressure is the same as that shown in Figure 2A, and the discontinuity at each floor (Figure 2B) represents the pressure difference across it. Total stack effect for the building remains the same, but some of the total pressure difference maintains flow through openings in the floors and vertical shafts. As a result, the pressure difference across the exterior wall at any level is less than it would be with no internal flow resistance.

Maintaining airtightness between floors and from floors to vertical shafts is a means of controlling indoor-outdoor pressure differences, and therefore infiltration. Good separation is also conducive to the proper operation of mechancial ventilation and smoke control systems. Tamura and Wilson (1967b) showed that when vertical shaft leakage is at least two times the envelope

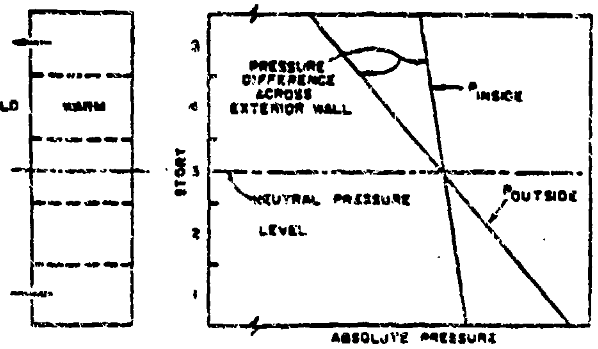

Fig. 2A Stack Effect in a Building with No Internal Partition

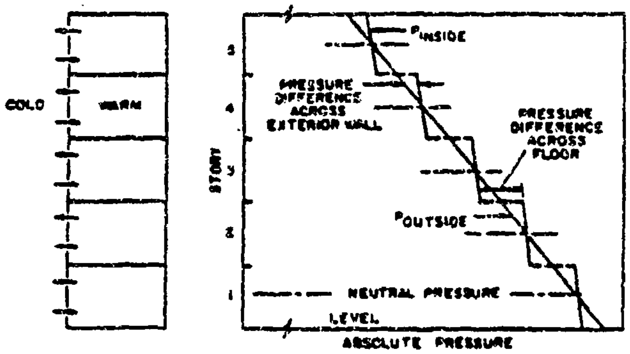

Fig. 2B Stack Effect in a Building with Airtight Separation of Each Story

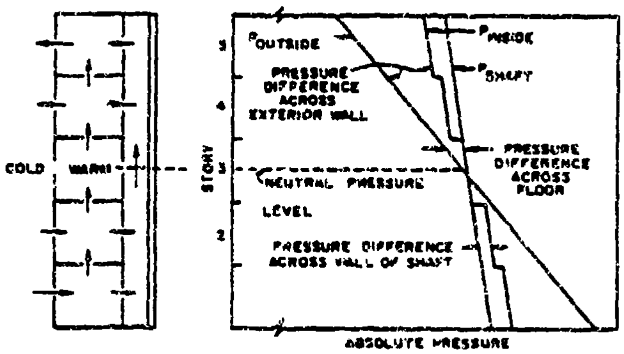

Fig. 2C Stack Effect for an Idealized Building

leakage, the thermal draft coefficient is almost 1. Openings in floors are less effective in providing communication between floors; as the building height increases, they become even less effective. Measurements of pressure differences in three tall office buildings by Tamura and Wilson (1967a) indicated that the thermal draft coeffcient ranged from 0.8 to 0.9 with the ventilation systems off.

Mechanical Systems

Changes in pressure differences and airflow rates caused by mechanical equipment are unpredictable unless the location of each opening in the envelope and the relationship between pressure difference and airflow rate for each opening are known. The interaction of mechanical ventilation system operation and envelope airtightness has been discussed for low-rise buildings (Nylund 1980) and for office buildings (Tamura and Wilson 1966 and 1967b, Persily and Grot 1985a).

Air exhausted from a building must be balanced by increasing the airflow into the building through other openings. In this situation the NPL rises, and the airflow at some locations changes direction from outflows to inflows (in the winter). Thus the effects a mechanical system has on a building must be considered. Depressurization caused by an improperly designed system can increase radon entry rates into a building and interfere with the proper operation of combustion device venting or other exhaust systems. Overpressurization can force moist indoor air through the building envelope and, in cold climates, moisture may condense within the building envelope.

The interaction between mechanical systems and the building envelope also holds for systems serving zones of buildings. The performance of zone-specific exhaust or pressurization systems is affected by the leakage in zone partitions, as well as in exterior walls.

Building envelope airtightness and interzone airflow resistance can also affect the performance of mechanical systems. The actual airflow rate delivered by these systems, particularly ventilation systems, depends on the pressure that they work against. This effect is the same as the interaction of a fan with its associated ductwork discussed in Chapter 32 (Duct Design) and Chapter 3 in the 1988 EQUIPMENT Volume. The building envelope and its leakage can be considered part of the ductwork in determining the pressure drop of the system.

Combining Driving Forces

The pressure differences just discussed are considered in combination by adding them together and determining the airflow rate through each opening due to this total pressure difference. Because the airflow rate through these openings is not linearly related to pressure difference, the driving forces must be combined in this manner, as opposed to adding the airflow rates due to the separate driving forces.

Figure 3 qualitatively shows the addition of driving forces for a building with uniform openings above and below midheight and without significant internal resistance to airflow. The slopes of the pressure lines are functions of the densities of the indoor and outdoor air. In Figure 3A, with inside air warmer than outside, and pressure differences caused solely by thermal forces, the NPL is at midheight, with inflow through lower openings and outflow through higher openings. A chimney or mechanical exhaust decreases the inside pressure and shifts the inside pressure line to the left, raising the NPL; an excess of outdoor supply air over exhaust would lower it. Figure 3B shows qualitative pressure differences caused by wind alone, with the effect on windward and leeward sides equal but opposite. When both the temperature difference and wind effects both act, the pressures due to each are added together to determine the total pressure difference across the building envelope. Figure 3C shows the combination where the wind force of Figure 3B has just balanced the thermal force of Figure 3A, causing no pressure difference at the top windward or bottom leeward side. Total airflow is similar to that with the wind acting alone, but significantly larger than the airflow due only to the stack effect.

The relative importance of the wind and stack pressures in a building depends on building height, internal resistance to vertical airflow, local terrain, and the immediate shielding of the building. The taller the building and the lesser the internal resistance to airflow, the stronger the stack effect. The more exposed a building, the more susceptible it will be to wind. For any building, there will be ranges of wind speed and temperature difference for which the building's infiltration is dominated by the stack effect, the wind, or a regime in which the driving pressures of both must be considered (Sinden 1978). The above factors determine, for specific values of temperature difference and wind speed, in which regime the building's infiltration lies.

The effect of mechanical ventilation on envelope pressure differences is more complex and depends on the direction of the ventilation flow (exhaust or supply) and differences in these ventilation flows among the zones of the building. If mechanically supplied outdoor air is provided uniformly to each story, the change in the exterior wall pressure difference pattern from thermal pressures is uniform. With a nonuniform supply of outdoor air (for example, to one story only), the extent of pressurization varies from story to story and depends on the internal airflow resistance. Pressurizing all levels uniformly has little effect on the pressure differences across floors and vertical shaft enclosures, but pressurizing individual stories increases the pressure drop across these internal separations. Pressurization of the ground level is often used in tall buildings to reduce the stack pressures across entries.

Various rules have been proposed for combining the infiltration due to stack and wind pressures, as well as mechanical ventilation airflow rates. One model to compute the total airflow rate is based on the rate being proportional to the square root of the pressure difference, and is given by:

$$Q_{ws} = (Q_w^2 + Q_s^2)^{0.5} \tag{10}$$

where

Q_{ws} = infiltration from both wind and stack effects, cfm
Q_w = infiltration from the wind, cfm
Q_s = infiltration from the stack effect, cfm

Shaw and Tamura (1977) used a computer model that calculates infiltration in high-rise buildings to develop the following alternate expression for the total infiltration:

$$Q_{ws}/Q_{max} = 1 + 0.24\,(Q_{min}/Q_{max})^{3.3} \tag{11}$$

where Q_{max} and Q_{min} are the maximum and minimum of the wind- and stack-induced infiltration rates, respectively. Equation (10) gives a slightly larger estimate of total infiltration than does Equation (11).

Additional terms for ventilation flow are needed when mechanical systems are used. Balanced mechanical systems do not change the interior pressure in the building, as long as they supply to and exhaust from each zone of the building at an equal rate; therefore, they are simply added to the other terms. Unbalanced flows change the building pressure distribution, and Sherman and Grimsrud (1980) suggested that they be added in quadrature. Equations (12) through (14) summarize these rules (Sherman and Modera 1986):

Superposition:

$$Q = Q_{bal} + (Q_{unbal}^2 + Q_{ws}^2)^{0.5} \tag{12}$$

Balanced (additional) ventilation:

$$Q_{bal} = \text{minimum of } (Q_{supply}, Q_{exhaust}) \tag{13}$$

Unbalanced (additional) ventilation:

$$Q_{unbal} = \text{maximum of } (Q_{supply}, Q_{exhaust}) - Q_{bal} \tag{14}$$

Levins (1982) and Kiel and Wilson (1987) further discuss the combination of mechanical ventilation airflow rates with naturally induced infiltration rates.

Shaw and Brown (1982) compared air infiltration in identical homes, with and without a gas furnace, with a chimney. Figure 4 shows the effects of exfiltration through the chimney and ceiling with and without the gas furnace, and also the impact of the chimney on the NPL.

AIRFLOW THROUGH OPENINGS

The relationship between the airflow q through an opening in the building envelope and the pressure difference Δp across it is called the leakage function of the opening. The form of the leakage function depends on the geometry of the opening. Background material relevant to leakage functions may be found in Chapter 2, Hopkins and Hansford (1974), Etheridge (1977), Kronvall (1980a), and Chastain *et al.* (1987).

The fundamental equation for the airflow rate through an opening is:

$$Q = C_3 C_D A \sqrt{2\,\Delta p / \rho} \tag{15}$$

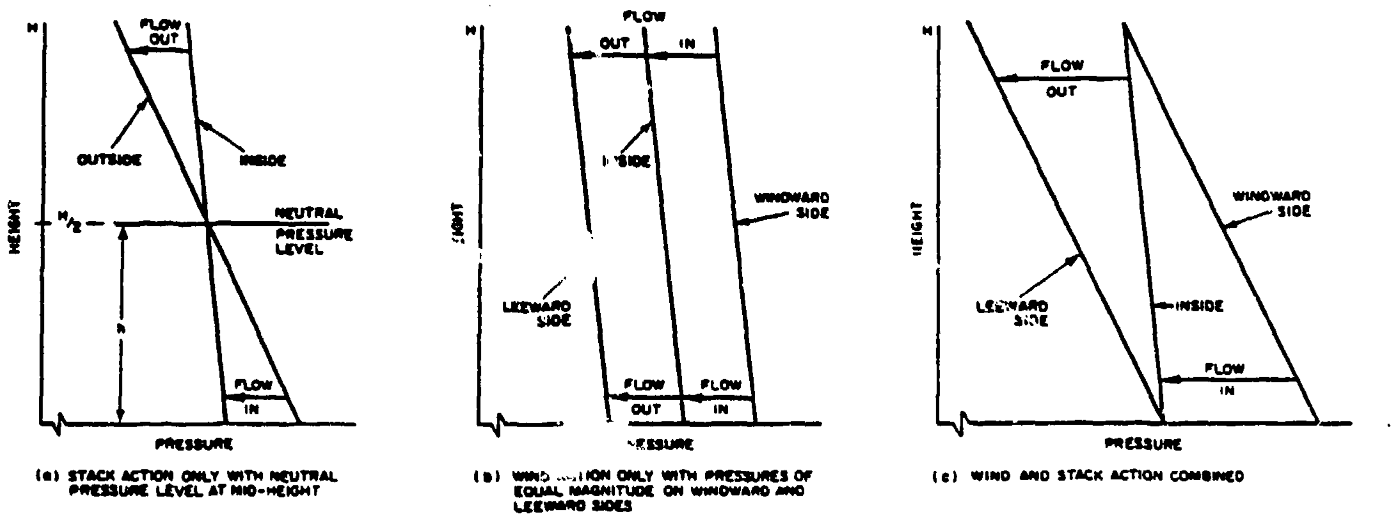

Fig. 3 Distribution of Inside and Outside Pressures Over the Height of a Building

where

Q = airflow rate, cfm
C_D = discharge coefficient for the opening
A = cross-sectional area of the opening, ft^2
ϱ = air density, lb/ft^3
Δp = pressure difference across opening, in. of water
C_1 = conversion factor = 776

The discharge coefficient C_D is a dimensionless number that depends on the opening geometry and the Reynolds number of the flow.

Airflow through constant area ducts is well characterized. At sufficiently low Reynolds numbers, the fluid velocity varies only in the direction perpendicular to the flow, and the flow may be visualized as many sheets or laminae flowing parallel to the duct walls. Thus, this type of flow is referred to as laminar. In laminar flow, C_D depends on the square root of the pressure difference; therefore Q is proportional to Δp. At large Reynolds numbers, the flow becomes turbulent. The velocity at a given point fluctuates rapidly and at random, even if the net flow rate is constant. In turbulent flow, the discharge coefficient is constant and therefore the flow Q is proportional to $\sqrt{\Delta p}$.

The case of fully developed flow impinging on a hole or orifice in a thin plate is also described by Equation (15). Again, for a sufficiently large value of the Reynolds number, the discharge coefficient is constant. The value of C_D for an orifice depends on Reynolds number and the relative areas of the orifice and the duct in which the orifice is placed.

This discussion of laminar and turbulent flow applies to constant area ducts and orifices in such ducts. The openings in a building envelope are much less uniform in geometry. Generally, the flow never becomes fully developed, thereby preventing the applicability of the simple relations between Q and Δp. Each opening in the building envelope can still be described by Equation (15), where A is an average cross-sectional area and C_D depends on opening geometry and the pressure difference across it. Equation (16) is sometimes used instead:

$$Q = c\,(\Delta p)^n \tag{16}$$

where

c = flow coefficient, cfm/(in. of water)^n
n = flow exponent, dimensionless

Equation (16) only approximates the relationship between Q and Δp. In fact, the values of c and n depend on the range of Δp over which Equation (16) is applied. Honma (1975) measured Q as a function of Δp for several simple openings, and the measured data were fit to Equation (16). The cracks with larger flow resistances, *i.e.*, greater depths or narrower widths, tended to have an exponent n closer to 1 than did gaps with less resistance. For openings in the shell of a building, the value of n depends on the opening geometry, as well as on entrance and exit effects.

The combination of all the openings in a building's envelope produces a relationship between pressure difference and airflow rate for the whole building and is referred to as the air leakage of the building.

The air leakage of a building can be measured (as described in the section on air leakage) and is a physical property of the building envelope that depends on the envelope design, construction, and deterioration over time. A building's air leakage is measured by imposing a uniform pressure difference over the entire building envelope and measuring the airflow rate required to maintain this difference. Such a distribution of envelope pressures never occurs naturally, but it does provide a useful measure of the airtightness of a building.

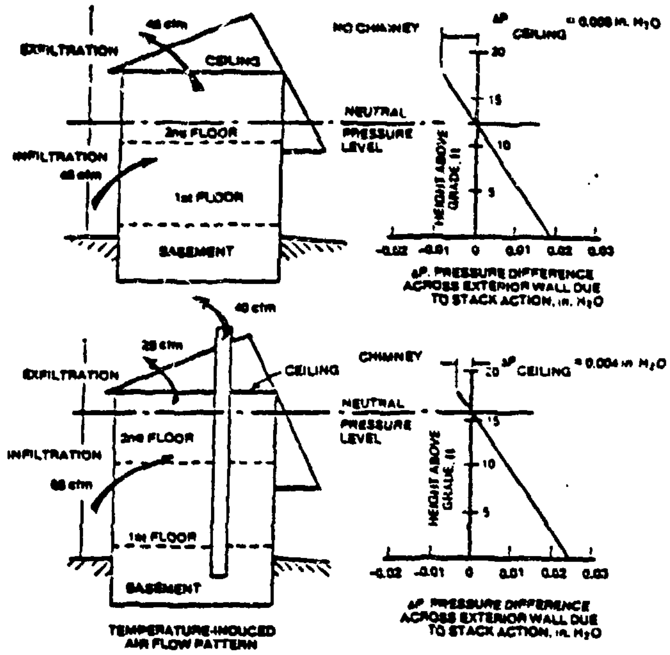

Fig. 4 Temperature-Induced Pressure and Airflow Patterns Under Operation of Electric or Gas Furnace for Δt = 50°F

NATURAL VENTILATION FLOW RATES

Natural ventilation can effectively control both temperature and contaminants, particularly in mild climates. Temperature control by natural ventilation is often the only means of providing cooling when mechanical air conditioning is not available. The arrangement, location, and control of ventilation openings should combine the driving forces of wind and temperature to achieve a desired ventilation rate and good distribution of ventilation air through the building.

Natural Ventilation Openings

Natural ventilation openings include: (1) windows, doors, monitor openings, and skylights; (2) roof ventilators; (3) stacks connecting to registers; and (4) specially designed inlet or outlet openings.

Windows transmit light and provide ventilation when open. They may open by sliding vertically or horizontally; by tilting on horizontal pivots at or near the center; or by swinging on pivots at the top, bottom, or side. The type of pivoting used is important for weather protection and airflow rate.

Roof ventilators provide a weatherproof air outlet. Capacity is determined by the ventilator's location on the roof; the resistance the ventilator and its ductwork offer to airflow; its ability to use kinetic wind energy to induce flow by centrifugal or ejector action; and the height of the draft.

Natural draft or gravity roof ventilators can be stationary, pivoting, oscillating, or rotating. Selection criteria include ruggedness, corrosion resistance, stormproofing features, dampers and operating mechanisms, noise, cost, and maintenance. Natural ventilators can be supplemented with power-driven supply fans; the motors need only be energized when the natural exhaust capacity is too low. Gravity ventilators can have manual dampers or dampers controlled by thermostat or wind velocity.

A roof ventilator should be positioned so that it receives the full, unrestricted wind. Turbulence created by surrounding obstructions, including higher adjacent buildings, impairs a ventilator's ejector action. The ventilator inlet should be conical or bell mounted to give a high flow coefficient. The opening area at the inlet should be increased if screens, grilles, or other structural members cause flow resistance. Building air inlets at lower levels should be larger than the combined throat areas of all roof ventilators.

Stacks or vertical flues should be located where wind can act on them from any direction. Without wind, stack effect alone removes air from the room with the inlets.

Required Flow

The ventilation airflow rate required to remove a given amount of heat from a building can be calculated from Equation (17) if the quantity of heat to be removed and the indoor-outdoor temperature difference are known.

$$Q = H / c_p \varrho (t_i - t_o) \tag{17}$$

where

Q = airflow rate required to remove heat, cfm
H = heat to be removed, Btu/min
c_p = specific heat of air, Btu/lb$_m$ °F (about 0.24)
ϱ = air density, lb$_m$/ft^3 (about 0.075)
$t_i - t_o$ = indoor-outdoor temperature difference, °F

Flow Caused by Wind

Factors that affect the ventilation rate due to wind forces include average speed, prevailing direction, seasonal and daily variation in speed and direction, and local obstructions such as nearby buildings, hills, trees, and shrubbery.

Wind speeds are usually lower in summer than in winter; directional frequency is also a function of season. There are relatively few places where speed falls below half the average for more than a few hours a month. Therefore, natural ventilation systems are often designed for wind speeds of one-half the seasonal average. Equation (18) shows the quantity of air forced through ventilation inlet openings by wind or determines the proper size of openings to produce given airflow rates:

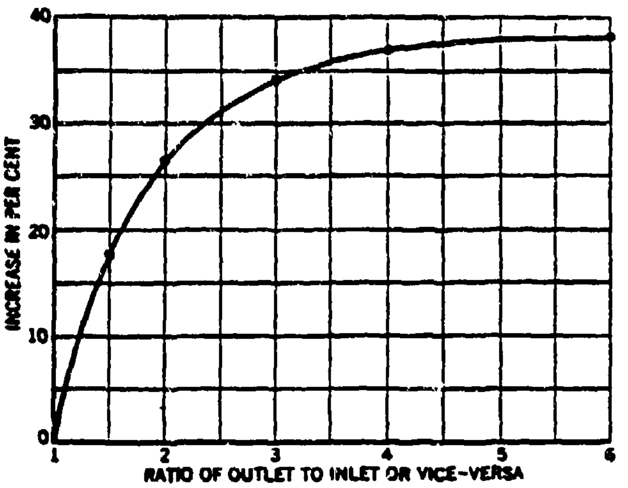

Fig. 5 Increase in Flow Caused by Excess of One Opening Over Another

$$Q = C_c C_v A v \tag{18}$$

replace

where

Q = airflow rate, cfm
A = free area of inlet openings, ft^2
v = wind speed, mph
C_v = effectiveness of openings (C_v is assumed to be 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds)
C_c = unit conversion factor = 88.0

Inlets should face directly into the prevailing wind. If they are not advantageously placed, flow will be less than that in the equation; if unusually well-placed, flow will be slightly more. Desirable outlet locations are (1) on the leeward side of the building directly opposite the inlet, (2) on the roof, in the low-pressure area caused by a flow discontinuity of the wind, (3) on the side adjacent to the windward face where low-pressure areas occur, (4) in a monitor on the leeward side, (5) in roof ventilators, or (6) by stacks. Chapter 14 gives a general description of the wind pressure distribution on a building, which relates to inlet location.

Flow Caused by Thermal Forces

If building internal resistance is not significant, the flow caused by stack effect can be expressed by:

$$Q = C_c K A [2g\Delta h_{NPL}(t_i - t_o)/t_i]^{0.5} \tag{19}$$

reset perenata

where

Q = airflow rate, cfm
K = discharge coefficient for opening
Δh_{NPL} = height from lower opening to NPL, ft
~~C_c = unit conversion factor = 60~~

add

Equation (19) applies when $t_i > t_o$. If $t_i < t_o$, replace t_i in the denominator with t_o, and replace $(t_i - t_o)$ in the numerator with $(t_o - t_i)$. If the building has more than one opening, the outlet and inlet areas are considered equal. The discharge coefficient K accounts for all viscous effects such as surface drag and interfacial mixing.

Calculating Δh_{NPL} is difficult. If one window or door represents a large fraction (approximately 90%) of the total opening area in the envelope, the NPL is at the midheight of that aperture, and Δh_{NPL} equals to one-half its height. For this condition, flow through the opening is bidirectional, *i.e.*, air from the warmer side flows through the top of the opening, and air from the colder side flows through the bottom. Interfacial mixing occurs across the counterflow interface, and the orifice coefficient can be calculated according to:

$$K = 0.40 + 0.0025\,|t_i - t_o| \tag{20}$$

If enough other openings are available, the airflow through the opening will be unidirectional and mixing cannot occur. A discharge coefficient of $K = 0.65$ should then be used. Additional information on stack-driven airflows for natural ventilation can be found in Foster and Down (1987).

Greatest flow per unit area of openings is obtained when inlets and outlets are equal; Equations (18) and (19) are based on this equality. Increasing the outlet area over inlet area, or vice versa, increases airflow but not in proportion to the added area. When openings are unequal, use the smaller area in the equations and add the increase, as determined from Figure 5.

Natural Ventilation Guidelines

Several general guidelines should be observed in designing for natural ventilation. Some of these may conflict with other climateresponsive strategies (such as orientation and shading devices to minimize solar gain) or other design considerations.

(1) In hot, humid climates, maximize air velocities in the occupied zones for bodily cooling. In hot, arid climates, maximize airflow throughout the building for structural cooling, particularly at night when temperatures are low.

(2) Take advantage of topography, landscaping, and surrounding buildings to redirect airflow and give maximum exposure to breezes. Use vegetation to funnel breezes and avoid wind dams, which reduce the driving pressure differential around the building. Site objects should not obstruct inlet openings.

(3) Shape the building to expose maximum surface area to breezes.

(4) Use architectural elements such as wingwalls, parapets, and overhangs to promote airflow into the building interior.

(5) The long facade of the building and the majority of the door and window openings should be oriented with respect to the prevailing summer breezes. If there is no prevailing direction, openings should be sufficient to provide ventilation regardless of wind direction.

(6) Windows should be located in opposing pressure zones. Two openings on opposite sides of a space increase the ventilation flow. Openings on adjacent sides force air to change direction, providing ventilation to a greater area. The benefits of the window arrangement depend on the outlet location relative to the direction of the inlet airstream.

(7) If a room has only one external wall, better airflow is achieved with two widely spaced windows.

(8) If the openings are at the same level and near the ceiling, much of the flow may bypass the occupied level and be ineffective in diluting contaminants there.

(9) The stack effect requires vertical distance between openings to take advantage of the stack effect; the greater the vertical distance, the greater the ventilation.

(10) Openings in the vicinity of the NPL are least effective for thermally induced ventilation. If the building has only one opening, the NPL tends to move to that level, which reduces the pressure across the opening.

(11) Greatest flow per unit area of total opening is obtained by inlet and outlet openings of nearly equal areas. An inlet window smaller than the outlet creates higher inlet velocities. An outlet smaller than the inlet creates lower but more uniform air speed through the room.

(12) Openings with areas much larger than calculated are sometimes desirable when anticipating increased occupancy or very hot weather.

(13) Horizontal windows are generally better than square or vertical windows. They produce more airflow over a wider range of wind directions and are most beneficial in locations where prevailing wind patterns shift.

(14) Window openings should be accessible to and operable by occupants.

(15) Inlet openings should not be obstructed by indoor partitions. Partitions can be placed to split and redirect airflow, but should not restrict flow between the building's inlets and outlets.

(16) Vertical airshafts or open staircases can be used to increase and take advantage of stack effects. However, enclosed staircases intended for evacuation during a fire should not be used for ventilation.

INFILTRATION

Although the terms infiltration and air leakage are sometimes used synonymously, they are different, though related, quantities. Infiltration is the rate of uncontrolled air exchange through unintentional openings that occurs under given conditions, while air leakage is a measure of the airtightness of the building shell. The greater the air leakage of a building, the greater its infiltration rate, all else (weather, exposure, and building geometry) being equal.

Infiltration may be reduced either by reducing the surface pressures driving the flow, or reducing the air leakage of the shell. Surface pressures caused by the wind can be reduced by changing the landscaping in the vicinity of the building (Mattingly and Peters 1977). Stack pressures can be reduced by increasing the airflow resistance between floors and from floors to any vertical shafts within the building, although this is almost exclusively an issue in tall buildings.

The infiltration rate of an individual building depends on weather conditions, equipment operation, and occupant activities. The rate can vary by a factor of five from weather effects alone (Malik 1978). When associating a building with an infiltration rate, it is important to provide the corresponding weather conditions and equipment status, or to describe it as a seasonal or annual average.

Typical infiltration values in housing in North America vary by a factor of about ten, from tight housing with seasonal average air change rates of about 0.2 per hour to housing with air exchange rates as great as 2.0 per hour. Figures 6 and 7 show histograms of

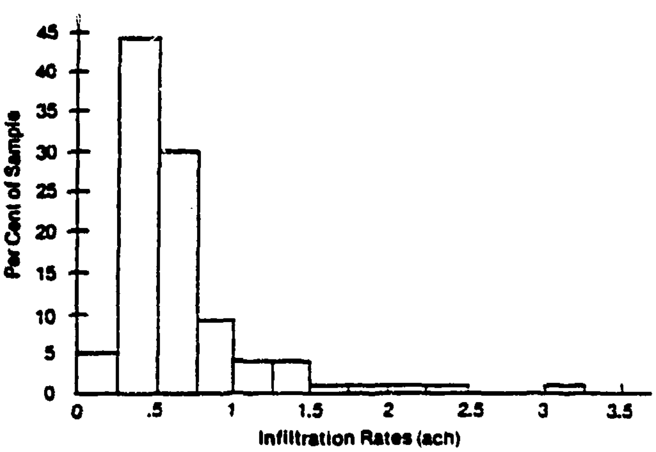

Fig. 6 Histogram of Infiltration Values—New Construction

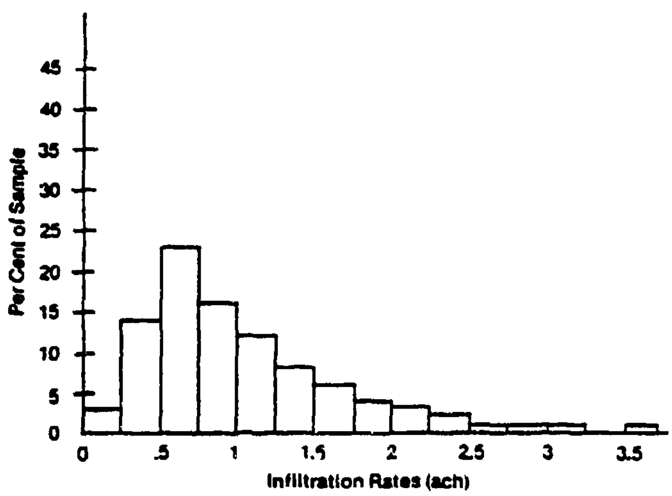

Fig. 7 Histogram of Infiltration Values—Low-Income Housing

infiltration rates measured in two different samples of North American housing (Grimsrud *et al.* 1982, Grot and Clark 1979). Figure 6 shows the average seasonal infiltration of 312 houses located in different areas in North America. The median infiltration value of this sample is 0.5 air changes per hour (ach). Figure 7 represents measurements in 266 houses located in 16 cities in the United States. The median value of this sample is 0.90 ach. The group of houses contained in the Figure 6 sample is biased toward new energy-efficient houses, while the group in Figure 7 represents older, low-income housing in the United States. While these do not represent random samples of North American housing, they indicate the distribution of infiltration rates expected in a group of buildings.

The infiltration values listed are appropriate for unoccupied structures. Although occupancy influences have not been measured directly, Desrochers and Scott (1985) estimate they add an average of 0.10 to 0.15 ach to unoccupied values.

Grot and Persily (1986) found eight recently constructed office buildings had infiltration rates ranging from 0.1 to 0.6 air changes per hour with no outdoor air intake. The infiltration rates of these buildings exhibited varying degrees of weather dependence, generally much lower than that measured in houses.

AIR EXCHANGE MEASUREMENT

The only reliable way to determine the air exchange rate of a building is to measure it. Several tracer gas measurement procedures exist, all involving an inert or nonreactive gas used to label the indoor air (Hunt 1980, Sherman *et al.* 1980, Harrje *et al.* 1981, Lagus and Persily 1985, Persily 1988). The tracer is released into the building in a specified manner, and the concentration of the tracer within the building is monitored and related to the building's air exchange rate. A variety of tracer gases, and associated concentration detection devices, have been used. Desirable qualities of a tracer gas are detectability, nonreactivity, nontoxicity, and relatively low concentration in ambient air (Hunt 1980).

All tracer gas measurement techniques are based on a mass balance of the tracer gas within the building. Assuming the outdoor concentration is zero, this mass balance takes the form:

$$V(dc/d\theta) = F(\theta) - Q(\theta)c(\theta) \tag{21}$$

where

V = volume of space being tested, ft³
$c(\theta)$ = tracer gas concentration at time θ
$dc/d\theta$ = time rate of change of concentration, min^{-1}
$F(t)$ = tracer gas injection rate at time θ, cfm
$Q(t)$ = airflow rate out of the building at time θ, cfm
θ = time, min

In Equation (21) density differences between indoor and outdoor air are generally ignored; therefore Q also refers to the airflow rate into the building. While Q is often referred to as the infiltration rate, any measurement includes both mechanical and natural ventilation in addition to envelope infiltration. The ratio of the air exchange rate Q to the volume being tested V has units of volume/time (often converted to ach) and is called the air change rate I.

Equation (21) is based on the assumption that airflow out of the building is the dominant process removing the tracer gas from the space, *i.e.*, the tracer gas does not react chemically within the space and is not absorbed onto interior surfaces. It is also based on the assumption that the tracer gas concentration within the building can be represented by a single value, *i.e.*, the tracer gas concentration is uniform within the space. Three different tracer gas procedures are used to measure air exchange rates: (1) decay, (2) constant concentration, and (3) constant injection.

Decay

The simplest tracer gas measurement technique is the decay method, which is a standardized procedure (ASTM 1983). In the decay method, a small amount of tracer gas is injected into the space and is allowed to mix with the interior air. After the injection, F = 0 and the solution to Equation (21) is:

$$c(\theta) = c_o e^{-I\theta} \tag{22}$$

where c_o is the concentration at θ = 0.

Equation (22) is generally used to solve for I by measuring the tracer gas concentration periodically during the decay and fitting the data to the log form of Equation (22):

$$\ln c(\theta) = \ln c_o - I\theta \tag{23}$$

As with all tracer gas techniques, the tracer gas decay method has advantages and disadvantages. The advantages include the fact that Equation (22) is an exact solution to the tracer gas mass balance equation. Also, because logarithms of concentration are taken, only relative concentrations are needed, which can simplify the calibration of the concentration-measuring equipment. Finally, the tracer gas injection rate need not be measured, although it must be controlled so that the tracer gas concentrations are within the range of the concentration-measuring device. The concentration-measuring equipment can be located on site, or building samples can be collected in suitable containers and analyzed elsewhere.

The most serious problem with the decay technique is imperfect mixing of the tracer gas with the interior air, both at initial injection and during the decay. Equations (21) and (22) employ the assumption that the tracer gas concentration within the building is uniform. If the tracer is not well mixed, this assumption is not appropriate and the determination of I will be subject to errors. It is difficult to estimate the magnitude of the errors due to poor mixing, and little analysis of this problem has been done.

Constant Concentration

In the constant concentration technique, the tracer gas injection rate is adjusted to maintain a constant concentration within the building. If the concentration is truly constant, then Equation (21) reduces to:

$$Q(\theta) = F(\theta) / c \tag{24}$$

There is less experience with this technique than with the decay procedure, but several applications do exist (Kumar *et al.* 1979, Collet 1981, Bohac *et al.* 1985).

Because the tracer gas injection is continuous, it requires no initial mixing period. Another advantage is that the tracer concentration in each zone of the building can be separately controlled by injecting into each zone; thus, the amount of outdoor air flowing into each zone can be determined. This procedure has the disadvantage of requiring the measurement of absolute tracer concentrations and injection rates. Also, imperfect mixing of the tracer and the interior air causes a delay in the response of the concentration to changes in the injection rate. This delay in concentration response, makes it impossible to keep the concentration constant, and therefore Equation (24) is only an approximation. The magnitude of these errors have not been well examined.

Constant Injection

In the constant injection procedure, the tracer is injected at a constant rate and the solution to Equation (21) becomes:

$$c(\theta) = (F/q)(1 - e^{-I\theta}) \tag{25}$$

After sufficient time, the transient term reduces to zero, the concentration attains equilibrium, and Equation (25) reduces to:

$$Q = F / c \tag{26}$$

This relation is valid only when the air exchange rate is constant; thus this technique is appropriate for systems at or near equilibrium. It is particularly useful in spaces with mechanical ventilation or with high air exchange rates. Constant injection requires the measurement of absolute concentrations and injection rates.

Dietz *et al.* (1986) introduced a special case of the constant injection technique. This technique uses permeation tubes as a tracer gas source. The tubes release the tracer at an ideally constant rate into the building being tested. A sampling tube packed with an adsorbent collects the tracer from the interior air at a constant rate by diffusion. After a sampling period of one week or more, the sampler is removed and analyzed to determine the average tracer gas concentration within the building during the sampling period.

Solving Equation (21) for c and taking the time average gives

$$\langle c \rangle = \langle \frac{F}{Q} \rangle = F \langle \frac{1}{Q} \rangle \tag{27}$$

where $\langle \ldots \rangle$ denotes time average. (Note that the time average of $dc/d\theta$ is assumed to equal zero.)

Equation (27) shows that the average tracer concentration and the injection rate can be used to calculate the average of the inverse air exchange rate. The average of the inverse is less than the actual average, with the magnitude of this difference depending on the distribution of air exchange rates during the measurement period. Sherman and Wilson (1986) calculated these differences to be about 20% for one-month averaging periods. Differences greater than 30% have been measured when there were large changes in air exchange rate due to occupant airing of houses; errors from 5 to 30% were measured when the variation was due to weather effects (Bohac *et al.* 1987). Longer averaging periods and large changes in air exchange rates during the measurement periods generally lead to larger differences between the average inverse exchange rate and the actual average rate.

AIR LEAKAGE

The air leakage of a building characterizes the relationship between the pressure difference across the building envelope and the airflow rate through the envelope. Building air leakage is a physical property of a building and is determined by its design, construction, seasonal effects, and deterioration over time. Although airtightness is just one factor in determining the air exchange rate of a building, it is useful for comparing buildings to one another or to airtightness standards, for evaluating design and construction quality, and for studying the effectiveness of airtightening retrofits. No simple relationship exists between a building's air leakage and its air exchange rate, but calculation methods do exist (see Calculating Air Exchange).

Measurement

While tracer gas measurement procedures provide building air exchange rates, they are somewhat expensive and time-consuming. In many cases it is sufficient, or preferable, to measure the air leakage of a building with pressurization testing (Stricker 1975, Tamura 1975, Kronvall 1978, Blomsterberg and Harrje 1979). Fan pressurization is relatively quick and inexpensive and characterizes building envelope airtightness independent of weather conditions. In this procedure, a large fan or blower is mounted in a door or window and induces a large and roughly uniform pressure difference across the building shell (CGSB 1986, ASTM 1987). The airflow required to maintain this pressure difference is then measured. The leakier the building, the more airflow is necessary to induce a specific indoor-outdoor pressure difference. The airflow rate is generally measured at a series of pressure differences ranging from about 0.04 to 0.30 in. of water.

The results of a pressurization test, therefore, consist of several combinations of pressure difference and airflow rate. An example of typical data is shown in Figure 8. These data points characterize the air leakage of a building and are generally converted to a single value that serves as a measure of the building's airtightness. There are several different measures of airtightness, and most of them involve fitting the data to a curve in the form of Equation (16), *i.e.*, $Q = c\Delta p^n$. The airtightness ratings are based on airflow rates predicted at particular reference pressures by Equation 16. The basic difference between the different airtightness ratings is the value of the reference pressure.

In some cases, the predicted airflow rate is converted to an equivalent or effective leakage area by rearranging Equation (15) into the following form:

$$L = C_6 q_r (\rho / 2\Delta p_r)^{0.5} / C_D \tag{28}$$

where

L = equivalent or effective leakage area, in^2
Δp_r = reference pressure difference, in. of water
q_r = predicted airflow rate at Δp_r (from a curve fit to the pressurization test data), cfm
C_D = discharge coefficient
C_6 = unit conversion factor = 0.186

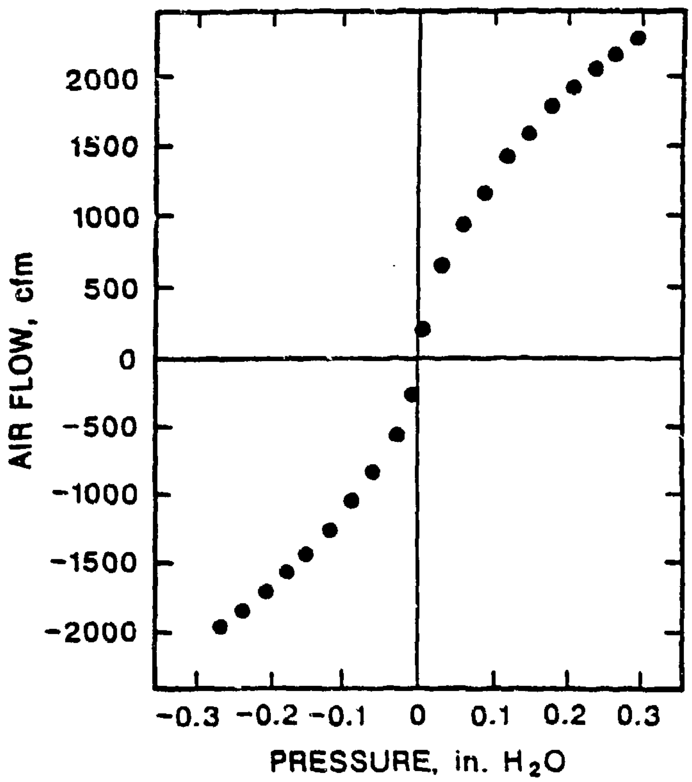

Fig. 8 Airflow Rate Versus Pressure Difference Data from a Whole House Pressurization Test

By calculating L, all the openings in the building shell are combined into an overall opening area and discharge coefficient for the building. Some users of the leakage area approach set the discharge coefficient equal to 1. Others set $C_D \approx 0.6$, *i.e.*, the discharge coefficient for a sharp-edged orifice. The leakage area of a building is therefore the area of an orifice (with an assumed value of C_D) that would produce the same amount of leakage as the building envelope at the reference pressure.

Whether an airtightness rating based on leakage area or a predicted airflow rate is used, either quantity is generally normalized by some factor to account for building size. These normalization factors include floor area, exterior envelope area, and building volume.

With the wide variety of possible approaches to normalization and reference pressure, and the use of the leakage area concept, many different airtightness ratings are being used. Reference pressure differences in use include 0.016, 0.04, 0.10, 0.20, and 0.30 in. of water. Reference pressures of 0.016 and 0.04 in. of water are advocated because they are closer to the pressures that actually induce air exchange. While this may be true, they are outside the range of measured values in the test; therefore the predicted airflow rates at 0.016 or 0.04 in. of water are subject to significant uncertainty. The uncertainty in these predicted airflow rates and the implications for quantifying airtightness are discussed in Persily and Grot (1985b).

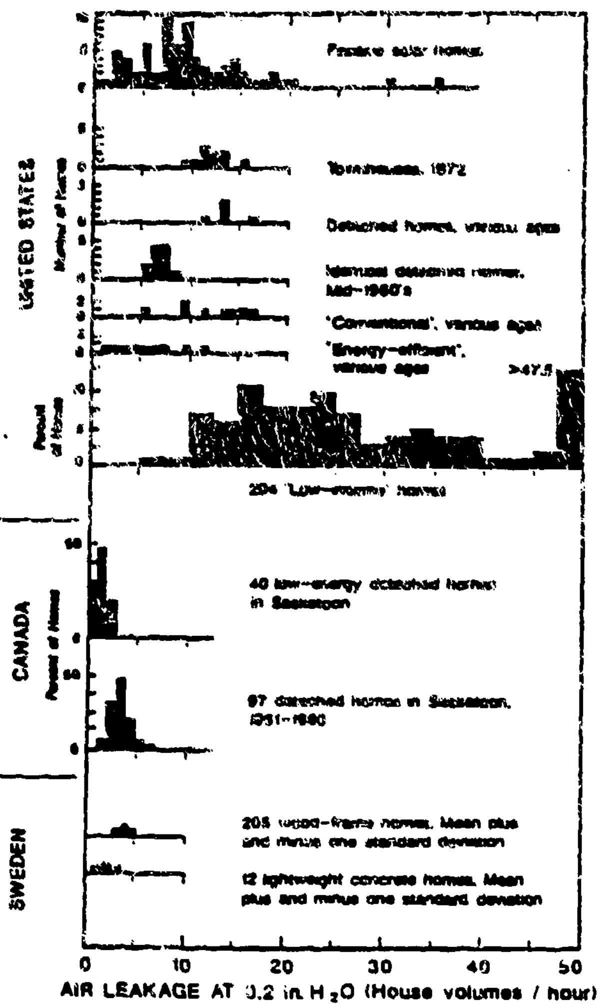

Fig. 9 Comparison of Pressurization Test Results

Some common airtightness ratings include the effective leakage area at 0.016 in. of water assuming $C_D = 1.0$ (Sherman and Grimsrud 1980); the equivalent leakage area at 0.04 in. of water assuming $C_D = 0.611$ (CGSB 1986); and the airflow rate at 0.20 in. of water, divided by the building volume to give units of air changes per hour (Blomsterberg and Harrje 1979).

Leakage areas at one reference pressure can be converted to leakage areas at some other reference pressure according to:

$$L_{r,2} = L_{r,1}\,(C_{D,1}/C_{D,2})\,(\Delta p_{r,2}/\Delta p_{r,1})^{n-0.5} \qquad (29)$$

where

$L_{r,1}$ = leakage area at reference pressure $\Delta p_{r,1}$, in^2
$L_{r,2}$ = leakage area at reference pressure $\Delta p_{r,2}$, in^2
$C_{D,1}$ = discharge coefficient used to calculate $L_{r,1}$
$C_{D,2}$ = discharge coefficient used to calculate $L_{r,2}$
n = flow exponent

A leakage area at one reference pressure can be converted to an airflow rate at some other reference pressure according to:

$$q_{r,2} = C_7\,C_{D,1}\,L_{r,1}\,(2/\varrho)^{0.5}\,(\Delta p_{r,1})^{0.5-n}\,(\Delta p_{r,2})^{n} \qquad (30)$$

where

$q_{r,2}$ = airflow rate at reference pressure $\Delta p_{r,2}$, cfm
$L_{r,1}$ = leakage area at reference pressure, in^2
$C_{D,1}$ = discharge coefficient used to calculate $L_{r,1}$
C_7 = conversion factor = 5.39

Finally, one may convert a leakage area to a flow coefficient in Equation (16) according to:

$$c = C_7 C_D\,L\,(2/\varrho)^{0.5}\,(\Delta p_r)^{1/2-n} \qquad (31)$$

where

c = flow coefficient, cfm / (in. of water)^n
C_D = discharge coefficient used to calculate L
L = leakage area at reference pressure Δp_r
C_7 = conversion factor = 5.39

Equations (29) through (31) require the assumption of a value of n, unless it is reported with the measurement results. When fitting pressurization test data to Equation (16), the value of n generally lies between 0.6 and 0.7. Therefore, using a value of n in this range is reasonable.

Fan pressurization measures a property of a building that ideally varies little with time and weather conditions. In reality, unless the wind and temperature difference during the measurement period are sufficiently mild, the pressure differences they induce during the test will interfere with the test pressures and cause measurement errors. Persily (1982) presents an experimental study of the effects of wind speed on pressurization test results. Several experimental studies have also shown variations on the order of 20 to 40% over a year in the measured airtightness in homes (Persily 1982, Kim and Shaw 1986, Warren and Webb 1986).

Figure 9 shows several pressurization test results for residential buildings (Persily 1986). These results are in units of air changes per hour at 0.20 in. of water, and show the wide range in airtightness among houses, even houses of identical design. The passive solar and energy-efficient data also show that houses that might be expected to be relatively airtight are not necessarily that tight. The houses in Sweden—which have a residential building airtightness standard of ~~3~~ air changes per hour at 0.20 in. of water for single-family detached houses (Swedish Building Code 1980)—are exceptionally tight, as are the houses in Canada.

Se

/0.3

ASHRAE Standard 119 (1988) establishes air leakage performance levels for residential buildings These levels are in terms of the normalized leakage L_n:

$$L_n = C_1 (L/A)(H/H_o)^{0.3} \quad (32)$$

where

L = effective leakage area at 0.016 in. of water (C_D = 1.0), in.²
A = floor area, ft²
H = building height, ft
H_o = reference height of one-story building = 8 ft
C_1 = conversion factor = 6.94

Table 2 presents the leakage classes of Standard 119. The values of L_n in this table correspond approximately to building air exchange rates in units of air changes per hour. The standard specifies appropriate leakage classes for a building based on climate.

Persily and Grot (1985) ran whole building pressurization tests in large office buildings, which showed pressurization airflow rate divided by the building volume is relatively low compared to that of houses. However, if these airflow rates are normalized by building envelope area instead of by volume, the results indicate envelope airtightness levels similar to typical American houses.

Table 2 Leakage Classes

Range of Normalized Leakage	Leakage Class
$L_n < 0.10$	A
$0.10 \le L_n < 0.14$	B
$0.14 \le L_n < 0.20$	C
$0.20 \le L_n < 0.28$	D
$0.28 \le L_n < 0.40$	E
$0.40 \le L_n < 0.57$	F
$0.57 \le L_n < 0.80$	G
$0.80 \le L_n < 1.13$	H
$1.13 \le L_n < 1.60$	I
$1.60 \le L_n$	J

Air Leakage of Building Components

The fan pressurization procedure discussed earlier enables the measurement of whole building air leakage. The location and size of individual openings in building envelopes are extremely important, as they influence the air infiltration rate of a building as well as the heat and moisture transfer characteristics of the envelope. Additional test procedures exist for pressure testing individual building components such as windows, walls, and doors; they are discussed in ASTM *Standards* E283 and E783 for laboratory and field tests, respectively. The following sections discuss component air leakage in both residential and commercial buildings.

Leakage Distribution in Residential Buildings

Dickeroff *et al.* (1982) and Harrje and Born (1982) studied the air leakage of individual building components and systems. The following points summarize the percentages of whole building leakage associated with various components and systems. The values in parentheses include the range determined for each component, and the mean of the range.

Walls (18 to 50%; 35%). Both interior and exterior walls contribute to the leakage of the structure. Leakage between the sill plate and the foundation, cracks below the bottom of the gypsum wall board, electrical outlets, plumbing penetrations, and leaks into the attic at the top plates of walls all occur. Since interior walls are not filled with insulation, open paths connecting these walls and the attic permit the walls to behave like heat exchanger fins within the conditioned living space of the house.

Ceiling Details (3 to 30%; 18%). Leakage across the top ceiling of the heated space is particularly insidious because it reduces the effectiveness of insulation on the attic floor and contributes to infiltration heat loss. Ceiling leakage also reduces the effectiveness of ceiling insulation in buildings without attics. Recessed lighting, plumbing, and electrical penetrations leading to the attic are some particular areas of concern.

Heating System (3 to 28%; 18%). The location of the furnace or ductwork in conditioned or unconditioned spaces, the venting arrangement of a fuel-burning device, and the existence and location of a combustion air supply all affect leakage.

Windows and Doors (6 to 22%; 15%). More variation is seen in window leakage among window types (*e.g.*, casement versus double-hung) than among new windows of the same type from different manufacturers (Weidt *et al.* 1979). Windows that seal by compressing the weatherstrip (casements, awnings) show significantly lower leakage than windows with sliding seals.

Fireplaces (0 to 30%; 12%). When a fireplace is not in use, poor-fitting dampers allow air to escape. Glass doors reduce excess air while a fire is burning but rarely seal the fireplace structure more tightly than a closed damper does. Chimney caps or fireplace plugs with telltale signs that warn they are in place effectively reduce leakage through a cold fireplace.

Vents in Conditioned Spaces (2 to 12%; 5%). Vents in conditioned spaces frequently have no dampers or dampers that do not close properly.

Diffusion Through Walls (<1%). Diffusion, in comparison to infiltration through holes and other openings in the structure, is not an important flow mechanism. Typical values for the permeability of building materials at 0.02 in. of water (a relatively large pressure for infiltration) produce an air exchange rate of less than 0.01 air changes per hour by wall diffusion in a typical house.

Component Leakage Areas. Table 3 shows effective leakage areas for a variety of residential building components at 0.016 in. of water with a C_D assumed equal to 1 (Reinhold and Sonderegger 1983). These leakage areas are normalized by the length or area appropriate to the component, and may be converted to leakage areas at other reference pressures, airflow rates, or flow coefficients using Equations (29) through (31).

Commercial Building Envelope Leakage

The building envelopes of large commercial buildings are often thought to be quite airtight. The National Association of Architectural Metal Manufacturers specifies a maximum leakage per unit of exterior wall area of 0.060 cfm/ft² at a pressure difference of 0.30 in. of water exclusive of leakage through operable windows. Tamura and Shaw (1976a) found that air leakage measurements in eight Canadian office buildings with sealed windows, assuming a flow exponent of 0.65 in Equation (16), ranged from 0.120 to 0.480 cfm/ft². Other measurements taken by Persily and Grot (1986) in eight U.S. office buildings ranged from 0.213 to 1.028 cfm/ft² at 0.30 in. of water. Therefore, office building envelopes are leakier than expected. Typical air leakage values per unit wall area at 0.30 in. of water are 0.10, 0.30, and 0.60 cfm/ft² for tight, average, and leaky walls respectively (Tamura and Shaw 1976a).

Air Leakage Through Internal Partitions

In large buildings, the air leakage associated with internal partitions becomes very important. Elevator, stair, and service shaft walls, floors, and other interior partitions are the major separations of concern in these buildings. Their leakage characteristics are needed to determine infiltration through exterior walls and airflow patterns within a building. These internal resistances are also important in the event of a fire to predict smoke movement patterns and evaluate smoke control systems.

Table 4 gives leakage areas (calculated at 0.30 in. of water with $C_D = 0.65$) for different internal partitions of commercial buildings (Klote and Fothergill 1983). Figure 10 shows examples of measured air leakage rates of elevator shaft walls (Tamura and Shaw 1986b), the type of data used to derive the values in Table 4. Chapter 58 of the 1987 HVAC Volume also discusses these issues.

Leakage openings at the top of elevator shafts are equivalent to orifice areas of 620 to 1550 in^2. Air leakage rates through stair shaft and elevator doors are shown in Figure 11 as a function of average crack width around the door. The leakage areas associated with other openings within commercial buildings are also important for air movement calculations. These include interior doors and partitions, suspended ceilings in buildings where the space above the ceiling is used in the air distribution system, and other components of the air distribution system.

Air Leakage Through Exterior Doors

Door infiltration depends on the type of door, room, and building. In residences and small buildings where doors are used infrequently, the air exchange associated with a door can be

Table 3 Effective Leakage Area of Building Components (0.016 in. of water)

Component	Best estimate	Max	Min
SILL FOUNDATION — WALL			
Caulked, in^2/ft of perimeter	0.04	0.06	0.02
Not caulked, in^2/ft of perimeter	0.19	0.19	0.05
JOINTS BETWEEN CEILING AND WALLS			
Joints, in^2/ft of wall (only if not taped or plastered and no vapor barrier)	0.07	0.12	0.02
WINDOWS			
Casement			
Weatherstripped, in^2/ft^2 of window	0.011	0.017	0.006
Not weatherstripped, in^2/ft^2 of window	0.023	0.034	0.011
Awning			
Weatherstripped, in^2/ft^2 of window	0.011	0.017	0.006
Not weatherstripped, in^2/ft^2 of window	0.023	0.034	0.011
Single Hung			
Weatherstripped, in^2/ft^2 of window	0.032	0.042	0.026
Not weatherstripped, in^2/ft^2 of window	0.063	0.083	0.052
Double Hung			
Weatherstripped, in^2/ft^2 of window	0.043	0.063	0.023
Not weatherstripped, in^2/ft^2 of window	0.086	0.126	0.046
Single Slider			
Weatherstripped, in^2/ft^2 of window	0.026	0.039	0.013
Not weatherstripped, in^2/ft^2 of window	0.052	0.077	0.026
Double Slider			
Weatherstripped, in^2/ft^2 of window	0.037	0.054	0.02
Not weatherstripped, in^2/ft^2 of window	0.074	0.011	0.04
DOORS			
Single Door			
Weatherstripped, in^2/ft^2 of door	0.114	0.215	0.043
Not weatherstripped, in^2/ft^2 of door	0.157	0.243	0.086
Double Door			
Weatherstripped, in^2/ft^2 of door	0.114	0.215	0.043
Not weatherstripped, in^2/ft^2 of door	0.16	0.32	0.1
Access to Attic or Crawl Space			
Weatherstripped, in^2 per access	2.8	2.8	1.2
Not weatherstripped, in^2 per access	4.6	4.6	1.6
WALL — WINDOW FRAME			
Wood Frame Wall			
Caulked, in^2/ft^2 of window	0.004	0.007	0.004
No caulking, in^2/ft^2 of window	0.024	0.039	0.022
Masonry Wall			
Caulked, in^2/ft^2 of window	0.019	0.03	0.016
No caulking, in^2/ft^2 of window	0.093	0.15	0.082
WALL — DOOR FRAME			
Wood Wall			
Caulked, in^2/ft^2 of door	0.004	0.004	0.001
No caulking, in^2/ft^2 of door	0.024	0.024	0.009
Masonry Wall			
Caulked, in^2/ft^2 of door	0.0143	0.0143	0.004
No caulking, in^2/ft^2 of door	0.072	0.072	0.024

Component	Best estimate	Max	Min
DOMESTIC HOT WATER SYSTEMS			
Gas Water Heater (only if in conditioned space), in^2	3.1	3.9	2.325
ELECTRIC OUTLETS AND LIGHT FIXTURES			
Electric Outlets and Switches			
Gasketed, in^2 per outlet and switch	0	0	0
Not gasketed, in^2 per outlet and switch	0.076	0.16	0
Recessed Light Fixtures, in^2 per fixture	1.6	3.10	1.6
PIPE AND DUCT PENETRATIONS THROUGH ENVELOPE			
Pipes			
Caulked or sealed, in^2 per pipe	0.155	0.31	0
Not caulked or sealed, in^2 per pipe	~~[illegible]~~ 0.93	1.55	0.31
Ducts			
Sealed or with continuous vapor barrier, in^2 per duct	0.25	0.25	0
Unsealed and without vapor barrier, in^2 per duct	3.7	3.7	2.2
FIREPLACE			
Without Insert			
Damper closed, in^2 per fireplace	10.7	13.0	8.4
Damper open, in^2 per fireplace	54.0	59.0	50.0
With Insert			
Damper closed, in^2 per fireplace	5.6	7.1	4.03
Damper open or absent, in^2 per fireplace	10.0	14	6.2
EXHAUST FANS			
Kitchen Fan			
Damper closed, in^2 per fan	0.775	1.1	0.47
Damper open, in^2 per fan	6.0	6.5	5.6
Bathroom Fan			
Damper closed, in^2 per fan	1.7	1.9	1.6
Damper open, in^2 per fan	3.1	3.4	2.8
Dryer Vent			
Damper closed, in^2 per vent	0.47	0.9	0
Heating Ducts and Furnace — Forced Air Systems			
DUCTWORK (only if in unconditioned space)			
Joints taped or caulked, in^2 per house	11	11	5
Joints not taped or caulked, in^2 per house	22	22	11
FURNACE (only if in conditioned space)			
Sealed combustion furnace, in^2 per furnace	0	0	0
Retention head burner furnace, in^2 per furnace	5	6.2	3.1
Retention head plus stack damper, in^2 per furnace	3.7	4.6	2.8
Furnace with stack damper, in^2 per furnace	4.6	6.2	3.1
AIR CONDITIONER			
Wall or window unit, in^2 per unit	3.7	5.6	0

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Table 4 Leakage Areas for Internal Partitions in Commercial Buildings

Construction Element	Wall Tightness	Area Ratio
		A/A_w
STAIRWELL WALLS	Tight	0.14×10^{-4}
	Average	0.11×10^{-3}
	Loose	0.35×10^{-3}
ELEVATOR SHAFT WALLS	Tight	0.18×10^{-4}
	Average	0.84×10^{-3}
	Loose	0.18×10^{-2}
		A/A_f
FLOORS	Average	0.52×10^{-4}

A = leakage area A_w = wall area A_f = floor area

estimated based on air leakage through cracks between the door and the frame. A frequently opened single door, as in a small retail store, has a much larger amount of airflow. An ASHRAE research program provided data on air leakage characteristics of swinging door entrances (Min 1958, Tamura and Wilson 1966 and 1967a) and revolving doors (Schutrum *et al.* 1961). A design chart (Min 1961) based on this report (Schutrum *et al.* 1961) evaluates infiltration through manual and power-operated revolving doors.

CONTROLLING AIR LEAKAGE

New Buildings

It is much easier to build a tight building than to tighten an existing building. Elmroth and Levin (1983), Eyre and Jennings (1983), and Marbek (1984) provide information and construction details on airtight building design for houses. However, little corresponding information is available for commercial buildings.

A continuous air infiltration barrier is one of the most effective means of reducing air leakage through walls, around window and door frames, and at joints between major building elements. The air infiltration barrier can be installed on the inside of the wall framing, in which case it also usually functions as a vapor retarder, or on the outside of the wall framing, in which case it should have a permeance rating high enough to permit diffusion of water vapor from the wall. For a discussion of moisture transfer in building envelopes, see Chapters 20 and 21.

When the air infiltration barrier is also a continuous plastic film vapor retarder, particular care must be taken to ensure its continuity at all wall, floor, and ceiling joints; at window and door frames; and at all penetrations of the air-vapor barrier, such as electrical outlets and switches, plumbing connections, and utility service penetrations. Joints in the air-vapor barrier must be lapped and sealed. Plastic vapor retarders installed in the ceiling should be tightly sealed with the vapor retarder in the outside walls and continuous over the partition walls. A seal at the top of the partition walls prevents leakage into the attic; a plate on top of the studs generally gives a poor seal.

A continuous air-infiltration barrier installed on the outside of wall framing can eliminate many difficult construction details associated with the installation of continuous air-vapor barriers. Interior air-vapor barriers must be lapped and sealed at electrical outlets and switches, at joints between walls and floors and joints between walls and ceilings, and at plumbing connections penetrating the wall's interior finish. The exterior air-infiltration barrier can cover these problem areas with a continuous material. Joints in the air-infiltration barrier should be lapped and sealed or taped. Exterior air-infiltration barriers are generally made of a material stronger than plastic film and are more likely to withstand damage during construction. Sealing the wall against air leakage at the exterior of the insulation also cuts down on convective currents within the wall cavity, allowing insulation to retain more of its effectiveness.

Existing Buildings

The air-leakage sites must first be located to tighten the envelope of an existing building. As discussed earlier, air leakage in buildings is due not only to windows and doors, but to a wide

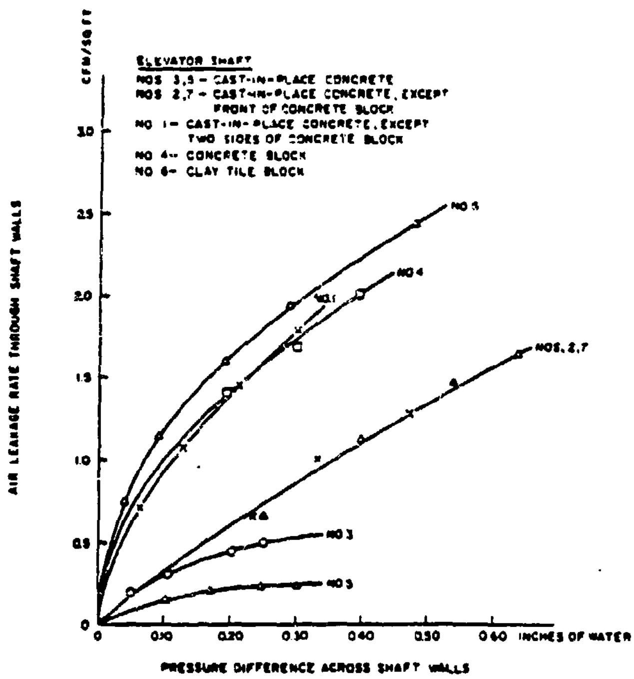

Fig. 10 Air-Leakage Rates of Elevator Shaft Walls

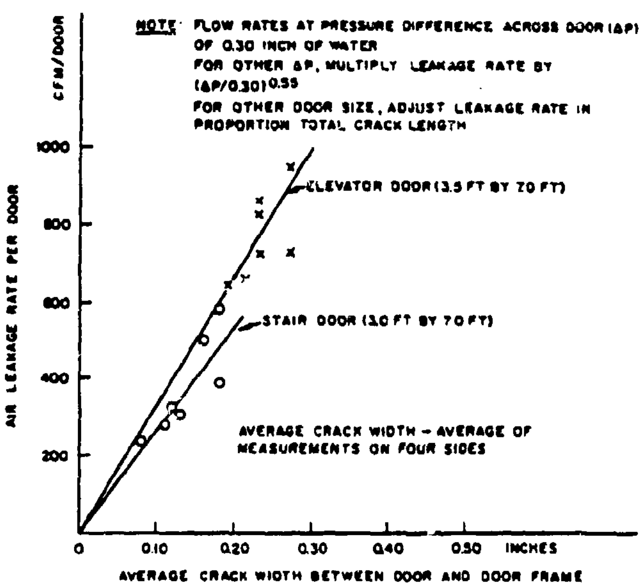

Fig. 11 Air-Leakage Rate of Door Versus Average Crack Width

range of unexpected and unobvious construction defects. Many important leakage sites can be very difficult to find. A variety of techniques developed to locate leakage sites are described in ASTM *Standard* E1186.

Once leakage sites are located, they can be repaired with materials and techniques appropriate to the size and location of the leak. Harrje *et al.* (1979), Diamond *et al.* (1982), and Energy Resource Center (1983) include information on air tightening in existing residential buildings. By using these procedures, the air leakage of residential buildings can be improved dramatically. Depending on the extent of the tightening effort and the experience of those doing the work, residential buildings can be tightened anywhere from 5 to more than 50% (Blomsterberg and Harrje 1979, Harrje and Mills 1980, Jacobson *et al.* 1986, Verschoor and Collins 1986, Giesbrecht and Proskiw 1986). Much less experience is available for airtightening large, commercial buildings, but the same general principles apply.

RESIDENTIAL VENTILATION SYSTEMS

Infiltration has traditionally met ventilation requirements for houses. When the building envelope is leaky, infiltration usually meets ventilation needs, but under mild weather conditions, these outdoor air requirements may not be met. During typical, or more severe, weather conditions, ventilation requirements are exceeded and energy is wasted to condition the excessive amounts of outdoor air. The only way to control the ventilation rate of a building is to have a tight building envelope and a properly designed and operated mechanical ventilation system. The use of mechanical ventilation in houses is not well-developed, but Fisk *et al.* (1984) and Hekmat *et al.* (1986) describe several options.

One residential ventilation option is balanced mechanical ventilation with heat recovery in an air-to-air heat exchanger or heat-recovery ventilator. In this technique, roughly equal amounts of air are supplied to and exhausted from the building. In the heat exchanger, heat, and in some cases moisture, is transferred between the incoming and outgoing airstreams to reduce the energy consumption associated with the mechanical ventilation rate. Performance concerns with these systems include the balance between the supply and exhaust airflow rates, leakage between the two airstreams, biological contamination of wet surfaces, frosting within the devices, and air distribution.

Another option is whole building exhaust ventilation with supply through intentional and controllable openings in the building envelope. In this technique, energy can be recovered from the exhaust airstream with a heat pump to supplement domestic hot water or space heating.

CALCULATING AIR EXCHANGE

Techniques for calculating building air exchange rates have improved in recent years (Liddament and Allen 1983). This section describes several calculation procedures, ranging from simple estimation techniques to more physical models. The air exchange rate of a building cannot be reliably estimated from the building's construction or age, or from a simple visual inspection. Some measurement is necessary, such as a pressurization test of envelope airtightness or a detailed quantification of the leakage sites and their magnitude. As discussed in the section on driving mechanisms, it is straightforward to calculate the air exchange rate of a building given the location and leakage function for every opening in the building envelope and between major building zones, the wind pressure coefficients over the building envelope, and any mechanical ventilation airflow rates. These inputs are generally unavailable for all except very simple structures or extremely well-studied buildings. Therefore, assumptions as to their values must be made. The appropriateness of these assumptions determines the accuracy of predictions of air exchange rates.

Empirical Models

These models of residential infiltration are based on statistical fits of infiltration rate data for specific houses. They use pressurization test results to account for house airtightness, and take the form of simple relations between infiltration rate, an airtightness rating, and, in most cases, weather conditions. The models account for envelope infiltration only and do not deal with intentional ventilation. In one approach, the air changes per hour at 0.20 in. of water from a pressurization test, is simply divided by a constant approximately equal to 20 (Sherman 1987). This estimate does not account for the effects of weather on air exchange. Empirical models that do account for weather effects have been developed by Reeves *et al.* (1979), Kronvall (1980a), and Shaw (1981). The latter two models account for building air leakage using the values of c and n from Equation (16). The only other inputs required are the wind speed and temperature difference. Such empirical models predict infiltration rates very well in the houses from which they were developed; they do not, however, work as well in other houses due to the building-specific nature of leakage distribution, wind pressure, and internal partitioning. Persily and Linteris (1983) and Persily (1986) show comparisons between measured and predicted house infiltration rates for these and other models. The average differences between measurements and predictions are generally on the order of 40% for both models, although individual predictions can be off by 100% or more.

Single-Cell Models

Several procedures have been developed to calculate building air exchange rates that are based on physical models of the building interior as a single zone. These models are only appropriate to buildings with no internal resistance to airflow, and are therefore inappropriate to large, multizone buildings. Models of this type have been developed by the Institute of Gas Technology (IGT), (Cole *et al.* 1980), the Building Research Establishment (Warren and Webb 1980), and the Lawrence Berkeley Laboratory (LBL) (Sherman and Grimsrud 1980). The LBL model has been widely used and serves as the basis of the calculation procedure described in the residential calculation example section that follows. It uses pressurization test results to characterize house air leakage through the effective leakage area at 0.016 in. of water ($C_D = 1$). In addition to the wind speed and temperature difference, the user must input information on leakage distribution, a shielding parameter, and a local terrain coefficient. The predictive accuracy of this model can be very good when the inputs are well known for the building in question (Sherman and Modera 1986), but the predictions are not as accurate when the inputs are not known. All these single-zone models are sensitive to the values of the inputs, and it is generally quite difficult to determine appropriate values. These models have exhibited average errors on the order of 40% for many measurements on groups of houses and can be off by 100% in individual cases (Persily 1986).

Multicell Models

Multicell models of air exchange treat buildings as a series of interconnected zones and assume that the air within each zone is well mixed. Several such models have been developed by Etheridge and Alexander (1980), Liddament and Allen (1983), Walton (1984), and Herrlin (1985). They are all based on a mass balance for each zone of the building. These mass balances are used to solve for an interior static pressure within the building by requiring that the inflows and outflows for each zone balance to zero. These models require the user to input a location and leakage function for every opening in the building envelope and relevant interior partitions, a value for the wind pressure coefficient C_p at the location of each building envelope leakage site, and any mechanical ventilation airflow rates. This information is difficult to obtain for a building. Wind pressure coefficient data in the literature, air leakage measurement results from the building or its components, and air-leakage data from the literature, can be used. These models not only solve for whole building and individual zone air exchange rates, but also determine airflow rates between zones. These interzone airflow rates are useful for predicting pollutant transport within buildings and smoke movement patterns in the event of a fire. Multizone models have the advantage of providing a physically correct determination of airflow rates, and very complex representations of buildings can be easily modeled on personal computers.

Residential Calculation Example

This section presents a simple, single-zone approach to calculating air infiltration rates in houses based on the LBL model. The approach requires the effective leakage area at 0.016 in. of water, which can be obtained from a whole building pressurization test. If a test value is not available, the data in Table 3 can be used to estimate the leakage area of the building. The values in the tables present results in terms of leakage area per component. Per unit component means either per component, per unit surface area, or per unit length of crack, whichever is appropriate. To obtain the building's total leakage area, multiply the overall dimensions or number of occurrences of each building component by the appropriate table entry. The sum of the resulting products is the total building leakage area.

Table 5 gives the result of an example calculation of the effective leakage area of a residence. Each leakage component is identified in the first column, and described in the second. The length, area, or number of components is in the third column. The fourth column contains the leakage area per unit component, from Table 3 and the fifth contains the total leakage area associated with that component. The sum of the terms in the last column is the total leakage area of the building, in this case 131 in.^{2}.

Using the effective leakage area, the airflow rate due to infiltration is calculated according to:

$$Q = L\,(A\,\Delta t + B\,v^2)^{1/2} \qquad (33)$$

where

Q = airflow rate, cfm
L = effective leakage area, in.^{2}
A = stack coefficient, (cfm)^2(in.)$^{-4}$(F)$^{-1}$
Δt = average indoor-outdoor temperature difference for the time interval of the calculation, °F
B = wind coefficient, (cfm)^2(in.)$^{-4}$(mph)$^{-2}$
v = average wind speed measured at a local weather station for the time interval of interest, mph

The infiltration rate of the building is obtained by dividing Q by the building volume. The value of B depends on the local shielding class of the building. Table 6 lists five different shielding classes.

Table 7 presents values of A for one, two, and three-story houses. Table 8 presents values of B for one, two, and three-story houses in shielding classes one through five. In calculating the values in Tables 7 and 8, several assumptions are made regarding inputs to the LBL model. They include terrain classes of 3 (rural area with scattered obstacles), R = 0.5 (half of the building leakage in the walls), and X = 0 (equal amounts of leakage in the floor and ceiling). The height of the one, two, and three-story buildings are 8, 16, and 24 ft, respectively.

Example 1. Estimate the infiltration at design conditions for a two-story house in Lincoln, Nebraska. The house has an effective leakage area of 77 in.^{2}, a volume of 12,000 ft^3, and is surrounded by a thick hedge (Shielding Class 3).

Solution: The 97.5% design temperature for Lincoln is −2°F. Assume a design wind speed of 15 mph. Choosing A (0.0313) from Table 6 and B (0.0086) from Table 8, the airflow rate due to infiltration is:

$$Q = 77\,[(0.0313)70) + (0.0086 \times 15^2)]^{0.5}$$
$$= 156 \text{ cfm} = 9384 \text{ ft}^3/\text{h}$$

The infiltration rate I is equal to Q divided by the building volume:

$$I = (9384 \text{ ft}^3/\text{h}) / (12{,}000 \text{ ft}^3)$$
$$\text{or } I = 0.78 \text{ ach}$$

Example 2. Calculate the average infiltration during a one-week period in January for a one-story house in Portland, Oregon. During this period, the average indoor-outdoor temperature difference is 30°F and the average wind speed is 6 mph.

The house has a volume of 9,000 ft^3, an effective leakage area of 107 in.^{2}, and is located in an area with buildings and trees within 30 ft in most directions (Shielding Class 4).

Solution: The airflow rate due to infiltration is:

$$Q = 107[(0.0156) \times 30) + (0.0039 \times 6^2)]^{1/2}$$
$$= 83.5 \text{ cfm} = 5{,}000 \text{ ft}^3/\text{h}$$

The infiltration rate is therefore:

$$I = (5{,}000 \text{ ft}^3/\text{h}) / (9{,}000 \text{ ft}^3)$$
$$I = 0.56 \text{ ach}$$

Table 5 Example of Calculation of Building Leakage Area Based on Component Leakage Areas

Component	Description	D_i	L_i	$D_i L_i$
Sills	Uncaulked	142 ft	0.19 in^2/ft	27.0
Electrical outlets		20	0.08 in^2 ea	1.6
Windows Framing	Sliding	141 ft^2 / 141 ft^2	0.057 in^2/ft^2 / 0.024 in^2/ft^2	11.4
Exterior doors Framing	Single	62 ft^2 / 62 ft^2	0.11 in^2/ft^2 / 0.024 in^2/ft^2	8.3
Fireplace	Without damper	1	54.0 in^2 ea	54.0
Penetrations	Pipes	7	0.93 in^2 ea	6.5
Heating Ducts	Ducts untaped, in basement	1	22.0 in^2 ea	22.0
			Calculated Building Leakage Area, L =	131 in^2

Table 6 Local Shielding Classes

Class	Description
1	No obstructions or local shielding
2	Light local shielding; few obstructions, a few trees, or small shed
3	Moderate local shielding; some obstructions within two house heights, thick hedge, solid fence, or one neighboring house
4	Heavy shielding; obstructions around most of perimeter, buildings or trees within 30 ft in most directions; typical suburban shielding
5	Very heavy shielding; large obstructions surrounding perimeter within two house heights; typical downtown shielding.

Table 7 Stack Coefficient, A

	House Height (stories)		
	One	Two	Three
Stack coefficient	0.0156	0.0313	0.0471

Table 8 Wind Coefficient, B

Shielding Class	House Height (stories) One	Two	Three
1	0.0119	0.0157	0.0184
2	0.0092	0.0121	0.0143
3	0.0065	0.0086	0.0101
4	0.0039	0.0051	0.0060
5	0.0012	0.0016	0.0018

This estimate of infiltration is an estimate of the average value over the one-week interval for which the weather information was obtained and averaged.

Example 3. Estimate the average infiltration over the heating season in a two-story house with a volume of 11,000 ft^3 and the leakage area calculated in Table 5 (131 in.^{2}). The house is located on a lot with several large trees but no other close buildings (Shielding Class 3). The average wind speed during the heating season is 7 mph, while the average indoor-outdoor temperature difference is 36°F.

Solution: From Equation (33) the airflow rate due to infiltration is:

$$Q = 131\ [(0.0313 \times 36) + (0.0086 \times 7^2)]^{1/2}$$
$$= 163 \text{ cfm} = 9780 \text{ ft}^3/\text{h}$$

The average infiltration is therefore:

$$I = 9780 \text{ ft}^3/\text{h} \div 11{,}000 \text{ ft}^3$$
$$I = 0.89 \text{ ach}$$

Place

Again, this estimate is valid for the time interval used in computing the average values of the weather variables. Therefore, since the temperature difference and wind speed are values averaged over the entire heating season, the infiltration estimate is valid over the same interval.

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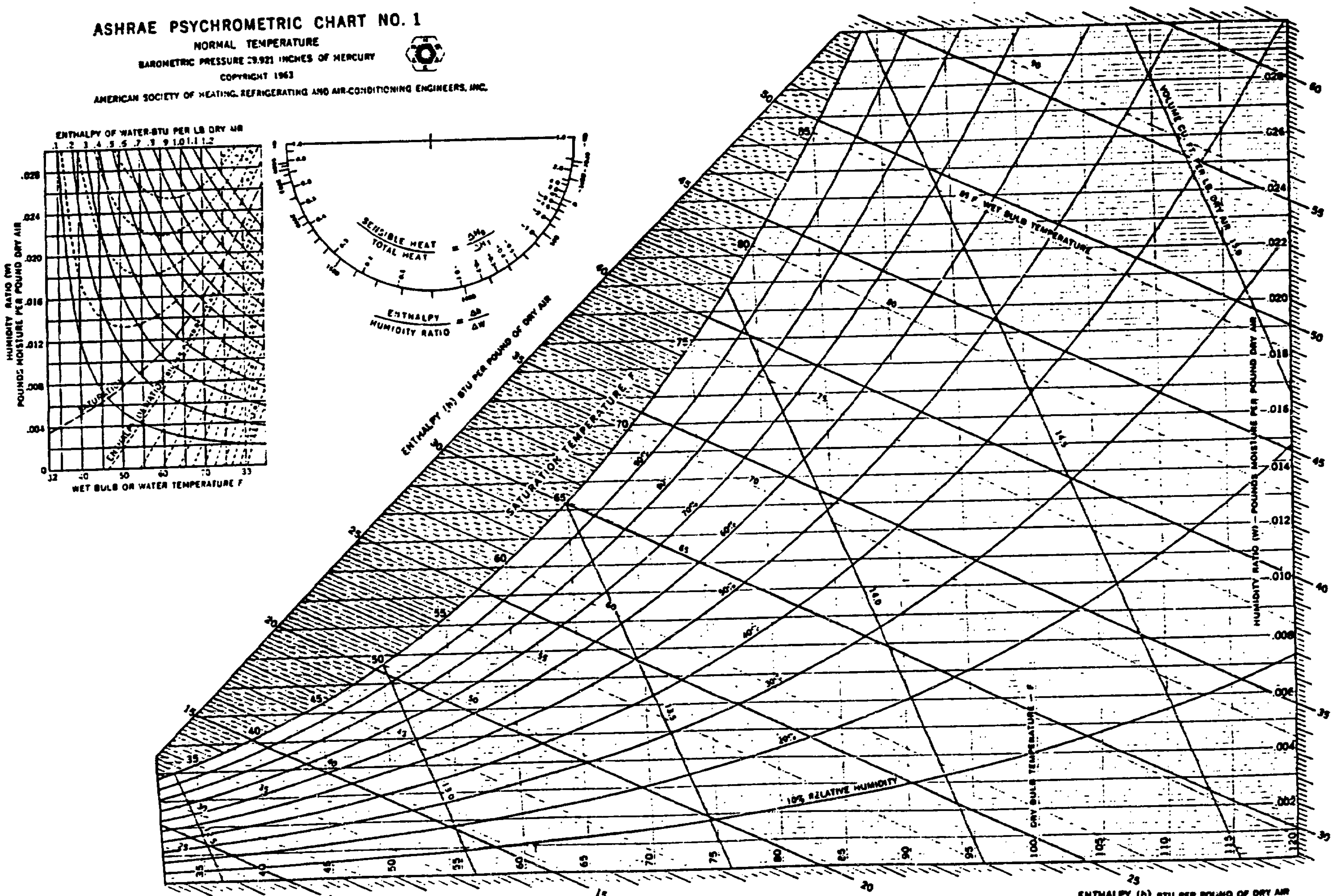

Fig. A.7 Psychrometric chart.

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Table 2. Typical Performance Values (for halocarbon compressors)

Compressor Size and Type		Operating Conditions and Refrigerants			
		Evap. Temp. -40 F Cond. Temp. 105 F Suction Gas 65 F Subcooling 0 F R-12, 500, 502	Evap. Temp. 0 F Cond. Temp. 110 F Suction Gas 65 F Subcooling 0 F R-12, 500, 502	Evap. Temp. 40 F Cond. Temp. 105 F Suction Gas 55 F Subcooling 0 F R-12, 500, 502, 22	Evap. Temp. -45 F Cond. Temp. 130 F Suction Gas 65 F Subcooling 0 F R-12, 500, 502, 22
Large, over 25 hp	Open	0.21 tons/hp (0.99 W/W)	0.40 tons/hp (1.89 W/W)	0.91 tons/hp (4.29 W/W)	0.74 tons/hp (3.49 W/W)
	Hermetic	3.15 Btu/h per W (0.92 W/W)	6.00 Btu/h per W (1.76 W/W)	13.12 Btu/h per W (3.85 W/W)	9.90 Btu/h per W (2.90 W/W)
Medium, 5 to 25 hp	Open	0.19 tons/hp (0.90 W/W)	0.37 tons/hp (1.74 W/W)	0.83 tons/hp (3.91 W/W)	0.65 tons/hp (3.06 W/W)
	Hermetic	2.89 Btu/h per W (0.85 W/W)	5.60 Btu/h per W (1.64 W/W)	12.04 Btu/h per W (3.53 W/W)	9.15 Btu/h per W (2.68 W/W)
Small, under 5 hp	Open	------	------	------	------
	Hermetic	------	3.80 Btu/h per W (1.11 W/W)	10.14 Btu/h per W (2.97 W/W)	7.76 Btu/h per W (2.27 W/W)

Example conversion, ton/hp to W/W: $\frac{0.4\ \text{ton}}{\text{hp}} \times \frac{12000\ \text{Btu}}{\text{ton}\cdot\text{hr}} \times \frac{\text{hp}}{0.746\ \text{kW}} \times \frac{\text{kWh}}{3413\ \text{Btu}} = 1.89\ \frac{\text{W}}{\text{W}}$

Example conversion, Btu/W·hr to W/W: $\frac{6.0\ \text{Btu}}{\text{W}\cdot\text{hr}} \times \frac{\text{kWh}}{3413\ \text{Btu}} \times \frac{1000\ \text{W}}{\text{kW}} = 1.76\ \frac{\text{W}}{\text{W}}$

Appendix D. ACRONYMS

A/C	air conditioning
AHU	air handling unit
Btu	British thermal unit
CHW	chilled water
cfm	cubic feet per minute
CNW	condenser water
DHW	domestic hot water
DX	direct expansion
EMCS	Energy Monitoring and Control System
ESA	Energy Savings Analysis computer program
°F	Fahrenheit
hr(s)	hour(s)
HVAC	Heating, Ventilating, and Air Conditioning
HW	hot water
kW	kilowatt
kWh	kilowatt-hour
lb	pound
MBtu	million Btu
MCWB	mean coincident wet bulb temperature
OA	outside air
yr	year

Appendix E. SELECTED REFERENCES

Total Energy Management
NEMA (National Electrical Manufacturers Association)

Handbook of Air Conditioning System Design ©1965
Carrier Air Conditioning Company

Local Climatological Data, Annual Summary with Comparative Data
National Climatic Data Center (NCDC)
Federal Building
Asheville, North Carolina 28801

Energy Conservation with Comfort
Honeywell

1983 ASHRAE Handbook--Equipment

1989 ASHRAE Handbook--Fundamentals
American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

Appendix F. BLANK FORMS

ESA Program Field Survey Data Sheets

GROUP

NOTE - UNITS OF MEASURE: Area = ft^2, Temperature = °F

See Appendix A for explanation of terms.

GROUP DATA

Group Desc ______________________

Location ______________________

Buildings in Group ______________________

Sketch project layout - locations, distances between buildings, important features, etc.

Page ________ of ________

GROUP	BUILDING

BUILDING DATA (1/3)

Building Hours of Operation: 0100-0800 0900-1600 1700-2400 Other ______ ____________

Heating Fuel Type: ____

Sketch Building - Locate Zones, Windows, Doors, etc.

Page ________ of ________

GROUP	BUILDING

ZONE DATA

ZONE ID ____	Systems Serving Zone ____
Location ____	Nominal hours/week occupied <OH> ____
Function ____	Warmup time before occupancy (hr) <WU> ____
Floor Area ____	Low Temperature Limit <LTL> ____
Occupied Summer Setpoint <SSP> ____	Summer Setpoint Reset <SSPR> ____ (SSPR ≤ AST-SSP)
Occupied Winter Setpoint <WSP> ____	
Days/Week Heating Equipment Operation <Dh> ____	Winter Setpoint Reset <WSPR> ____
Days/Week Cooling Equipment Operation <Dc> ____	(WSPR ≤ WSP-AWT, ≤ WSP-LTL)

SPECIAL REQUIREMENTS

Can ventilation be shut down for duty cycling? (Y/N) ____ For what % time? <DCST> ____

Can ventilation be shut down for demand limiting? (Y/N) ____ For what % time? <DLST> ____

Can ventilation be shut down during unoccupied hours? (Y/N) ____

If yes, what is the required OA purge time before occupancy? <PT> ____

REMARKS

ZONE DATA

ZONE ID ____	Systems Serving Zone ____
Location ____	Nominal hours/week occupied <OH> ____
Function ____	Warmup time before occupancy (hr) <WU> ____
Floor Area ____	Low Temperature Limit <LTL> ____
Occupied Summer Setpoint <SSP> ____	Summer Setpoint Reset <SSPR> ____ (SSPR ≤ AST-SSP)
Occupied Winter Setpoint <WSP> ____	
Days/Week Heating Equipment Operation <Dh> ____	Winter Setpoint Reset <WSPR> ____
Days/Week Cooling Equipment Operation <Dc> ____	(WSPR ≤ WSP-AWT, ≤ WSP-LTL)

SPECIAL REQUIREMENTS

Can ventilation be shut down for duty cycling? (Y/N) ____ For what % time? <DCST> ____

Can ventilation be shut down for demand limiting? (Y/N) ____ For what % time? <DLST> ____

Can ventilation be shut down during unoccupied hours? (Y/N) ____

If yes, what is the required OA purge time before occupancy? <PT> ____

REMARKS

GROUP	BUILDING

BUILDING DATA (2/3)

WALLS, EXTERIOR COMPONENTS	R-VALUES	SKETCH CROSS SECTION
Outside Air Film	________	
1. ____________	________	
2. ____________	________	
3. ____________	________	
4. ____________	________	
5. ____________	________	
6. ____________	________	
7. ____________	________	
Inside Air Film	________	
TOTAL R VALUE	________	
$1/R = <U_{wall}> =$	________	

ROOF COMPONENTS	R-VALUES	SKETCH CROSS SECTION
Outside Air Film	________	
1. ____________	________	
2. ____________	________	
3. ____________	________	
4. ____________	________	
5. ____________	________	
6. ____________	________	
7. ____________	________	
Inside Air Film	________	
TOTAL R VALUE	________	
$1/R = <U_{roof}> =$	________	

No. of Floors (above ground) ________	Calculated Total Areas (above ground):
Avg. Floor to Floor Height ________	Walls, gross ________
No. of Basement Levels ________	Windows $<A_{window}>$ ________
Gross Floor Area <Af> ________	Doors $<A_{door}>$ ________
Roof Area $<A_{roof}>$ ________	Other ________
Estimated total bldg. air infiltration (cfm) <I> ________	Walls, net $<A_{wall,\ net}>$ ________

Page ________ of ________

GROUP	BUILDING

BUILDING DATA (3/3)

WINDOW TYPE ______	R-VALUE ______	$<U_{window}>$ ______
WINDOW TYPE ______	R-VALUE ______	$<U_{window}>$ ______
WINDOW TYPE ______	R-VALUE ______	$<U_{window}>$ ______
DOOR TYPE ______	R-VALUE ______	$<U_{door}>$ ______
DOOR TYPE ______	R-VALUE ______	$<U_{door}>$ ______
DOOR TYPE ______	R-VALUE ______	$<U_{door}>$ ______
OTHER ______	R-VALUE ______	$<U_{other}>$ ______
OTHER ______	R-VALUE ______	$<U_{other}>$ ______
OTHER ______	R-VALUE ______	$<U_{other}>$ ______

$$U_oA_o = U_{wall} \times A_{wall,\ net} + U_{window} \times A_{window} + U_{door} \times A_{door} + U_{roof} \times A_{roof}$$

Remarks - Note air leaks, structural damage, broken/defective windows, fit of windows and doors, vents that remain open, etc.

GROUP	BUILDING	SYSTEM

Applicable Systems

A. Single Zone AHU	D. Multi-zone AHU	G. Two Pipe Fan Coil Unit
B. Terminal Reheat AHU	E. Single Zone DX-A/C	H. Four Pipe Fan Coil Unit
C. Variable Volume AHU	F. Multi-zone DX-A/C	

System Desc ______________________ Zones Served ______________________

Location ______________________ Total Area Served <Az> ______________________

System Efficiency <HSE> ______________________ Unit Supplying Heating Energy ______________________

Reheat Coil Reset <RHR> ______________________ Heating Energy Fuel Source ______________________

Present percent of OA used (decimal) <POA> ________ Unit Supplying Cooling Energy ______________________

Energy Used/Ton Refrigeration <CPT> ________ Cooling Energy Fuel Source ______________________

CURRENT OPERATING SCHEDULE

Hours/Week Heating System <Hh> ______________

Hours/Week at WSP <Hwsp> ______________

Hours/Week Cooling System <Hc> ______________

Hours/Week at SSP <Hssp> ______________

PROPOSED OPERATING SCHEDULE

Hours/Week Heating System <HhEMCS> ______________

Hours/Week Cooling System <HcEMCS> ______________

Can system be shut down when zone(s) unoccupied? (Y/N) ______________

FAN DATA Function	<CFM>	<HP>	PUMP DATA Function	<HP>	AUX DATA Function	<HP>
Supply Air						
Return Air						

MULTI-ZONE DATA

Percent of air passing through Hot Deck <Phd> ________ Summer Hot Deck Reset <SHDR> ______________

Percent of air passing through Cold Deck <Pcd> ________ Winter Hot Deck Reset <WHDR> ______________

Operating Hours/Week Dual Deck <Hhc> ________ Summer Cold Deck Reset <SCDR> ______________

MAX/MIN ZONE DATA			
	<WSP> ________	<SSP> ________	<WU> ________
	<LTL> ________	<WSPR> ________	<Dh> ________
	<OH> ________	<SSPR> ________	<Dc> ________
	<DCST> ________	<DLST> ________	<PT> ________

GROUP	BUILDING	SYSTEM

Applicable Systems

I. Electric Unit Heater	M. Direct Fired Boiler	Q. Hot Water Radiation
J. Electric Radiation	N. Steam Unit Heater	U. HTHW/Steam Converter
K. Heating/Ventilating Unit	O. Hot Water Unit Heater	V. HTHW/HW Converter
L. Direct Fired Furnace	P. Steam Radiation	

System Desc ______

Location ______

Electric Heater Power Rating (Kw) <PWR> ______

System Efficiency <HSE> ______

Present percent of OA used (decimal) <POA> ______

Zones Served ______

Total Area Served <Az> ______

Unit Supplying Heating Energy ______

Heating Energy Fuel Source ______

Max Total Input Rating (Btu/hr) <CAP> ______

Heating system Efficiency Increase <OAEI> ______

CURRENT OPERATING SCHEDULE

Hours/Week Heating System <Hh> ______

Hours/Week at WSP <Hwsp> ______

PROPOSED OPERATING SCHEDULE

Hours/Week Heating System <HhEMCS> ______

FAN DATA Function	<CFM>	<HP>	PUMP DATA Function	<HP>	AUX DATA Function	<HP>
Supply Air						
Return Air						

MAX/MIN ZONE DATA	<WSP> ______	<OH> ______	<WU> ______
	<LTL> ______	<WSPR> ______	<Dh> ______
	<DCST> ______	<DLST> ______	

REMARKS

GROUP	BUILDING	SYSTEM

Applicable Systems

R. Steam Boiler

S. Hot Water Boiler

System Desc ____________________

Zones Served ____________________

Location ____________________

Heating Energy Fuel Type ____________________

Efficiency Increase when Changing Boilers <BCEI> ____________________

Max Total Capacity (Btu/hr) <CAP> ____________________

Heating system Efficiency Increase <OAEI> ____________________

System Availability (days/year) ____________________

System Efficiency <HSE> ____________________

REMARKS

GROUP	BUILDING	SYSTEM

Applicable Systems

W. Water Cooled DX Compressor
X. Air Cooled DX Compressor
Y. Air Cooled Chiller
Z. Water Cooled Chiller

System Desc ____________________
Location ____________________
Chiller Type: (1) Centrifugal (2) Absorption (3) Reciprocal (4) Screw Comp
Centrifugal Chiller Motor HP <CHP> ____________
Centrifugal Chiller Motor Efficiency <CME> ____________
System Availability (days/year) ____________

Zones Served ____________________
Energy Used/Ton Refrigeration <CPT> ____________
Chiller Capacity (tons) <TON> ____________
Present Condenser Water Temperature <PCWT> ______
Is the condenser fan continuous or cycling? ____________
Chiller water temperature reset <CWTR> ____________

Efficiency increase when changing chillers <CSEI> ____________________
Can the centrifugal chiller be shut down for demand limiting? (Y/N) ______ For what % time? <SDT> ______
Can the centrifugal chiller capacity be stepped down for demand limiting? (Y/N) ______ By what %? <SDC> ______

CURRENT OPERATING SCHEDULE
Hours/Week Cooling System <Hc> ____________

PROPOSED OPERATING SCHEDULE
Hours/Week Cooling System <HcEMCS> ____________

FAN DATA Function	<HP>	PUMP DATA Function	<HP>

REMARKS

Page ________ of ________

GROUP	BUILDING	SYSTEM

Applicable Systems

AA. Lighting Control

System Desc ______________________ Zones Served ______________________

Location ______________________ Total Wattage <TC_L> ______________________

CURRENT OPERATING SCHEDULE

Hours/Week Lighting System <H_L> ______________

PROPOSED OPERATING SCHEDULE

Hours/Week Lighting System <H_LEMCS> ______________

REMARKS

GROUP	BUILDING	SYSTEM

PROJECT REMARKS

Page ________ of ________

ESA Program Screen Data Input Forms

GROUP	BUILDING

Climate

Variable Description	Symbol	Value	Units
Avg Entering Condenser Water Temperature	ACWT	________	°F
Annual Number of Days for Morning Warmup	ANDW	________	days/year
Average Summer Temperature	AST	________	°F
Average Winter Temperature	AWT	________	°F
Cooling Full-Load Hours	CFLH	________	hrs/year
Heating Full-Load Hours	HFLH	________	hrs/year
Weeks of Cooling	WKC	________	wks/year
Weeks of Heating	WKH	________	wks/year
Average Outside Air Enthalpy	OAE	________	Btu/lb
Percent Run Time	PRT	________	percent

Building

[ ] Check here if Chiller uses steam.

Heating Fuel Type: ** choice list

Variable Description	Symbol	Value	Units
Heating Value of Fuel	HV	________	Btu/________
Mod Comb Thermal Transmittance	UoAo	________	Btu/hr•°F
Total Air Infiltration	I	________	cfm
Gross Floor Area	Af	________	ft²
Building Thermal Transmission	BTT	***	Btu/hr•ft²•°F

** Heating Fuel Type:

Electricity (at the meter)	3413 Btu/kWh
Electricity (at point of generation)	11,600 Btu/kWh
Fuel oil, distillate #2	138,690 Btu/gallon
Fuel oil, residual #6	149,690 Btu/gallon
Natural gas (methane)	1,025 Btu/cf
Propane, gas	2500 Btu/cf
Propane, liquid	91,500 Btu/gallon
Bituminous coal	26,260,000 Btu/short ton
Steam (at point of consumption)	1000 Btu/lb
Steam (at point of generation)	1390 Btu/lb

*** BTT is calculated by the program.

Page ________ of ________

GROUP	BUILDING	SYSTEM

Applicable Systems

A. Single Zone AHU	D. Multi-zone AHU	G. Two Pipe Fan Coil Unit
B. Terminal Reheat AHU	E. Single Zone DX-A/C	H. Four Pipe Fan Coil Unit
C. Variable Volume AHU	F. Multi-zone DX-A/C	

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Area of zone	Az	______	ft^2
Winter thermostat setpoint, occupied	WSP	______	°F
Low temperature limit	LTL	______	°F
Heating operation without EMCS	Hh	______	hours/week
Heating operation with EMCS	HhEMCS	______	hours/week
Heating system efficiency	HSE	______	decimal
Summer thermostat setpoint, occupied	SSP	______	°F
Return air enthalpy when unoccupied	RAE	______	Btu/lb
Cooling operation without EMCS	Hc	______	hours/week
Cooling operation with EMCS	HcEMCS	______	hours/week
Cooling energy consumption per ton	CPT	______	****
Supply air capacity	CFM	______	cfm
Present fraction of outside air used	POA	______	decimal
Equipment motor horsepower	HP	______	hp
Equipment motor load factor	L	______	decimal
Zone occupied hours	OH	______	hours/week
Duty cycling shutdown time	DCST	______	percent
Demand limiting shed time	DLST	______	percent
Winter thermostat setpoint reset	WSPR	______	°F
Winter setpoint equipment operation	Hwsp	______	hours/week
Summer thermostat setpoint reset	SSPR	______	°F
Summer setpoint equipment operation	Hssp	______	hours/week

**** kW/ton or lb-ton/hr

Page ________ of ________

GROUP	BUILDING	SYSTEM

Applicable Systems

A. Single Zone AHU	D. Multi-zone AHU	G. Two Pipe Fan Coil Unit
B. Terminal Reheat AHU	E. Single Zone DX-A/C	H. Four Pipe Fan Coil Unit
C. Variable Volume AHU	F. Multi-zone DX-A/C	

System Data Entry (continued)

Shutdown system when bldg unoccupied?		______	Y or N
Present warmup time before occupancy	WU	______	hours/day
Heating equipment operating schedule	Dh	______	days/week
Cooling equipment operating schedule	Dc	______	•F
Purge time before occupancy	PT	______	•F
Fraction of total air thru hot deck	Phd	______	decimal
Hot/cold deck equipment operation	Hhc	______	hours/week
Summer hot deck reset	SHDR	______	•F
Winter hot deck reset	WHDR	______	•F
Fraction of total air thru cold deck	Pcd	______	decimal
Summer cold deck reset	SCDR	______	•F
Reheat cooling coil discharge reset	RHR	______	•F
Optimum start/stop heating savings		______	MBtu
Optimum start/stop htg-vent savings		______	MBtu
Optimum start/stop htg aux savings		______	kWh
Optimum start/stop cooling savings		______	MBtu or kWh
Optimum start/stop clg-vent savings		______	MBtu or kWh
Optimum start/stop clg aux saving		______	kWh
Economizer cooling savings		______	MBtu or kWh

GROUP	BUILDING	SYSTEM

Applicable Systems

A. Single Zone AHU	D. Multi-zone AHU	G. Two Pipe Fan Coil Unit
B. Terminal Reheat AHU	E. Single Zone DX-A/C	H. Four Pipe Fan Coil Unit
C. Variable Volume AHU	F. Multi-zone DX-A/C	

System Data Entry (continued)

Scheduled start/stop labor savings		______	mh
Optimum start/stop labor savings		______	mh
Duty cycling labor savings		______	mh
Demand limiting labor savings		______	mh
Day/night setback labor savings		______	mh
Economizer labor savings		______	mh
Vent/recirc labor savings		______	mh
Hot deck/cold deck labor savings		______	mh
Reheat coil labor savings		______	mh
Run time recording labor savings		______	mh
Safety alarm labor savings		______	mh

System Strategy Selection and Annual Savings

[ ] Scheduled Start/Stop	[ ] Run Time Recording
[ ] Optimum Start/Stop	[ ] Safety Alarm
[ ] Duty Cycling	
[ ] Demand Limiting	
[ ] Day/Night Setback	
[ ] Economizer	
[ ] Ventilation/Recirculation	
[ ] Hot/Cold Deck Reset	
[ ] Reheat Coil Reset	

GROUP	BUILDING	SYSTEM

Applicable Systems

I. Electric Unit Heater	L. Direct Fired Furnace	T. Steam/Hot Water Converter
J. Electric Radiation	M. Direct Fired Boiler	V. HTHW/Hot Water Converter
K. Heating/Ventilating Unit	Q. Hot Water Radiation	

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Area of zone	Az	______	ft²
Winter thermostat setpoint, occupied	WSP	______	°F
Low temperature limit	LTL	______	°F
Heating operation without EMCS	Hh	______	hours/week
Heating operation with EMCS	HhEMCS	______	hours/week
Heating system efficiency	HSE	______	decimal
Supply air capacity	CFM	______	cfm
Present fraction of outside air used	POA	______	decimal
Equipment motor horsepower	HP	______	hp
Equipment motor load factor	L	______	decimal
Zone occupied hours	OH	______	hours/week
Power rating of resistance unit	PWR	______	Kw
Duty cycling shutdown time	DCST	______	percent
Demand limiting shed time	DLST	______	percent
Winter thermostat setpoint reset	WSPR	______	°F
Winter setpoint equipment operation	Hwsp	______	hours/week
Shutdown system when bldg unoccupied?		______	Y or N
Present warmup time before occupancy	WU	______	hours/day
Heating equipment operating schedule	Dh	______	days/week
Purge time before occupancy	PT	______	minutes
Total input rating of boilers	CAP	______	Btu/hr
Heating system efficiency increase	OAEI	______	decimal

GROUP	BUILDING	SYSTEM

Applicable Systems

I. Electric Unit Heater	L. Direct Fired Furnace	T. Steam/Hot Water Converter
J. Electric Radiation	M. Direct Fired Boiler	V. HTHW/Hot Water Converter
K. Heating/Ventilating Unit	Q. Hot Water Radiation	

System Data Entry (continued)

Optimum start/stop cooling savings		______	MBtu or kWh
Optimum start/stop clg-vent savings		______	MBtu or kWh
Optimum start/stop clg aux savings		______	kWh
Scheduled start/stop labor savings		______	mh
Optimum start/stop labor savings		______	mh
Duty cycling labor savings		______	mh
Demand limiting labor savings		______	mh
Day/night setback labor savings		______	mh
Vent/recirc labor savings		______	mh
HW outside air reset labor savings		______	mh
Run time recording labor savings		______	mh
Safety alarm labor savings		______	mh

System Strategy Selection and Annual Savings

[ ] Scheduled Start/Stop [ ] Optimum Start/Stop [ ] Duty Cycling [ ] Demand Limiting [ ] Day/Night Setback [ ] Ventilation/Recirculation [ ] HW OA Reset [ ] Run Time Recording [ ] Safety Alarm	

GROUP	BUILDING	SYSTEM

Applicable Systems

N. Steam Unit Heater	P. Steam Radiation
O. Hot Water Unit Heater	U. HTHW/Steam Converter

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Area of zone	Az	_______	ft²
Winter thermostat setpoint, occupied	WSP	_______	°F
Low temperature limit	LTL	_______	°F
Winter thermostat set point reset	WSPR	_______	°F
Winter setpoint equipment operation	Hwsp	_______	hours/week
Heating system efficiency	HSE	_______	decimal
Day/night setback labor savings		_______	mh
Run time recording labor savings		_______	mh
Safety alarm labor savings		_______	mh

System Strategy Selection and Annual Savings

[ ] Day/Night Setback [ ] Run Time Recording [ ] Safety Alarm	

GROUP	BUILDING	SYSTEM

Applicable Systems

R. Steam Boiler	S. Hot Water Boiler

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Heating system efficiency	HSE	______	decimal
Total input rating of boilers	CAP	______	Btu/hr
Boiler conversion efficiency increase	BCEI	______	decimal
Heating system efficiency increase	OAEI	______	decimal
Steam boiler selection labor savings		______	mh
HW boiler selection labor savings		______	mh
HW Outside air reset labor savings		______	mh
Run time recording labor savings		______	mh
Safety alarm labor savings		______	mh

System Strategy Selection and Annual Savings

[ ] Steam Boiler Selection [ ] HW Boiler Selection [ ] HW OA Reset [ ] Run Time Recording [ ] Safety Alarm	

GROUP	BUILDING	SYSTEM

Applicable Systems

W. Water Cooled DX Compressor	Y. Air Cooled Chiller
X. Air Cooled DX Compressor	Z. Water Cooled Chiller

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Cooling operation without EMCS	Hc	______	hours/week
Cooling operation with EMCS	HcEMCS	______	hours/week
Cooling energy consumption per ton	CPT	______	**
Equipment motor horsepower	HP	______	hp
Equipment motor load factor	L	______	decimal
Zone occupied hours	OH	______	hours/wk
Duty cycling shutdown time	DCST	______	percent
Demand limiting shed time	DLST	______	percent
Total capacity of chillers	TON	______	tons
Chiller selection efficiency increase	CSEI	______	percent
Chiller water temperature reset	CWTR	______	°F
Chiller type		______	choice list ***
Present condenser water temperature	PCWT	______	°F
Present fan operation		______	choice list ****
Centrifugal chiller motor horsepower	CHP	______	hp
Centrifugal chiller motor efficiency	CME	______	decimal
Step down percent of capacity	SDC	______	percent
Step down percent of time	SDT	______	percent
Optimum start/stop cooling savings		______	MBtu or kWh
Optimum start/stop clg-vent savings		______	MBtu or kWh
Optimum start/stop clg aux savings		______	kWh

** kW/ton or lb-ton/hr

*** Chiller types: (1) Centrifugal (2) Absorbtion (3) Reciprocal (4) Screw Comp

**** Present fan operation (1) Fan now cycles (0) Fan now runs continuously, but will cycle

GROUP	BUILDING	SYSTEM

Applicable Systems

W. Water Cooled DX Compressor	Y. Air Cooled Chiller
X. Air Cooled DX Compressor	Z. Water Cooled Chiller

System Data Entry (continued)

Scheduled start/stop labor savings		________	mh
Optimum start/stop labor savings		________	mh
Duty cycling labor savings		________	mh
Demand limiting labor savings		________	mh
Chiller selection labor savings		________	mh
Chiller water reset labor savings		________	mh
Condenser water reset labor savings		________	mh
Chiller demand limit labor savings		________	mh
Run time recording labor savings		________	mh
Safety alarm labor savings		________	mh

System Strategy Selection and Annual Savings

[ ] Scheduled Start/Stop	
[ ] Optimum Start/Stop	
[ ] Duty Cycling	
[ ] Demand Limiting	
[ ] Chiller Selection	
[ ] Chiller Water Temp Reset	
[ ] Condenser Water Temp Reset	
[ ] Chiller Demand Limit	
[ ] Run Time Recording	[ ] Safety Alarm

GROUP	BUILDING	SYSTEM

Applicable Systems

AA. Lighting Control

System Data Entry

System Description:

Variable Description	Symbol	Value	Units
Total power consumption of lights	TCI	______	kW
Lighting operation without EMCS	HI	______	hours/week
Lighting operation with EMCS	HIEMCS	______	hours/week
Lighting control labor savings		______	mh
Run time recording labor savings		______	mh
Safety alarm labor savings		______	mh

System Strategy Selection and Annual Savings

[ ] Lighting Control [ ] Run Time Recording [ ] Safety Alarm	

Factor Summary

System Savings Summary

GROUP	BUILDING

Factor Summary

Ref	Factor		Calculated Value
4-4.1	ACWT	=	°F
4-4.2	ANDW	=	days/year
4-4.3	AST	=	°F
4-4.4	AWT	=	°F
4-4.5	CFLH	=	hrs/year
4-4.6	HFLH	=	hrs/year
4-4.7	WKH	=	weeks/year
4-4.7	WKC	=	weeks/year
4-4.8	[illegible]AE	=	Btu/lb
4-4.9	PRT	=	%
4-4.10	UoAo I Af BTT	= = = =	Btu/hr·°F cfm ft^2 Btu/hr·ft^2·°F

Page ________ of ________

GROUP	BUILDING	SYSTEM

System Savings Summary

Ref	Strategy	Savings MBtu/yr	kWh/yr	kW	Mh/yr
5-4.1	Scheduled Start/Stop				
5-4.2	Optimum Start/Stop				
5-4.3	Duty Cycling				
5-4.4	Demand Limiting				
5-4.5	Day/Night Setback				
5-4.6	OA Dry Bulb Economizer				
5-4.7	Ventilation and Recirculation				
5-4.8	Hot Deck/Cold Deck Temperature Reset				
5-4.9	Reheat Coil Reset				
5-4.10	Boiler Selection				
5-4.11	Hot Water Outside Air Reset				
5-4.12	Chiller Selection				
5-4.13	Chiller Water Temperature Reset				
5-4.14	Condenser Water Temperature Reset				
5-4.15	Chiller Demand Limit				
5-4.16	Lighting Control				
5-4.17	Run Time Recording				
5-4.18	Safety Alarm				
	MBtu Sub Total				
Fuel Type	+ HV (See Appendix A)				
Notes -	TOTALS		kWh/yr	kW	Mh/yr

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NAVSEASYSCOM / CODE 56Z4, WASHINGTON, DC
NAVSECGRUACT / CODE 31 PWO, FPO AA
NAVSECGRUACT / PWO (CODE 40), EDZELL, SCOTLAND, FPO AE
NAVSECGRUACT / PWO, CHESAPEAKE, VA
NAVSECGRUACT / PWO, FPO AP
NAVSECSTA / CODE 60, WASHINGTON, DC
NAVSHIPYD / CODE 308.05, PEARL HARBOR, HI
NAVSHIPYD / CODE 450, BREMERTON, WA
NAVSHIPYD / CODE 450.4, CHARLESTON, SC
NAVSHIPYD / CODE 453, CHARLESTON, SC

NAVSHIPYD / CODE 903, LONG BEACH, CA
NAVSHIPYD / MARE IS, CODE 202.13, VALLEJO, CA
NAVSHIPYD / MARE IS, CODE 421, VALLEJO, CA
NAVSHIPYD / MARE IS, CODE 440, VALLEJO, CA
NAVSHIPYD / MARE IS, CODE 457, VALLEJO, CA
NAVSHIPYD / PWO CODE 400, CHARLESTON, SC
NAVSTA / CODE 0DA2, SAN DIEGO, CA
NAVSTA / CODE 4216, MAYPORT, FL
NAVSTA / CODE 423, NORFOLK, VA
NAVSTA PUGET SOUND / CODE 922, EVERETT, WA
NAVSUBBAS / AMES, NEW LONDON, CT
NAVSUPCEN / CODE 700A.1, NORFOLK, VA
NAVSUPPACT / CO, NAPLES, ITALY, FPO AE
NAVSUPPACT / PWO, NAPLES, ITALY, FPO AE
NAVSUPPFAC / CONTRACT ASSISTANT, FPO AP
NAVSUPSYSCOM / CODE 0622, WASHINGTON, DC
NAVTECHTRACEN / UPSON, PENSACOLA, FL
NAVTRASTA / PWO, ORLANDO, FL
NAVWPNSTA EARLE / PWD (LENGYEL), COLTS NECK, NJ
NAWS / ROICC NIEMI, POINT MUGU, CA
NETC / 40E, NEWPORT, RI
NFESC / CODE ESC20, PORT HUENEME, CA
NORDA / CODE 352, NSTL, MS
NORTHDIV CONTRACTS OFFICE / ROICC, PORTSMOUTH, NH
NORTHNAVFACENGCOM / CODE 04, LESTER, PA
NORTHNAVFACENGCOM / CODE 164, LESTER, PA
NORTHNAVFACENGCOM / CODE 203/FB, LESTER, PA
NORTHNAVFACENGCOM / CODE 408AF, LESTER, PA
NRL / CODE 2511, WASHINGTON, DC
NRL / CODE 2530.1, WASHINGTON, DC
NRL / CODE 4670, WASHINGTON, DC
NSC / CODE 43, OAKLAND, CA
NSGA / UNIT 35167, APO AP
NSGA NORTHWEST / CODE 40A, CHESAPEAKE, VA
NUSC DET / CODE 5202 (SCHADY), NEW LONDON, CT
OICC / ENGR AND CONST DEPT, APO AE
PACIFIC MARINE TECH / M. WAGNER, DUVALL, WA
PACNAVFACENGCOM / CODE 1112, PEARL HARBOR, HI
PWC / CODE 101, GREAT LAKES, IL
PWC / CODE 123C, SAN DIEGO, CA
PWC / CODE 423/KJF, NORFOLK, VA
PWC / CODE 610, SAN DIEGO, CA
PWC / CODE 612, PEARL HARBOR, HI
PWC / CODE 612, PEARL HARBOR, HI
PWC ENVIRONMENTAL GROUP / CODE 951, OAKLAND, CA
PWC/ CODE 400, WASHINGTON, DC
RADIANT EQUIP CO / AMO, SAN ANDREAS, CA
SAN DIEGO PORT / AUSTIN, SAN DIEGO, CA
SEATTLE PORT / DAVE VAN VLEET, SEATTLE, WA
SEATTLE PORT / DAVID TORSETH, SEATTLE, WA

SOUTHNAVFACENGCOM / CODE 04A, NORTH CHARLESTON, SC
SOUTHNAVFACENGCOM / CODE 1611TF, NORTH CHARLESTON, SC
SOUTHNAVFACENGCOM / CODE 162, NORTH CHARLESTON, SC
SOUTHNAVFACENGCOM / CODE 1621, NORTH CHARLESTON, SC
SOUTHNAVFACENGCOM / CODE 403 (S. HULL), NORTH CHARLESTON, SC
SOUTHNAVFACENGCOM / CODE 404 (REL), NORTH CHARLESTON, SC
SOUTHNAVFACENGCOM / CODE 4051, NORTH CHARLESTON, SC
SPCC / CODE 082, MECHANICSBURG, PA
TECHNOLOGY UTILIZATION / K WILLINGER, WASHINGTON, DC
TENNESSEE TECH UNIV / T. LUNDY, COOKEVILLE, TN
TEXAS A&M UNIV / ENERGY TRNG DIV (DONALDSON), HOUSTON, TX
TRIDENT TRAINING FAC / ANDERSON, KINGS BAY, GA
TRIKEFFAC / BANGOR, CODE 213, BREMERTON, WA
UNIV OF ALABAMA / DIR FAC MGMT (BAKER), BIRMINGHAM, AL
UNIV OF ALABAMA / PRUITT, BIRMINGHAM, AL
UNIV OF FLORIDA / ARCH DEPT (MORGAN), GAINESVILLE, FL
UNIV OF NEW HAMPSHIRE / ELEC ENGRG DEPT, DURHAM, NH
UNIV OF NEW MEXICO / NMERI (FALK), ALBUQUERQUE, NM
UNIV OF PENNSYLVANIA / INST ENVIRON MEDICINE, PHILADELPHIA, PA
UNIV OF PITTSBURGH / HOLLAND, PITTSBURGH, PA
US DEPT OF INTERIOR / BLM, ENGRG DIV (730), WASHINGTON, DC
USAEH / DAIM-FDF-U, FT BELVOIR, VA
USCG / G-ECV-4B, WASHINGTON, DC
USN / CAPT COLIN M JONES, HONOLULU, HI
USPS / BILL POWELL, ARLINGTON, VA
VENTURA COUNTY / DEPUTY PW DIR, VENTURA, CA
WESTNAVFACENGCOM / CODE 162, SAN BRUNO, CA
WESTNAVFACENGCOM / CODE 405, SAN BRUNO, CA
WESTNAVFACENGCOM / ROICC, SILVERDALE, WA