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ACI WEB SESSIONS

American Concrete Institute®
Advancing concrete knowledge

The Art of Thermal Mass Modeling for Energy Conservation in Buildings, Part 1

ACI Spring 2012 Convention
March 18 – 21, Dallas, TX

ACI WEB SESSIONS

Dr. Jeffrey S. Haberl, P.E., is a Professor of Architecture and Associate Department Head for Research at Texas A&M University. He is an ASHRAE Fellow and IPMVP Fellow, and obtained his B.S., M.S., and Ph.D. degrees from the University of Colorado at Boulder, followed by post-doctoral research at Princeton University's Center for Energy and Environmental Studies. He is a Registered Engineer in the State of Texas, has authored or co-authored 48 publications, 23 books or book chapters, 180 conference proceedings, 228 reports and holds numerous U.S. patents. He is currently the chairman of ASHRAE TC 4.7, and was the chairman for ASHRAE's Performance Metric Protocols committee. He has received numerous awards and recognition including a Boulder County Energy Conservation Award, two USDOE innovative research awards, a 1990 GSA Design Award, a 1992 National Endowment of the Arts Federal Design Award, and a 2001 ASHRAE Distinguished Service Award.

ACI WEB SESSIONS

THERMAL MASS MODELING HOW WE GOT TO WHERE WE ARE TODAY

Jeff S. Haberl, Ph.D., P.E., FASHRAE

Juan-Carlos Baltazar, Ph.D.

Chunliu Mao

March 2012
Dallas

Energy Systems Laboratory
Texas Engineering Experiment Station
Texas A&M University System

Distribution/Age of U.S. Commercial Buildings

New York City has thousands of new / old buildings
Same pattern for other U.S. cities, such as Chicago

- *How are we going to create new high-performance buildings?*
- *Can we create high-performance buildings from existing buildings?*
- *What design methods were used to design existing buildings?*
- *How did the methods treat thermal mass ?*

Source: http://juliancarr.com/files/2009/10/new_york_from_empire_state_building.jpg
http://thebesttraveldestinations.com/willis-tower-sears-tower-chicago-usa/

History: Building Energy Load Calculation Methods

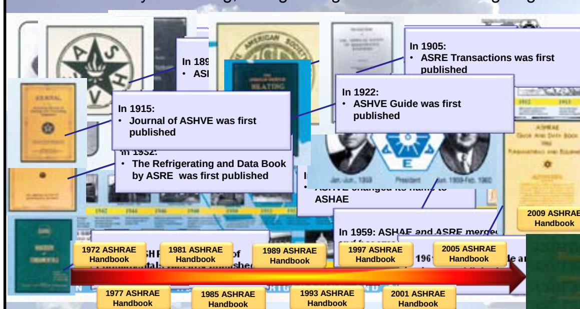
What methods are currently used to size the building systems and analyze building energy use?

- Peak Load Calculation Methods (R. Chapter 12; C. Chapter 18)
  - Peak Heating Load Calculation
  - Peak Cooling Load
- Annual Building Energy Use Calculation Methods (Chapter 19, Page 19.4)
  - Simulation
  - Forward
  - Inverse (Data-Driven)

- *How did the methods evolve from 1900 to Present?*
- *How did these methods treat the use of thermal mass?*

History of ASHVE, ASRE, ASHAE, ASHRAE

American Society of Heating, Refrigerating and Air-Conditioning Engineers



Source: http://www.ashrae.org/about-ashrae/ashrae-and-industry-history

History: Pre 1900 - Important Developments

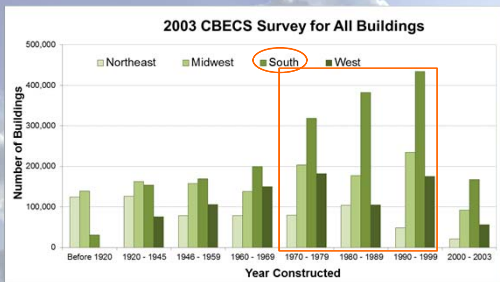
- Thermodynamics (Carnot, Joule, Thompson/Kelvin, Clausius, Gibbs)
- Heat Transfer (Newton, Fourier)
- Weather-reporting (Hooke, Le Roy)
- Electricity (Edison, Testla)
- Materiel Science
  - Insulation
  - Metals, welding
- Inventions
  - Thermometer/Thermostat
  - Humidity Measurements
  - Barometer
  - Vacuum Pump
  - Refrigeration
  - Air Handling Units, centrifugal fans
  - Steam engine
  - Steam heating system

Distribution/Age of U.S. Commercial Buildings

CBECS Survey: U.S. Census Regions and Divisions

Source: http://www.eia.gov/emeu/cbecs/census_maps.html

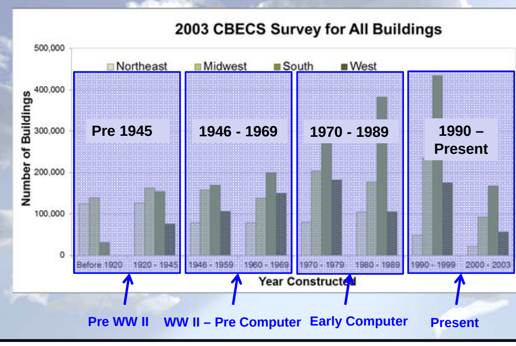
Distribution/Age of U.S. Commercial Buildings



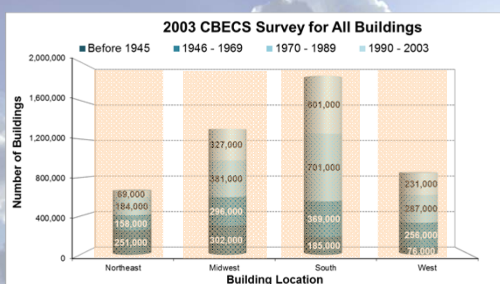
Observations:

- 52.3% of the buildings were built from1970 to1999
- 39.7% of the buildings were built in South

Distribution/Age of U.S. Commercial Buildings



Distribution/Age of U.S. Commercial Buildings



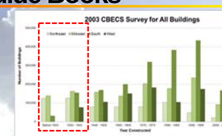
Observations:

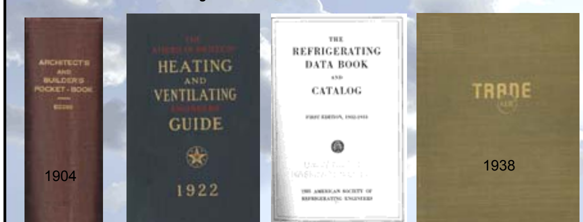
- 39.7%of buildings were built in South
- 27.9% in Midwest, 18.2% in West and 14.2% in Northeast

History: Pre 1945 – Guide Books

Guide Books:

1904 Frank E. *Kidder Architect's and Builder's Handbook*
1922 *ASHVE Guide*
1932 *The Refrigerating Data Book* by ASRE
1938 *Trane Air Conditioning Manual*





History: Pre 1945 – Important Developments

Computer Development:

- ❑ 1822 - 1832 Charles Babbage and Joseph Clement produced the first Difference Engine
- ❑ 1815-1852: first computer programmer: Ada Lovelace
- ❑ In 1930, differential analyzer available
- ❑ In 1946, first large scale electronic digital computer available - ENIAC

Source: http://www.computerhistory.org/babbage/engines/;
http://www.computerhistory.org/babbage/adalovelace/;
http://www.computerhistory.org/revolution/analog-computers/3/143/311;
K. Kempf "Historical Monograph: Electronic Computers Within the Ordnance Corps," U.S. Army Photo

History: Pre 1945 – Important Developments

In 1848, Dr. John Gorrie invented his "ice machine"

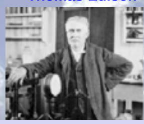
Figure 3: A model of Gorrie's ice machine from the John Gorrie Museum in Apalachicola, Fla.

Source: http://www.ashrae.org/File%20Library/docLib/Public/200362795143_326.pdf

History: Pre 1945 – Important Developments

In the late 1880s, "War of the Currents" began between Edison and Tesla

Thomas Edison V.S. **Nikola Tesla**



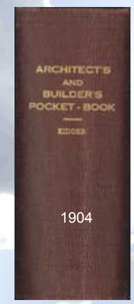

Before that, air handling systems were steam-driven!


Source: http://staff.fcps.net/rroyster/war.htm

History: Pre 1945 – Heating Load Calculation

Frank E. Kidder Architect's and Builder's Handbook
Peak Load Calculation:
Heat Loss Calculation

In 1904, "There appears to be ***no rule*** by which the architect can determine the size of the furnace that should be used to heat a given building other than by ***using the tables*** given by the various manufacturers……"



Source: Architect's and Builder's Handbook in 1904 by Frank E. Kidder

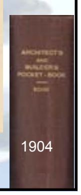
History: Pre 1945 – Heating Load Calculation
1904: Radiators

DATA FOR EXCELSIOR INDIRECT STEAM-RADIATORS.

Heating Surface → Size of Room → Size of Radiators

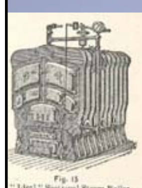
Heating Surface.	Cold-air Sup-						Ratio of 1 to 35.	Ratio of 1 to 40.
Sq. Ft.	Sq. In.	Inches.	Sq. In.	Inches.	Inches.	Cu. Ft.	Cu. Ft.	Cu. Ft.
24	36	6.8	48	4×12	8×8	720	840	960
36	54	8.3	72	8×12	9×12	1080	1260	1440
48	72	9.6	96	8×12	10×14	1440	1680	1920
60	90	10.0	120	12×12	12×15	1800	2100	2400
72	108	11.7	144	12×12	12×19	2160	2520	2880
84	126	12.7	168	12×16	14×22	2520	2940	3360
96	144	13.5	192	12×16	14×24	2880	3360	3840
108	162	14.4	226	12×20	16×20	3240	3780	4320
120	180	15.2	240	12×20	16×24	3600	4200	4800
132	198	15.9	264	12×24	20×20	3960	4620	5280
144	216	16.6	288	12×24	20×24	4320	5040	5760

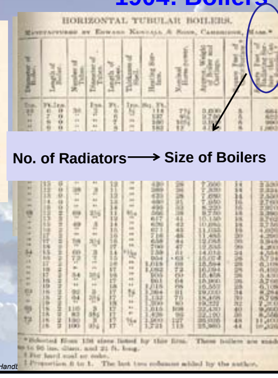
Fig. 12
Sterling Indirect Radiator.

Source: Architect's and Builder's Handbook in 1904 by Frank E. Kidder

History: Pre 1945 – Heating Load Calculation
1904: Boilers






Source: Architect's and Builder's Hand...

History: Pre 1945 – Cooling Load Calculation

1903 New York Stock Exchange, Board Room – earliest air conditioning system be designed and operated for comfort (Engr: Alfred Wolff, Henry Torrance, Carbondale Machine Co.)

- 3 – 100 ton absorption chillers
- Used steam from cogeneration system
- 42 distribution boxes in the ornate ceiling provided cooling to the exchange floor.
- Remained in operation for 20 years.
- Similar to systems Wolff designed for Cornell Medical College (1899), Hanover Nat'l Bank (1903).
- Based on Prof. Hermann Rietschel's 1894 *"Guide to Calculating and Design of Ventilating and Heating Installations"*, Berlin Royal Institute of Technology.

History: Pre 1945 – Cooling Load Calculation

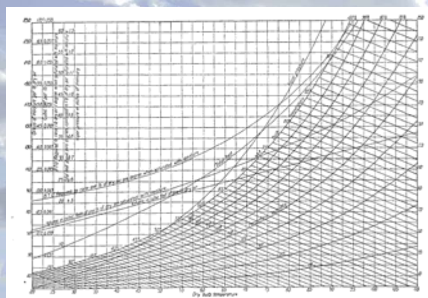
1904 St. Louis World's Fair – Missouri State building at the Louisiana Purchase Exposition. First demonstration of air conditioning to be experienced by large numbers of people (Engr: Gardner T. Voorhees).

- 1,000 seat auditorium
- 35,000 CFM cooled by direct expansion air conditioning

"The practical application of mechanical refrigeration to air cooling for the purpose of personal comfort, no doubt has a field,…and the day is at hand, or soon will be, when the modern office building…will be incomplete without a mechanical air cooling plant." Editors, Ice and Refrigeration, 1905.

History: Pre 1945 – Heating Load Calculation

- In 1905, Stuart Cramer first used the term ***"air conditioning"*** for treating air in textile mills in N.C.
- In 1908 Willis Carrier developed his ***Psychrometric chart & formula***

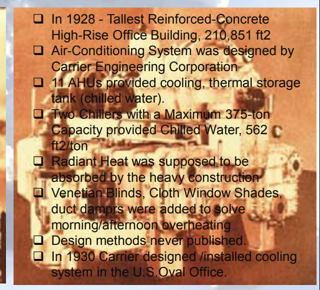


Source: Carrier, W., 1911. Rational Psychrometric Formulae: their relation to the problems of meteorology and of air conditioning. ASME Transactions, Vol.33

History: Pre 1945 – Cooling Load Calculation

In 1928, the first high-rise air-conditioned office building in U.S. was built in San Antonio "The Milam Building"

The Milam Building



- In 1928 - Tallest Reinforced-Concrete High-Rise Office Building, 210,851 ft2
- Air-Conditioning System was designed by Carrier Engineering Corporation
- 11 AHUs provided cooling, thermal storage tank (chilled water).
- Two Chillers with a Maximum 375-ton Capacity provided Chilled Water, 562 ft2/ton
- Radiant Heat was supposed to be absorbed by the heavy construction
- Venetian Blinds, Cloth Window Shades, duct dampers were added to solve morning/afternoon overheating
- Design methods never published.
- In 1930 Carrier designed /installed cooling system in the U.S Oval Office.

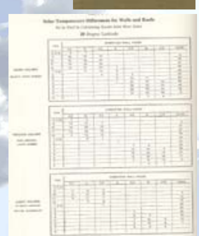
Original Carrier Centrifugal Refrigeration Unit

Source:www.alamoashrae.org/database/articles/Milam_Building_Report.pdf

History: Pre 1945 – Cooling Load Calculation

In 1938, TRANE Company Published its first design manual, called "TRANE Air-Conditioning Design Manual" and Provided a ***load estimate sheet*** for engineers to use.

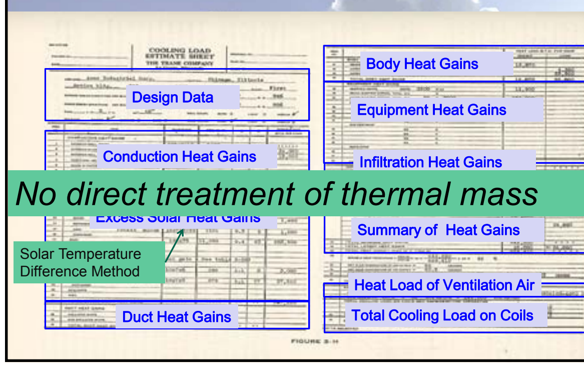
1938



Source: 1938 TRANE Air Conditioning Manual

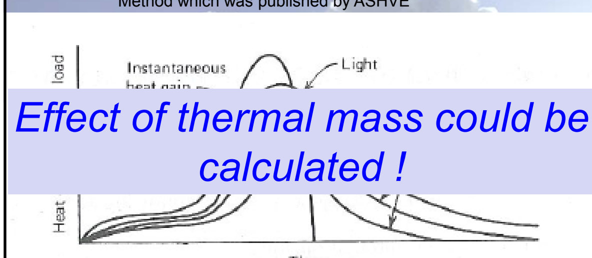
History: Pre 1945 – Load Estimate Sheet

TRANE Air-Conditioning Manual



History: Pre 1945 – Cooling Load Calculation

In 1944, Mackey and Wright developed Sol-Air Temperature Method which was published by ASHVE



Effect of thermal mass could be calculated !

Inside Surface Temperature $t_o = t_i + \frac{0.606(t_m - t_i)}{0.856 + L/k} + \sum_{n=1} \lambda_n t_n \cos(15n\theta - \alpha_n - \phi_n)$

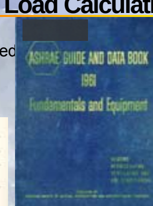
There is time lag for the peak and a reduction in amplitude.

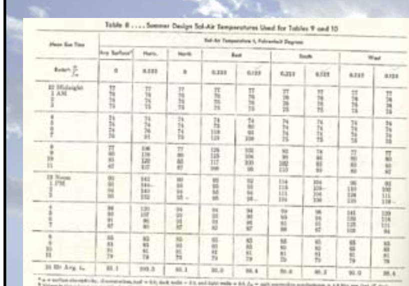
Phase angle

Source: Mackey, C.O., Wright, L.T., 1944. Periodic Heat Flow-Homogeneous Walls or Roofs. ASHVE Journal; Mcquiston, Parker, 1994. Heating, Ventilating and Air-Conditioning Analysis and Design, Fourth Edition

History: Pre 1945 – Cooling Load Calculation

Sol-Air Temperature Method:
Later sol-air temperature method was tabulated in the ***ASHRAE Guide and Data Book – Fundamentals and Equipment***

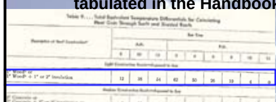




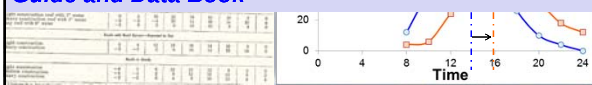
Source: 1961 ASHRAE Guide and Data Book – Fundamentals and Equipment

History: Pre 1945 – Cooling Load Calculation

ASHRAE Guide and Data Book – Fundamentals and Equipment – **Total Equivalent Temperature Difference** tabulated in the Handbook



The equations in Mackey and Wright and ASHRAE original test data were then tabulated in the ASHRAE Guide and Data Book



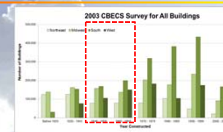
There is time lag for the peak and a reduction in amplitude.

Source: 1961 ASHRAE Guide and Data Book – Fundamentals and Equipment

History: 1946 – 1969 Guide Books

Guide Books:

1955 *TRANE Air Conditioning Design Manual*
1960 *Handbook of Air Conditioning System Design by Carrier*
ASHRAE Guide and Data Book
ASHRAE Handbook of Fundamentals



History: 1946 – 1969 Cooling Load Calculation

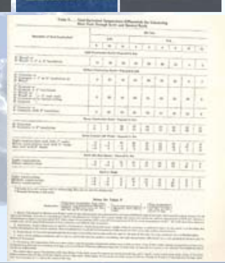
Peak Cooling Load Calculation

- TETD/TA Method:
  - ✓ **T**otal **E**quivalent **T**emperature **D**ifference/**T**ime **A**veraging Method
  - ✓ Original Outlined by Stewart in 1948 based on Mackey & Wright
  - ✓ TETD table added to **ASHRAE Guide and Data Book** in 1951

Basic heat gain equation for exterior surface:

$$q = UA(TETD)$$

Thermal mass is in the TETD

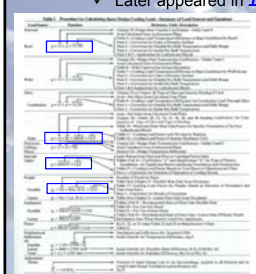


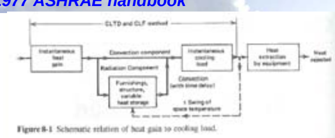
Source: 1961 ASHRAE Guide and Data Book- Fundamentals and Equipment

History: 1970 – 1989 Cooling Load Calculation

In 1977 TETD/TA replaced with CLTD/CLF Method:

- ✓ First developed by Rudoy and Duran in 1974 and published in *ASHRAE Transactions*
- ✓ Later appeared in ***1977 ASHRAE handbook***





Roof, Wall : $q = UA(CLTD)$

Glass, solar:

$$q = A \times SC \times SHGF \times CLF$$

Internal Lights:

$$q = INPUT \times CLF$$

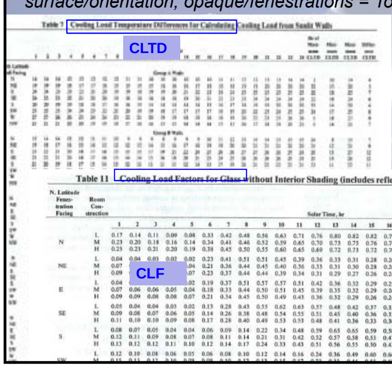
People:

$$q = No. \times Sens.H.G. \times CLF$$

Source: 1977 ASHRAE Handbook; Mcquiston and Parker, Heating and Ventilating, and Air Conditioning Analysis and Design

History: 1970 – 1989 Cooling Load Calculation

CLTD/CLF permitted hourly estimations of heat gain for each surface/orientation, opaque/fenestrations = Totalized by zone.



*Original CLTD/CLF GRP 158 method contained 36 roofs, 96 walls based on **transfer function method** (TFM), 40 N latitude, July 21st.*

Later modified by Sowell (RP-359), who classified 200,640 zones

Modified again by McQuiston & Harris 1988 (RP-472) who obtained compact CTFs.

Final modification by Splitler, McQuiston, Lindsey 1993 RP-626, who added CLTD/SCL/CLF method

History: 1946 – 1969 Cooling Load Calculation

Other Developments:

Finite Difference /Finite Element Method :

- ✓ FDM/FEM available, used as a basis for early computer algorithms, very time consuming

Chartered Institution of Building Services Engineers (CIBSE) Admittance Method:

- ✓ Original developed by Loudon in 1968
- ✓ Standard method in UK
- ✓ The concept of ***thermal admittance*** was first introduced by Institution of Heating and Ventilating Engineers (IHVE) Guide in 1970
- ✓ Later selected by CIBSE Guide A

History: 1946 – 1969 Annual Energy Use

Annual Building Energy Use Calculation:

Heating Degree-Day Method:

- ✓ Used to predict heating oil deliveries, crops & snow melt.
- ✓ Manual method was adopted by ASHVE
- ✓ Later appeared in ***ASHRAE Handbooks***

Equivalent Full Load Hours Method :

- ✓ Manual method was adopted by ASHVE
- ✓ Cooling energy requirement calculation
- ✓ Later appeared in ***ASHRAE Handbooks***

Classic Heating Degree-Day Method:

$$E = \frac{H_L \cdot D \cdot 24}{\Delta t \cdot k \cdot V} \cdot C_D$$

Where,
E: fuel or energy consumption for the estimate period, Btu
H_L: design heat loss, including infiltration and ventilation, Btu/h.
D: number of 65°F degree days in the estimation period
Δt: design temperature difference, °F
k: a correction factor that includes the effects of rated full load efficiency, part load performance, oversizing and energy conservation devices
V: heating value of fuel, units consistent with H_L and *E*
C_D: empirical correction factor for heating effect versus 65°F degree-days

Cooling Season Power:

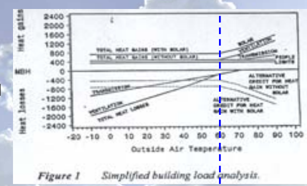
$$Pc = \frac{0.746(bhp)_t(T)H_e}{E}$$

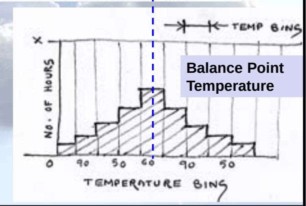
Where,
Pc: cooling season power (kWh)
$(bhp)_t$: brake horsepower per ton
T: maximum refrigeration design load (tons)
H_e: equivalent full-load refrigeration operating time (h)
E: motor efficiency at average load(decimal)

History: 1946 – 1969 Annual Energy Use

Bin Method:

- ✓ Manual method adopted in the mid-1960s
- ✓ Used for heating and/or cooling calculations
- ✓ Annual energy calculation
- ✓ Later appeared in ***1981 ASHRAE Handbook***





History : 1946 – 1969 Computer Developments

- ❑ **In 1957, FORTRAN I complier was developed by John Backus and colleagues at IBM**
- ❑ **During 1958 – Present, FORTRAN II, III, IV, FORTRAN 66, FORTRAN 77, Fortran 90, Fortran 95, Fortran 2003, Fortran 2008 now available**
- ❑ **In 1960, PDP-1, the first commercial mini computer was available**
- ❑ **In 1964, BASIC programming was available**

IBM Mainframe Computer 704 Series

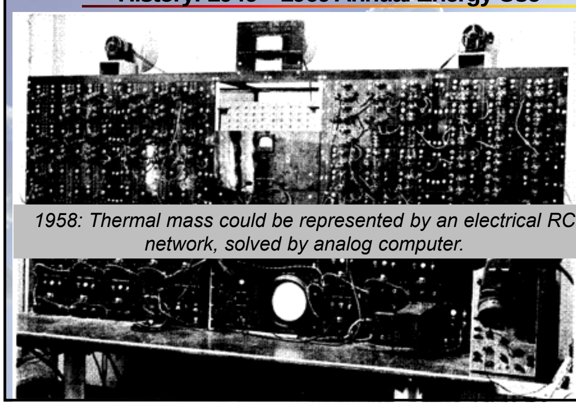
PDP-1 Mini Computer

IBM PC 5150

Today, most whole building simulation programs are still using FORTRAN

Source: http://www.mainframegurukul.com/ibm/what-is/mainframe-computer.html; http://pdp-1.computerhistory.org/pdp-1/index.php?f=showitem&id=26.21&l=1&popupwin=1; http://www-03.ibm.com/ibm/history/exhibits/pc25/pc25_intro.html

History: 1946 – 1969 Annual Energy Use



1958: Thermal mass could be represented by an electrical RC network, solved by analog computer.

History: 1946 – 1969 Annual Energy Use

Thermal Network Method:

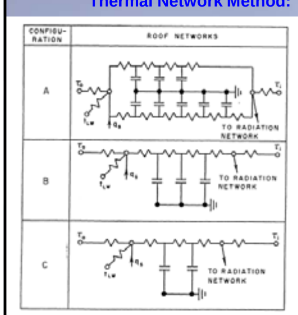
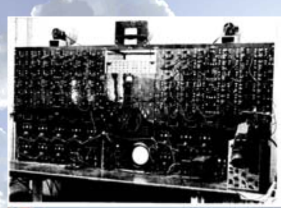


FIG. A-2—CONDUCTION PATH THERMAL NETWORK CONFIGURATIONS FOR ROOF SECTIONS



1950s RC Networks:

- ❑ layered walls, roofs.
- ❑ nodal temperatures to be determined.
- ❑ solved by analog computers (i.e., equiv. electrical circuits).
- ❑ Results viewed on oscilloscope

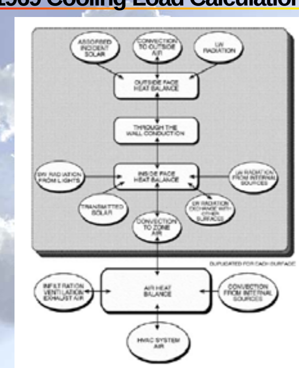
Source: Buchberg, H., 1958. Cooling Load from Thermal Network Solutions. ASHAE Transactions, Vol.64, pp. 111-128

History: 1946 – 1969 Cooling Load Calculation

Computer Algorithms:

Heat Balance Method:

- ✓ Earliest use for general thermal modeling in aerospace and other industries
- ✓ Used in detailed calculation procedures by Buchberg in 1958
- ✓ Later appeared in ***ASHRAE Handbooks***



Schematic of Heat Balance Processes in Zone
(Source: 2009 ASHRAE Handbook)

History : 1946 – 1969 Annual Energy Use

Computer Algorithms:

Thermal Response Factor Method:

- ✓ First developed by Stephenson and Mitalas in 1967, based on 1950s work by Brisken & Reque (1956), Hill (1957).
- ✓ Appeared as part of the *Weighting Factor Methods* in ***ASHRAE Handbook***
- ✓ ***Used for CLTD/CLF tables***

Heat Gain Weighting Factors: $v_0, v_1, v_2, \cdots, w_1, w_2, \ldots$

For each type of heat gain q_θ, cooling load for Q_θ:

$$Q_\theta = v_0 q_\theta + v_1 q_{\theta-1} + \ldots - w_1 Q_{\theta-1} - w_2 Q_{\theta-2} - \ldots$$

Air Temperature Weighting Factors: $g_0, g_1, g_2, \cdots, P_1, P_2, \ldots$

History: 1946 – 1969 Annual Energy Use

Computer Algorithms:

Thermal Mass: Transfer Function Method:

- ✓ First introduced in the 1972 ASHRAE Handbook of Fundamentals
- ✓ Associated Sol-Air Temperature

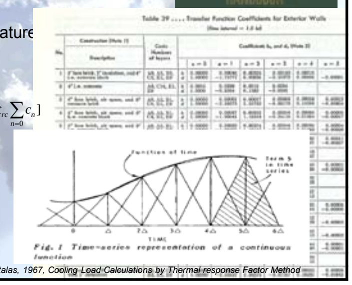
Heat gain through a wall or roof:

$$q_{e,r} = A\left[\sum_{n=0} b_n (t_{e,r-n\Delta}) - \sum_{n=1} d_n \left(\frac{q_{e,r-n\Delta}}{A}\right) - t_{rc} \sum_{n=0} c_n\right]$$

where,

$b_n \; c_n \; d_n$

Transfer function coefficients

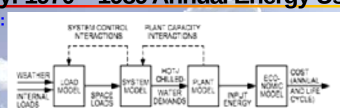


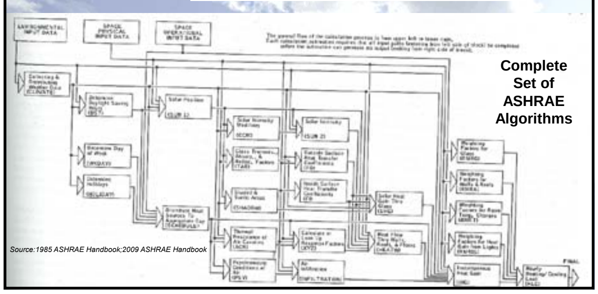
Source: 1972 ASHRAE Handbook; Stephenson and Mitalas, 1967, Cooling Load Calculations by Thermal response Factor Method

History: 1970 – 1989 Annual Energy Use

Computer Algorithms:

DOE-2 (Weighting Factor Method)





Complete Set of ASHRAE Algorithms

Source:1985 ASHRAE Handbook;2009 ASHRAE Handbook

History: 1970 – 1989 Guide Books

Guide Books:

1972 *ASHRAE Handbook of Fundamentals*

1977 *TRANE Air Conditioning Manual*

1975 *ASHRAE Task Group on Energy Requirements:*

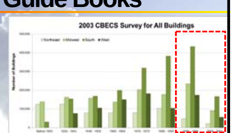
Procedure for Determining Heating and Cooling Loads for Computerizing Energy Calculations

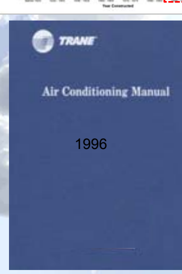
History: 1990 – Present Guide Books

Guide Books:

1993 - 2009 *ASHRAE Handbook of Fundamentals*

1996 *TRANE Air Conditioning Manual*





History: 1990 – Present Cooling Load Calculation

Computer Algorithms:

Radiant Time Series Method:

- ✓ First proposed by Spitler, Fisher and Pedersen in 1997 to replace RF, TETD, CLTD/CLF
- ✓ Later appeared in ***2001 ASHRAE Handbook of Fundamentals***
- ✓ ***Requires software.***

Source: Steven F. Bruning 2012 ASHRAE Journal

Source: 2001 ASHRAE Handbook of Fundamentals

History: 1990 – Present Cooling Load Calculation

Residential Heat Balance (RHB) and Residential Load Factor (RLF) Methods:

- ✓ First introduced by Barnaby, Spitler and Xiao in 2004
- ✓ Both methods used for residential calculations
- ✓ Later appeared in ***2005 ASHRAE Handbook of Fundamentals***

Table 1 RLF Limitations

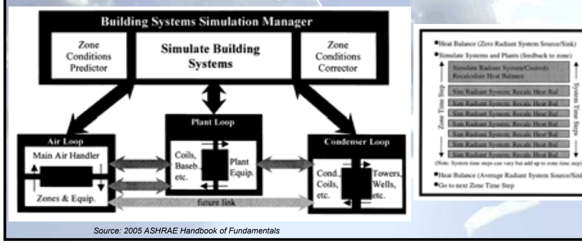
Item	Valid Range	Notes
Latitude	20 to 60°N	Also approximately valid for 20 to 60°S with N and S orientations reversed for southern hemisphere.
Date	July 21	Application must be summer peaking. Buildings in mild climates with significant SE/S/SW glazing may experience maximum cooling load in fall or even winter. Use RHB if local experience indicates this is a possibility.
Elevation	Less than 2000 m	RLF factors assume 50 m elevation. With elevation-corrected C_s, method is acceptably accurate except at very high elevations.
Climate	Warm/hot	Design-day average outdoor temperature assumed to be above indoor design temperature.
Construction	Lightweight residential construction (wood or metal framing, wood or stucco siding)	May be applied to masonry veneer over frame construction; results are conservative. Use RHB for structural masonry or unconventional construction.
Fenestration area	0 to 15% of floor area on any façade, 0 to 30% of floor area total	Spaces with high fenestration fraction should be analyzed with RHB.
Fenestration tilt	Vertical or horizontal	Skylights with tilt less than 30° can be treated as horizontal. Buildings with significant sloped glazing areas should be analyzed with RHB.

Source: 2005 ASHRAE Handbook of Fundamentals

History: 1990 – Present Cooling Load Calculation

Modeling Radiant HVAC Systems Using a Heat Balance Simulation:

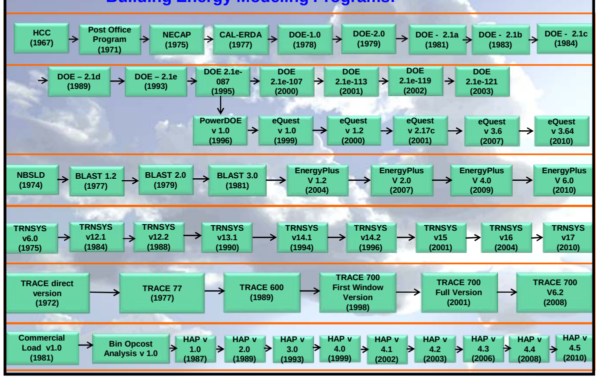
- ✓ First studied by Strand & Pedersen in 1994.
- ✓ First published by Strand in 2001 thesis.
- ✓ Required the development of ***new type of transfer functions.***
- ✓ Now a module in the EnergyPlus program



Source: 2005 ASHRAE Handbook of Fundamentals

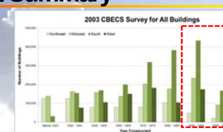
History: 1960 – Present Annual Energy Use

Building Energy Modeling Programs:

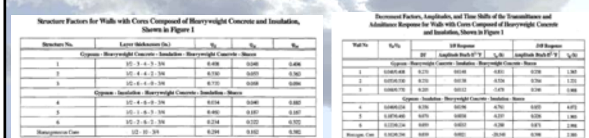


History: 1990 – Present Summary

Thermal Mass Studies (Examples):



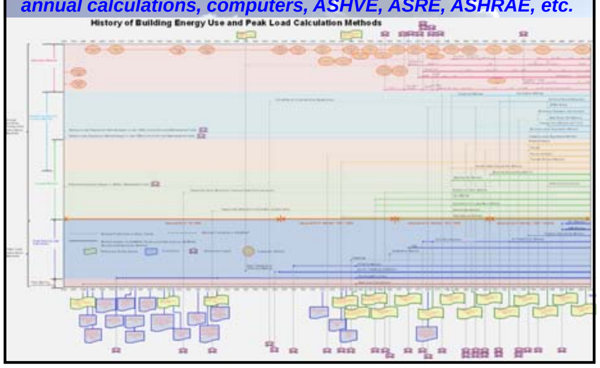
- ❑ *Thermal structure factors* proposed by Kossecka in 1992
- ❑ *Thermal mass factors* introduced by ISO Standards 9869 in 1994
- ❑ Radiant Floor Heating and Cooling systems (Olesen 1997, 2002)



Source: Kossecka, E. and Kosny, J. - "The Effect of Structure of Exterior Walls on the Dynamic Thermal Performance of a Whole Buildings" - Propblemy Projektowania, Realizowania i Eksploatacji Budynków o Niskim Zapotrzebowaniu na Energie - Politechnika Krakowska - IV Conference - Krakow-Mogilany, Poland - October 14-17, 1998.

History: Overview Chart 1900 - Present

Complex history: contributions from 100s of people, load calcs, annual calculations, computers, ASHVE, ASRE, ASHRAE, etc.



Summary:

- Important to consider age of building stock in the U.S. 1900 to present
- History of building load calculation methods tied to:
  - The development of ASHVE, ASRE, ASHAE, ASHRAE.
  - The development of computers, FORTRAN programming language, graphics, etc.
  - Previous developments: thermo, H.T., materials, etc.
- 1904 – 1938 no direct consideration of thermal mass in building heat load calculation.

Summary

- Other considerations:
  - •1848 - Invention of refrigeration
  - •Late 1800s – resolution of A.C. vs D.C. for electric motors
  - •1911 – psychrometric chart (Willis Carrier)
  - •1903 – 1928 air conditioning (NYSE, St. Louis World's Fair, Milam Building, San Antonio, TX)
- 1944 – First use of thermal mass: Mackey and Wright developed sol-air temperature with decrement factor, phase angle.
- 1951 – Total Equivalent Temperature Difference/Time Average (TETD/TA) method developed based on Mackey & Wright

Summary

- 1977 – TETD/TA replaced with Cooling Load Temperature Difference/Cooling Load Factor (CLTD/CLF) Method, later modified to CLTD/SCL/CLF
- Annual Calculation Methods: 1950s - heating degree days, equivalent full load hours, 1970s - bin method, 1980s modified bin method.
- 1944 - 1958 – thermal network models created, based on electrical RC circuits. Solved with analog computers.

Summary

- Computer Algorithms (1960 – present):
  - thermal response factors,
  - transfer functions,
  - weighting factors/ heat balance method,
  - radiant time series,
  - residential heat balance, residential load factors
  - new transfer functions for radiant heating HVAC systems
- Examples of Thermal Mass Studies: thermal mass structural factors, thermal mass factors, radiant floor systems, etc.

Questions?