THERMAL MASS MODELING
HOW WE GOT TO WHERE WE ARE TODAY

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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

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

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?

History: Building Energy Load Calculation Methods

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

**Peak Load Calculation Methods**
- Peak Heating Load Calculation
- Peak Cooling Load Calculation

**Annual Building Energy Use Calculation Methods**
- Simulation
  - Forward
  - Inverse (Data-Driven)

(R. Chapter 12; C. Chapter 18)
What methods are currently used to size the building systems and analyze building energy use?

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
In 1894:
- Hugh Barron, led an effort to establish a new engineering society
In 1894:
- ASHVE was established
History of ASHVE, ASRE, ASHAE, ASHRAE

American Society of Heating, Refrigerating and Air-Conditioning Engineers

In 1895:
- ASHVE Transactions was first published

Source: http://www.ashrae.org/about-ashrae/ashrae-and-industry-history
In 1904:
- ASRE was established
In 1905:
- ASRE Transactions was first published

Source: http://www.ashrae.org/about-ashrae/ashrae-and-industry-history
History of ASHVE, ASRE, ASHAE, ASHRAE

American Society of Heating, Refrigerating and Air-Conditioning Engineers

In 1915:
- Journal of ASHVE was first published

Source: http://www.ashrae.org/about-ashrae/ashrae-and-industry-history
In 1922:
• ASHVE Guide was first published

Source: http://www.ashrae.org/about-ashrae/ashrae-and-industry-history
In 1932:

- The Refrigerating and Data Book by ASRE was first published
In 1954:
• ASHVE changed its name to ASHAE
History of ASHVE, ASRE, ASHAE, ASHRAE

American Society of Heating, Refrigerating and Air-Conditioning Engineers

In 1959: ASHAE and ASRE merged and became ASHRAE

Source: http://www.ashrae.org/about-ashrae/ashrae-and-industry-history
In 1961: ASHRAE Guide and Data book was published

Source: http://www.ashrae.org/about-ashrae/ashrae-and-industry-history
In 1967: ASHRAE Handbook of Fundamentals was first published

Source: http://www.ashrae.org/about-ashrae/ashrae-and-industry-history
Distribution/Age of U.S. Commercial Buildings

CBECS Survey: U.S. Census Regions and Divisions

Source: http://www.eia.gov/emeu/cbecs/census_map.html
Observations:

- 52.3% of the buildings were built from 1970 to 1999
- 39.7% of the buildings were built in South
Distribution/Age of U.S. Commercial Buildings

2003 CBECES Survey for All Buildings

- **Pre 1945**
- **1946 - 1969**
- **1970 - 1989**
- **1990 – Present**

- **Northeast**
- **Midwest**
- **South**
- **West**

Year Constructed:
- Pre WW II
- WW II – Pre Computer
- Early Computer
- Present
Observations:
• 39.7% of buildings were built in South
• 27.9% in Midwest, 18.2% in West and 14.2% in Northeast
52.3% of the buildings were built from 1970 to 1999

Four periods are studied:

- Pre 1945
- 1946 – 1969
- 1970 – 1989
- 1990 – present

39.7% of buildings were built in South, 27.9% in Midwest, 18.2% in west and 14.2% in Northeast
History: Building Energy Load Calculation Methods

2003 CBECSC Survey for All Buildings

Number of Buildings

<table>
<thead>
<tr>
<th>Northeast</th>
<th>Midwest</th>
<th>South</th>
<th>West</th>
</tr>
</thead>
</table>

Year Constructed

- Pre WW II
- WW II – Pre Computer
- Early Computer
- Present
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 – Guide Books

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/
- K. Kempf "Historical Monograph: Electronic Computers Within the Ordnance Corps," U.S. Army Photo
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.

History: Pre 1945 – Important Developments

In the late 1880s, “War of the Currents” began between Edison and Tesla.

Thomas Edison

Nikola Tesla

V.S.

DC motor

AC motor

Source: http://staff.fcps.net/rroyster/war.htm
History: Pre 1945 – Important Developments

In the late 1880s, “War of the Currents” began between Edison and Tesla.

Thomas Edison

Nikola Tesla

Before that, air handling systems were steam-driven!

Source: http://staff.fcps.net/rrroyster/war.htm
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……”

1904:
There were no standardized annual building energy use calculations

Source: Architect’s and Builder’s Handbook in 1904 by Frank E. Kidder
History: Pre 1945 – Heating Load Calculation

Radiators

Source: Architect’s and Builder’s Handbook in 1904 by Frank E. Kidder
# Radiators

## History: Pre 1945 – Heating Load Calculation

### Data for Excelsior Indirect Steam-Radiators

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</table>

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

#### Heating Load Calculation

<table>
<thead>
<tr>
<th>Size of Room</th>
<th>Size of Radiators</th>
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<td>144</td>
<td>216</td>
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</table>

**Source:** Architect’s and Builder’s Handbook in 1904 by Frank E. Kidder
History: Pre 1945 – Heating Load Calculation

Boilers

Source: Architect’s and Builder’s Handbook in 1904 by Frank E. Kidder
# History: Pre 1945 – Heating Load Calculation

## Boilers

### Horizontal Tubular Boilers


<table>
<thead>
<tr>
<th>Diameter of Boiler</th>
<th>Length of Boiler</th>
<th>Number of Tubes</th>
<th>Diameter of Tubes</th>
<th>Length of Tubes</th>
<th>Thickness of Shell</th>
<th>Nominal Horse-power</th>
<th>Approx. Weight of Boiler and Coals</th>
<th>Square Feet of Grate Surface</th>
<th>Square Feet of Radiating Surface that can be Supplied</th>
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<tbody>
<tr>
<td>6 in.</td>
<td>8 ft.</td>
<td>36</td>
<td>3/8 in.</td>
<td>6 ft.</td>
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<td>32,000</td>
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</tbody>
</table>

*Selected from 150 sizes listed by this firm. These boilers are made up to 96 ins. diam. and 21 ft. long.

1. For hard coal or coke.
2. Proportion 8 to 1. The last two columns added by the author.

Source: Architect’s and Builder’s Handbook in 1904 by Frank E. Kidder
History: Pre 1945 – Heating Load Calculation

Boilers

<table>
<thead>
<tr>
<th>No. of Radiators</th>
<th>Size of Boilers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tbody>
</table>

Source: Architect's and Builder's Handbook in 1904 by Frank E. Kidder
History: Pre 1945 – Heating Load Calculation

Boilers

1904:

- Method existed for sizing the steam radiator
- Steam boilers were sized = number/type of radiators
- Air conditioning had yet to used commercially

Source: Architect’s and Builder’s Handbook in 1904 by Frank E. Kidder
In 1911, Willis Carrier developed his *Psychrometric chart*.
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

Original Carrier Centrifugal Refrigeration Unit

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

- Tallest Reinforced-Concrete High-Rise Office Building
- Air-Conditioning System was designed by Carrier Engineering Corporation
- 11 AHUs provided cooling, two Chillers with a Maximum 375-ton Capacity provided Chilled Water
- Radiant Heat was Absorbed by the Heavy Construction
- Venetian Blinds, Cloth Window Shades, Duct dampers were Added to Solve the Problem

Source: www.alamoashrae.org/database/articles/Milam_Building_Report.pdf
Until 1938, TRANE Company Published its first design manual, called “TRANE Air-Conditioning Design Manual” and Provided a *load estimate sheet* for engineers to use.

Source: 1938 TRANE Air Conditioning Manual
### History: Pre 1945 – Load Estimate Sheet

#### TRANE Air-Conditioning Manual

<table>
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<tr>
<th>COOLING LOAD ESTIMATE SHEET</th>
<th>PROPOSAL NO.</th>
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<td>THE TRANE COMPANY</td>
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**Entire building**

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<th>Type</th>
<th>Area</th>
<th>Height</th>
<th>Room</th>
<th>heat gain</th>
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<td>Entire</td>
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<td>100</td>
<td>First</td>
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</tr>
</tbody>
</table>

**Conduction Heat Gains**

- 100 x 1000 = 100000
- 5 x 1000 = 5000

**Excess Solar Heat Gains**

- 100 x 100 = 10000
- 5 x 100 = 500

**Duct Heat Gains**

- 100 x 1000 = 100000
- 5 x 1000 = 5000

**Body Heat Gains**

- 100 x 100 = 10000
- 5 x 100 = 500

**Equipment Heat Gains**

- 100 x 100 = 10000
- 5 x 100 = 500

**Infiltration Heat Gains**

- 100 x 100 = 10000
- 5 x 100 = 500

**Miscellaneous Heat Gains**

- 100 x 100 = 10000
- 5 x 100 = 500

**Summary of Heat Gains**

- Total heat gain: 200000
- Heat load of ventilation air: 10000
- Total cooling load on coils: 200000

**Solar Temperature Difference Method**

- Solar temperature
- Difference method
**History: Pre 1945 – Load Estimate Sheet**

**TRANE Air-Conditioning Manual**

<table>
<thead>
<tr>
<th>Design Data</th>
</tr>
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<table>
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<tr>
<td>Excess Solar Heat Gains</td>
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<td>Duct Heat Gains</td>
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<table>
<thead>
<tr>
<th>Body Heat Gains</th>
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</thead>
<tbody>
<tr>
<td>Equipment Heat Gains</td>
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<tr>
<td>Infiltration Heat Gains</td>
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</table>

<table>
<thead>
<tr>
<th>Summary of Heat Gains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Load of Ventilation Air</td>
</tr>
<tr>
<td>Total Cooling Load on Coils</td>
</tr>
</tbody>
</table>

*No direct treatment of thermal mass*

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

Inside Surface Temperature

\[ t_o = t_i + \frac{0.606(t_m - t_i)}{0.856 + L/k} + \sum_{n=1}^{\infty} \lambda_n \cos(15n\theta - \alpha_n - \phi_n) \]

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

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

Inside Surface Temperature

\[ t_o = t_i + \frac{0.606(t_m - t_i)}{0.856 + L/k} + \sum_{n=1}^{\infty} \lambda_n t_n \cos(15n\theta - \alpha_n - \phi_n) \]

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

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

\[ t_o = t_i + \frac{0.606(t_m - t_i)}{0.856 + L/k} + \sum_{n=1}^{\infty} \lambda_n t_n \cos(15n\theta - \alpha_n - \phi_n) \]

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

Sol-Air Temperature Method:
Later in 1961, sol-air temperature method was tabulated in the *ASHRAE Guide and Data Book – Fundamentals and Equipment*

### Table 8: Summer Design Sol-Air Temperatures Used for Tables 9 and 10

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<thead>
<tr>
<th>Mean Sun Time</th>
<th>Any Surface</th>
<th>Horizon</th>
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<tr>
<td>24 Hr Avg. $T_a$</td>
<td>65.1</td>
<td>58.1</td>
<td>53.0</td>
<td>48.4</td>
<td>43.0</td>
<td>38.2</td>
</tr>
</tbody>
</table>

* $w$ = surface absorptivity, dimensionless; $a$ = 0.9; $h_d = 0.1$; and $h_l = 0.05$, $f_{w} = \frac{u_{w}}{u_{a}}$ = unit convective conductance = 6.0 Btu per hr (°F deg).

Values in this column are magnitudes of $T_a$, the outdoor air temperature.
There is time lag for the peak and a reduction in amplitude.

History: Pre 1945 – Cooling Load Calculation


The curves shown in Mackey and Wright and ASHRAE original test data were finally tabulated in the ASHRAE Guide and Data Book.

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

In the 1967 ASHRAE Handbook, the Sol-Air Temperature table was further modified:

A heat balance at a sunlit surface gives:

$$q / A = \alpha I_t + h_o (t_o - t_s) - \varepsilon \Delta R$$

In terms of the sol-air temperature, $t_e$

$$q / A = h_o (t_e - t_s)$$

where,

$$t_e = t_o + \alpha I_t / h_o - \varepsilon \Delta R / h_o$$

Source: 1967 ASHRAE Handbook of Fundamentals
Guide Books:
1955 TRANE Air Conditioning Design Manual
1960 Handbook of Air Conditioning System Design by Carrier
1961 ASHRAE Guide and Data Book
1967 ASHRAE Handbook of Fundamentals
History: 1946 – 1969 Cooling Load Calculation

Peak Cooling Load Calculation:

- 1961 TETD/TA Method:
  - Total Equivalent Temperature Difference/Time Averaging Method
  - Original Outlined by Stewart in 1948
  - TETD table added to ASHRAE Guide and Data Book in 1961

Basic heat gain equation for exterior surface:

\[ q = UA(T_{ETD}) \]

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:

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

### Roof, Wall, Glass:

\[ q = UA(CLTD) \]

### Solar:

\[ q = A \times SC \times SHGF \times CLF \]

### Internal Lights:

\[ q = INPUT \times CLF \]

### People:

\[ q = No. \times Sens.H.G. \times CLF \]
History: 1970 – 1989 Cooling Load Calculation

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

Table 7. Cooling Load Temperature Differences for Calculating Cooling Load from Sunlit Walls

Table 11. Cooling Load Factors for Glass without Interior Shading
**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

**Finite Difference /Finite Element Method:**

- FDM/FEM became available in 1960
- Mainly used as a basis for a computer algorithm

**History:** 1946 – 1969 Cooling Load Calculation

Other Developments:
History: 1946 – 1969 Annual Energy Use

Annual Building Energy Use Calculation:

Heating Degree-Day Method:

- Degree Days first used to predict snow melt.
- Manual method was adopted in mid 1960s

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
- \( \Delta t \): 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

Equivalent Full Load Hours Method:

- Manual method was adopted in the mid-1960s
- Cooling energy requirement calculation

Cooling Season Power:

\[ P_c = \frac{0.746(bhp)_t (T)H_e}{E} \]

Where,
- \( P_c \): 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 was adopted in the mid-1960s
✓ Heating and Cooling
✓ Energy Calculation
✓ Later appeared in 1981 ASHRAE Handbook
History: 1946 – 1969 Computer Developments

- In 1957, FORTRAN I compiler was developed by John Backus and colleagues at IBM.
- In 1960, PDP-1, the first commercial mini computer was available.
- In 1964, BASIC programming was available.

Today, most whole building simulation programs are still using FORTRAN.

History: 1946 – 1969 Annual Energy Use

Thermal Network Method:

✓ Thermal Network Model varies
✓ Refinement of the Heat balance method
✓ Thermal network model was available in 1958
✓ Later appeared into *1997 ASHRAE Handbook*

History: 1946 – 1969 Annual Energy Use

Thermal Network Method:

History: 1946 – 1969 Annual Energy Use

Thermal Network Method:

- Thermal Network Model varies
- Refinement of the Heat balance method
- Thermal network model was available in 1958
- Later appeared into 1997 ASHRAE Handbook


Thermal mass was represented by an electrical RC network

Source: Buchanan, Transactions
History: 1946 – 1969 Annual Energy Use

Thermal Network Method:

- RC Network allowed for layered walls, roofs.
- RC Network allowed for nodal temperatures to be determined.

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
<th>ROOF NETWORKS</th>
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</thead>
<tbody>
<tr>
<td>A</td>
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<td>NETWORK</td>
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Table A—Magnitude of Decrement Factors

<table>
<thead>
<tr>
<th></th>
<th>λ₁</th>
<th>λ₂</th>
<th>ADD. TIME LAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Solar radiation transmitted through north glass ref. D.</td>
<td>0.54</td>
<td>0.95</td>
<td>3 hrs</td>
</tr>
<tr>
<td>B. Solar radiation transmitted through south glass ref. E. 2 in. floor</td>
<td>0.66</td>
<td>1.00</td>
<td>1 hr, approx.</td>
</tr>
<tr>
<td>C. Southwest wall ref. F. 6 in. floor</td>
<td>0.47</td>
<td>1.00</td>
<td>1 hr, approx.</td>
</tr>
<tr>
<td>D. Roof problem</td>
<td>0.93</td>
<td>0.92</td>
<td>0 hr</td>
</tr>
<tr>
<td></td>
<td>0.34</td>
<td>0.83</td>
<td>3 hr</td>
</tr>
</tbody>
</table>

History: 1946 – 1969 Annual Energy Use

Computer Algorithms:

Thermal Response Factor Method:

✓ First developed by Stephenson and Mitalas in 1967

✓ Later appeared as Weighting Factor Method in 1981 ASHRAE Handbook

Heat Gain Weighting Factors: \( v_0, v_1, v_2, \ldots, w_1, w_2, \ldots \)

For each type of heat gain \( q_\theta \), cooling load for \( Q_\theta \):

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

Air Temperature Weighting Factors: \( g_0, g_1, g_2, \ldots, P_1, P_2, \ldots \)
History: 1946 – 1969 Annual Energy Use

Computer Algorithms:

**Thermal Mass: Transfer Function Method:**

- Firstly introduced by 1972 ASHRAE Handbook of Fundamentals
- Associated Sol-Air Temperature

Heat gain through a wall or roof:

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

where,

- \( b_n \), \( c_n \), \( d_n \)
  - Transfer function coefficients

**Heat Balance Method:**

- Early used for general thermal modeling in aerospace and other industries
- Detailed calculation procedures by Buchberg in 1958
- Later appeared in *1981 ASHRAE handbook*

System Heat Transfer: \[ q_{sys,j} = a + bt_{aj} \]

where,

\[
\begin{align*}
t_{aj} &= \frac{a + \sum_{i=1}^{N} A_i h_{ci} t_{si,j} + \rho c V_{int,il} t_{o,j} + q_{c,int,j}}{-b + \sum_{i=1}^{N} A_i h_{ci} + \rho c V_{int,il} + \rho c V_{vent,j}}
\end{align*}
\]
History: 1970 – 1989 Annual Energy Use

Computer Algorithms:

DOE-2
(Weighting Factor Method)

Complete Set of ASHRAE Algorithms


Fig. 6 Flow Diagram For Calculation of Hourly Heating Cooling Loads Using ASHRAE Algorithms

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 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
- Later appeared in *2001 ASHRAE Handbook of Fundamentals*

Source: Steven F. Bruning 2012 ASHRAE Journal

Source: 2001 ASHRAE Handbook of Fundamentals
Residential Heat Balance (RHB) and Residential Load Factor (RLF) Methods:

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

### Table 1: RLF Limitations

<table>
<thead>
<tr>
<th>Item</th>
<th>Valid Range</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Latitude</td>
<td>20 to 60°N</td>
<td>Also approximately valid for 20 to 60°S with N and S orientations reversed for southern hemisphere. Application must be summer peaking. Buildings in mild climates with significant SE/S/W glazing may experience maximum cooling load in fall or even winter. Use RHB if local experience indicates this is a possibility.</td>
</tr>
</tbody>
</table>
| Date            | July 21              | RLF factors assume 50 m elevation. With elevation-corrected C
| Elevation       | Less than 2000 m     | method is acceptably accurate except at very high elevations. Design-day average outdoor temperature assumed to be above indoor design temperature. |
| Climate         | Warm/hot             | May be applied to masonry veneer over frame construction; results are conservative. Use RHB for structural masonry or unconventional construction. |
| Construction    | Lightweight residential construction (wood or metal framing, wood or stucco siding) | Spaces with high fenestration fraction should be analyzed with RHB. |
| Fenestration area | 0 to 15% of floor area on any façade, 0 to 30% of floor area total | Skylights with tilt less than 30° can be treated as horizontal. Buildings with significant sloped glazing areas should be analyzed with RHB. Applications with high internal gains and/or high occupant density should be analyzed with RHB or nonresidential procedures. |
| Fenestration tilt | Vertical or horizontal | Applications with extensive duct runs in unconditioned spaces should be analyzed with RHB. |
| Occupancy       | Residential          |                                                                                                                                 |
| Temperature swing | 1.7 K                |                                                                                                                                 |
| Distribution losses | Typical             |                                                                                                                                 |
Modeling Radiant Systems Using a Heat Balance Simulation:

- 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:

- HCC (1967)
- Post Office Program (1971)
- NECAP (1975)
- CAL-ERDA (1977)
- DOE-1.0 (1978)
- DOE-2.0 (1979)
- DOE - 2.1a (1981)
- DOE - 2.1b (1983)
- DOE - 2.1c (1984)

- DOE – 2.1d (1989)
- DOE – 2.1e (1993)
- DOE 2.1e-087 (1995)
- DOE 2.1e-107 (2000)
- DOE 2.1e-113 (2001)
- DOE 2.1e-121 (2003)

- PowerDOE v 1.0 (1996)
- eQuest v 1.0 (1999)
- eQuest v 1.2 (2000)
- eQuest v 2.17c (2001)
- eQuest v 3.6 (2007)

- NBSLD (1974)
- BLAST 1.2 (1977)
- BLAST 2.0 (1979)
- BLAST 3.0 (1981)
- EnergyPlus V 2.0 (2007)
- EnergyPlus V 4.0 (2009)


- TRNSYS v6.0 (1975)
- TRNSYS v12.2 (1988)
- TRNSYS v13.1 (1990)
- TRNSYS v14.2 (1996)
- TRNSYS v15 (2001)
- TRNSYS v16 (2004)
- TRNSYS v17 (2010)

- TRACE direct version (1972)
- TRACE 77 (1977)
- TRACE 600 (1989)
- TRACE 700 First Window Version (1998)
- TRACE 700 Full Version (2001)
- TRACE 700 V6.2 (2008)

- Commercial Load v1.0 (1981)
- Bin Opcost Analysis v 1.0
- HAP v 1.0 (1987)
- HAP v 2.0 (1989)
- HAP v 3.0 (1993)
- HAP v 4.0 (1999)
- HAP v 4.2 (2003)
- HAP v 4.3 (2006)
- HAP v 4.5 (2010)
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)

---

History: Overview Chart 1900 - Present

The image presents a timeline chart titled "History of Building Energy Use and Peak Load Calculation Methods." The chart spans from 1900 to the present and illustrates the evolution of energy usage and peak load calculation methods over time. Each year is marked with specific events or methods, such as the introduction of new calculation techniques, changes in energy usage patterns, and technological advancements. The chart includes a variety of methods and methodologies, allowing for a comprehensive view of how building energy use and peak load calculations have developed historically.
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, programming language.

- 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)
  • 1928 – first air-conditioned office building (Milam Building, San Antonio, TX)

• 1944 – First use of thermal mass: Mackey and Wright develop sol-air temperature with decrement factor. 1961 adopted into ASHRAE Guide and Data Book

• 1961 – Total Equivalent Temperature Difference/Time Average (TETD/TA) Method
Summary

• 1977 – TETD/TA replaced with Cooling Load Temperature Difference/Cooling Load Factor (CLTD/CLF) Method

• Annual Calculation Methods: 1960s - heating degree days, equivalent full load hours, bin method.

• 1958 – thermal network models created based on electrical RC circuits.
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

• Examples of Thermal Mass Studies: thermal mass structural factors, thermal mass factors, radiant floor systems
Questions?