ESL-TR-12-03-03

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

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

Distribution/Age of U.S. Commercial Buildings

New York City has thousands of new / old buildings

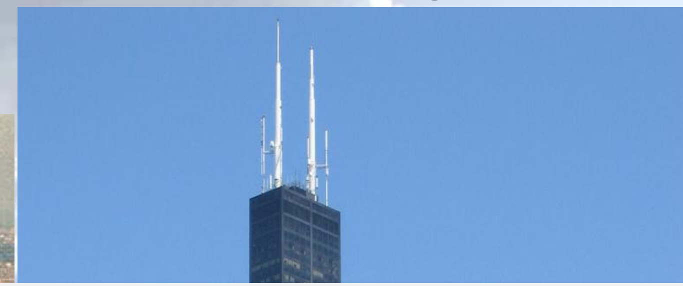
Same pattern for other U.S. cities, such as Chicago

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

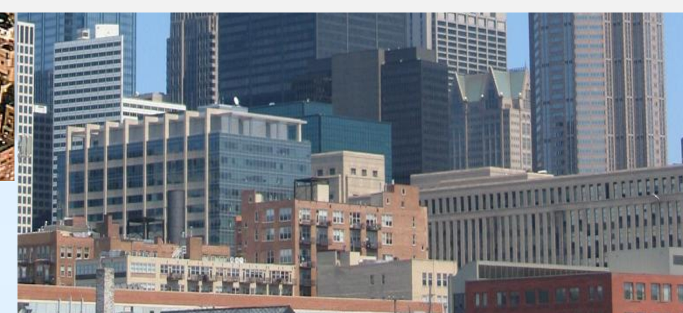
Distribution/Age of U.S. Commercial Buildings

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?*



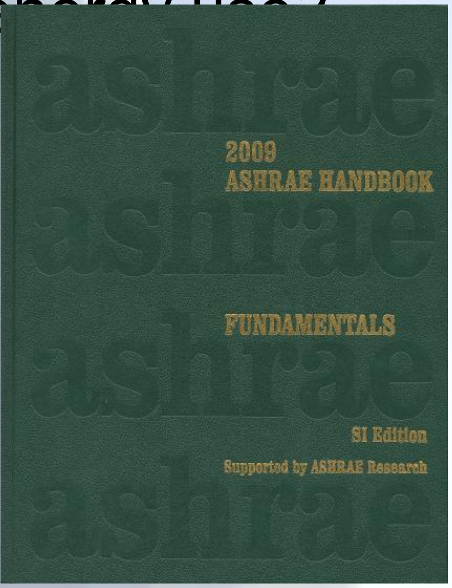
Source: http://juliancarr.com/files/2009/10/new_york_from_empire_state_building.jpg
http://thebesttraveldestinations.com/willis-tower-sears-tower-chicago-usa/

History: Building Energy Load Calculation Methods

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

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 Calculation

Annual Building Energy Use Calculation Methods
(Chapter 19, Page 19.4)

- Simulation
- Forward
- Inverse (Data-Driven)

History: Building Energy Load Calculation Methods

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

Peak Heating Load Calculation

Peak Load

How did the methods evolve from 1900 to Present?

How did these methods treat the use of thermal mass?

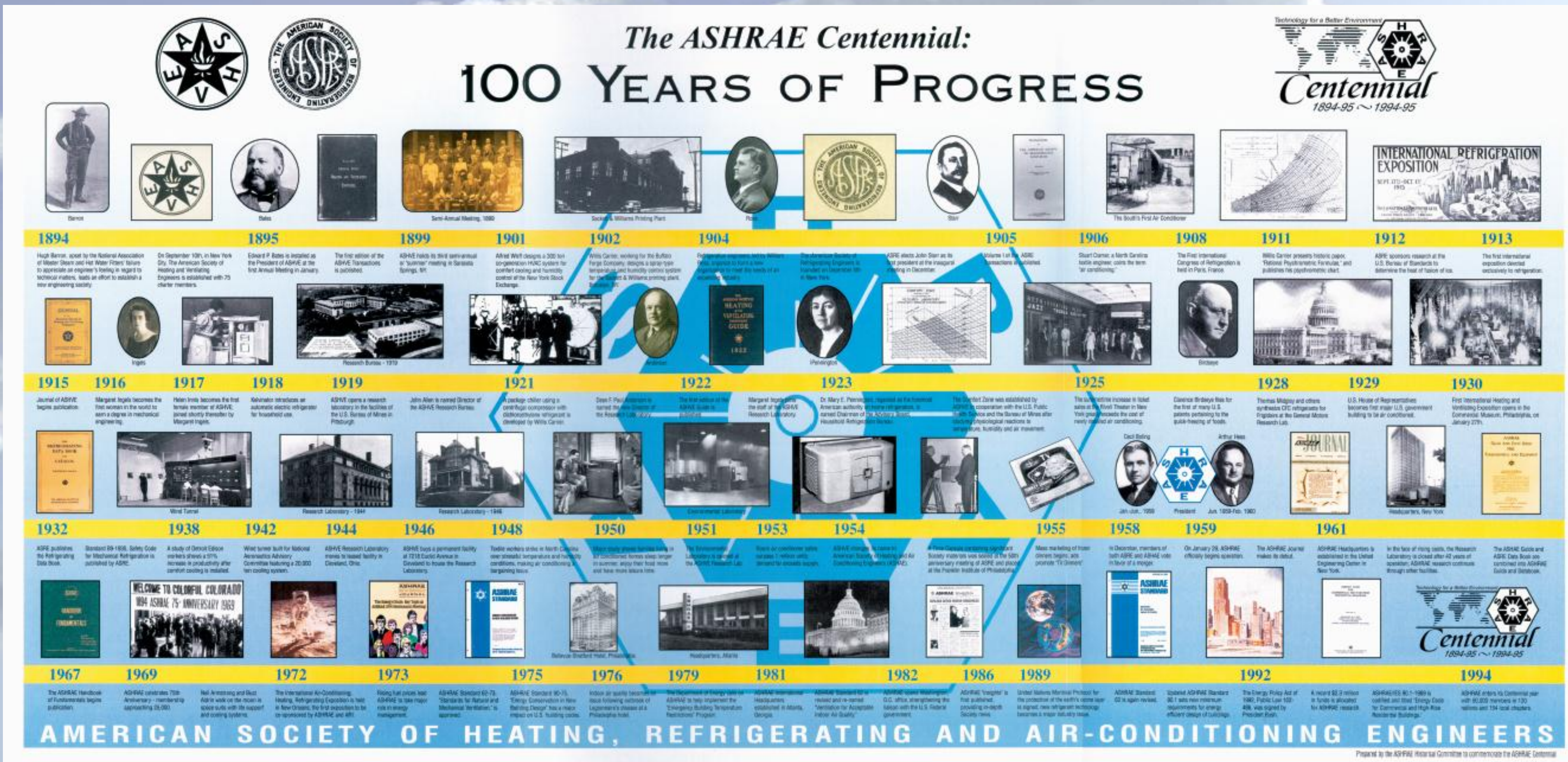
Energy Use Calculation Methods
(Chapter 19, Page 19.4)

Forward

Inverse (Data-Driven)

History of ASHVE, ASRE, ASHAE, ASHRAE

American Society of Heating, Refrigerating and Air-Conditioning Engineers



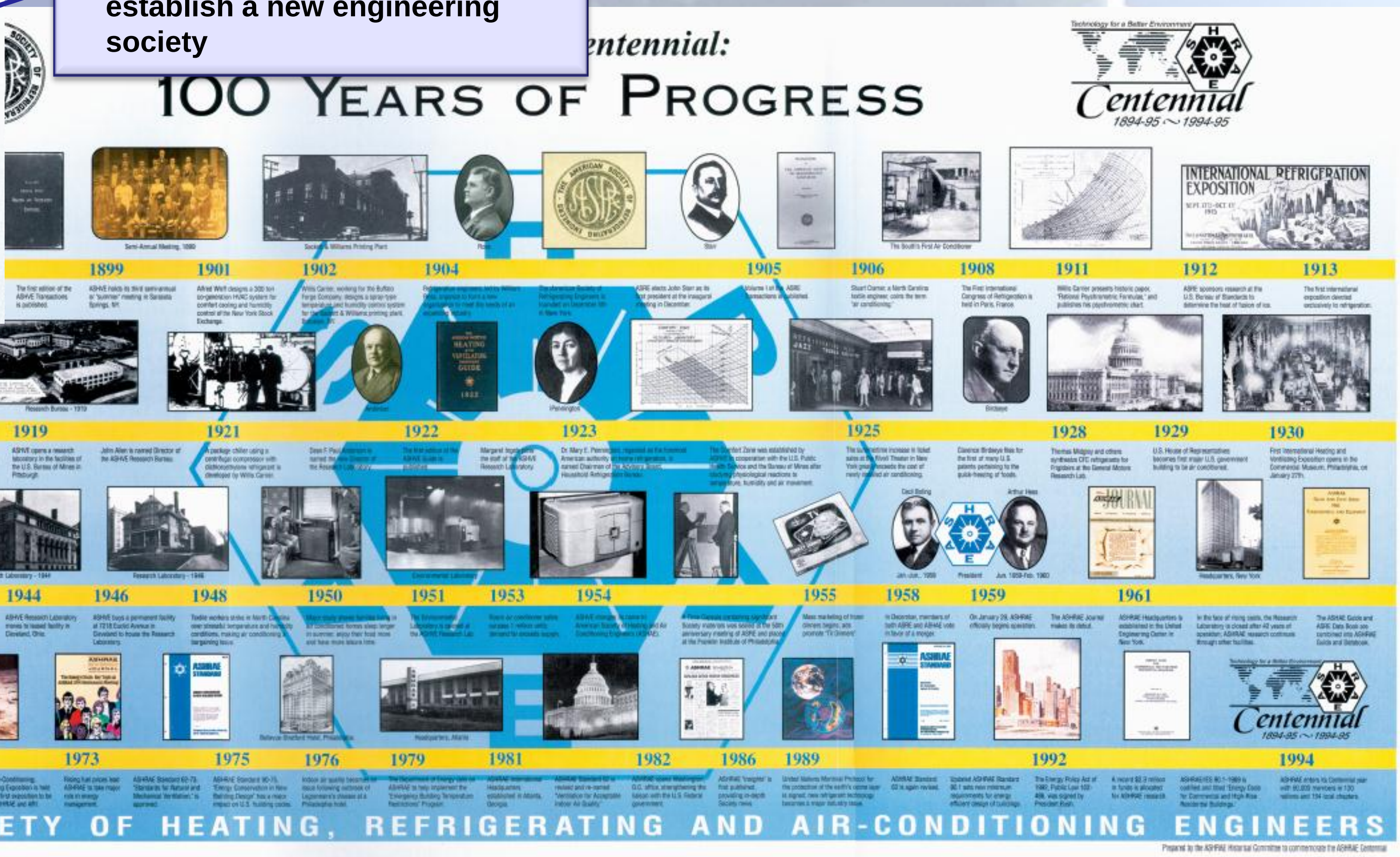
Source: http://www.ashrae.org/about-ashrae/ashrae-and-industry-history

History of ASHVE, ASRE, ASHAE, ASHRAE

In 1894:

- **Hugh Barron, led an effort to establish a new engineering society**

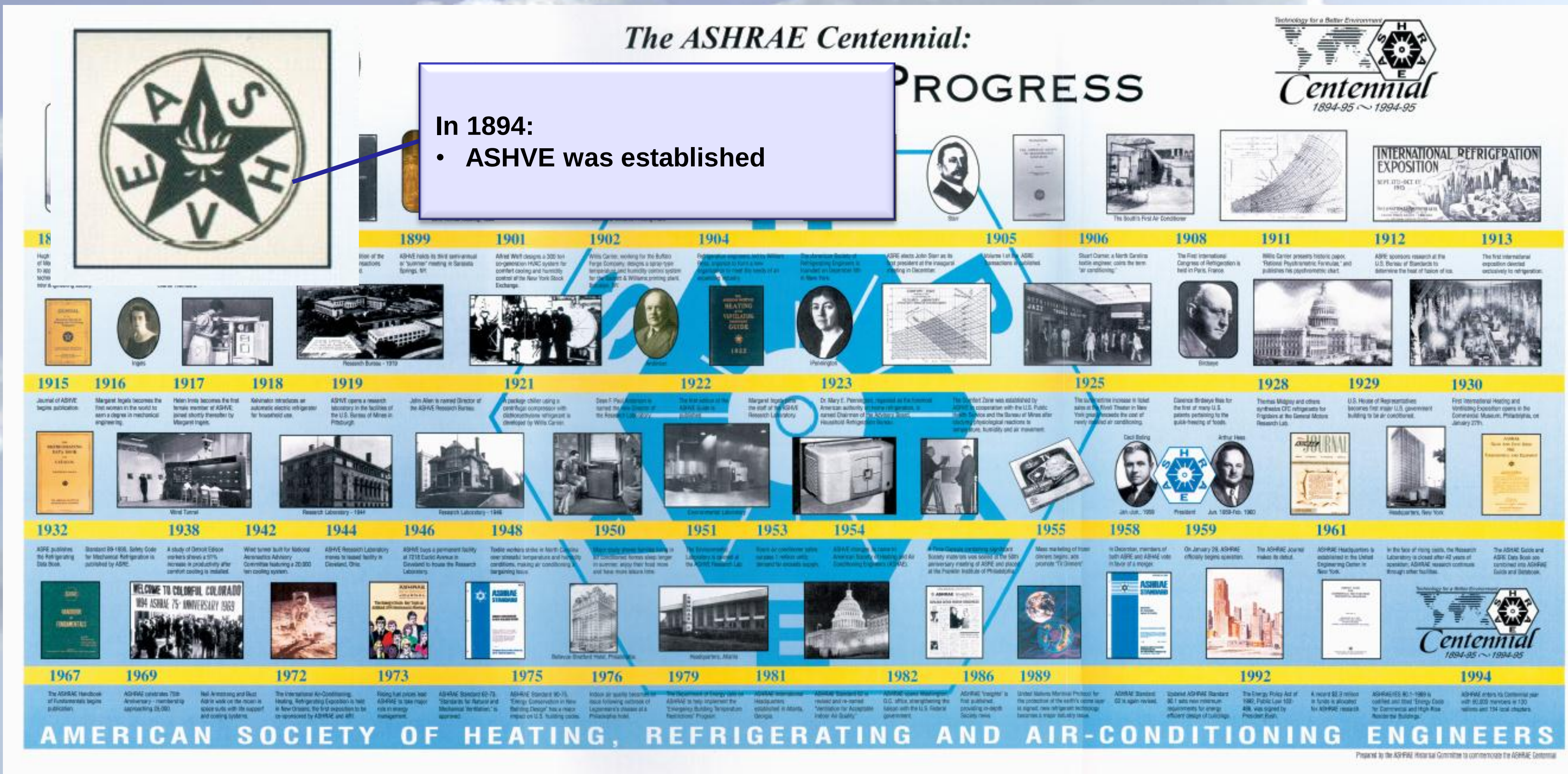
A… ety … ng and Air-Conditioning Engineers



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



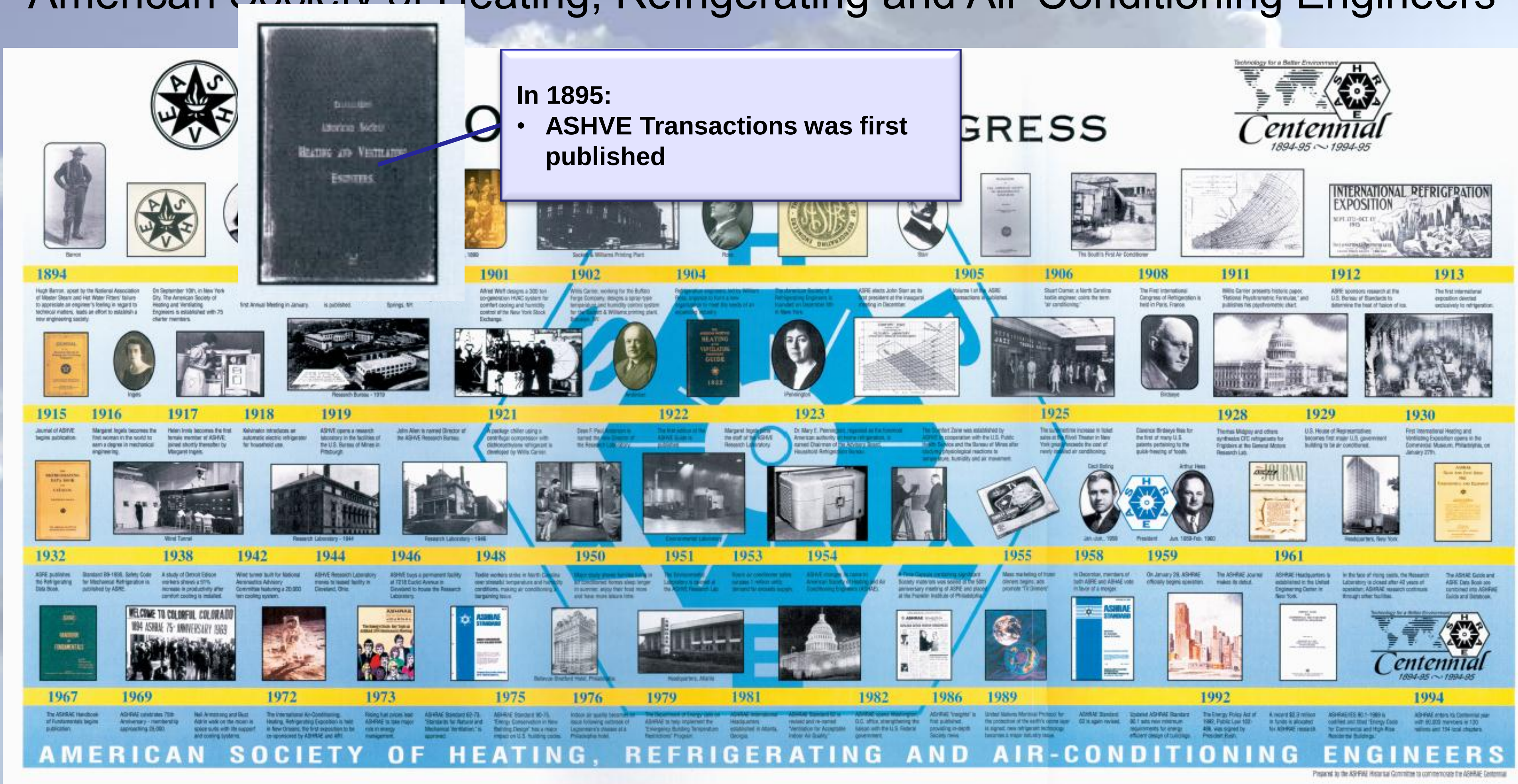
In 1894:

- **ASHVE was established**

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



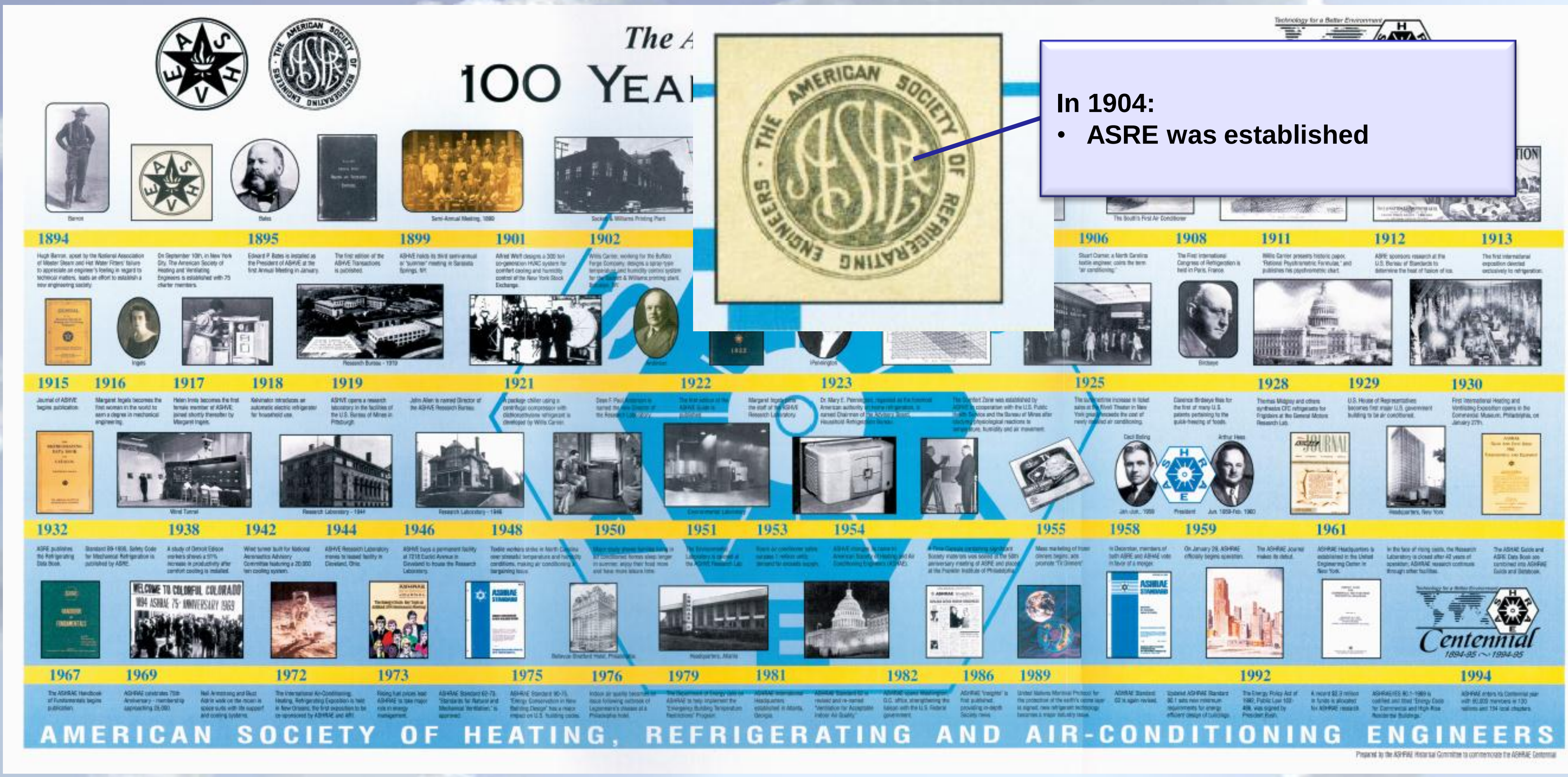
In 1895:

- **ASHVE 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



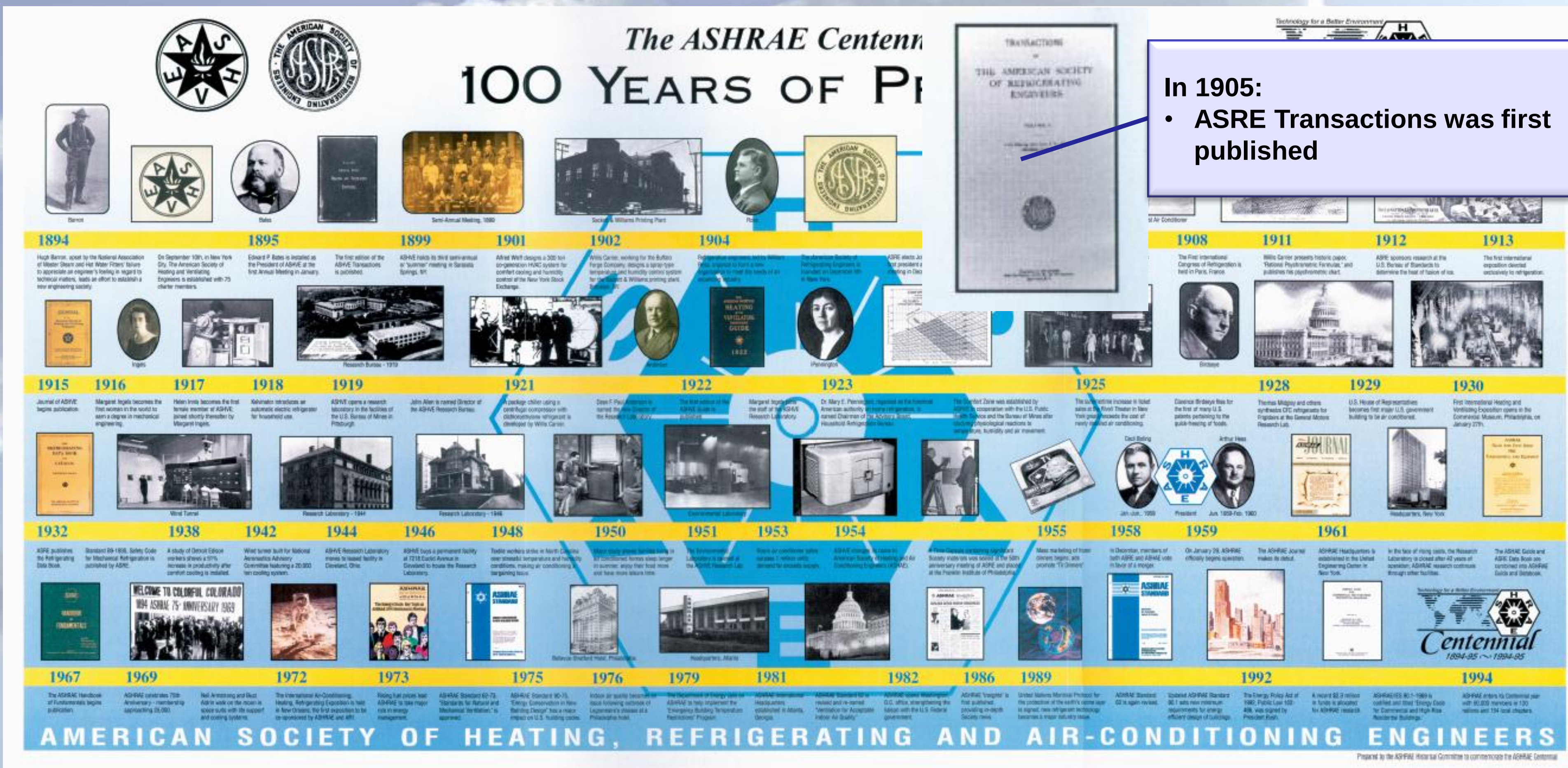
In 1904:

- **ASRE was established**

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



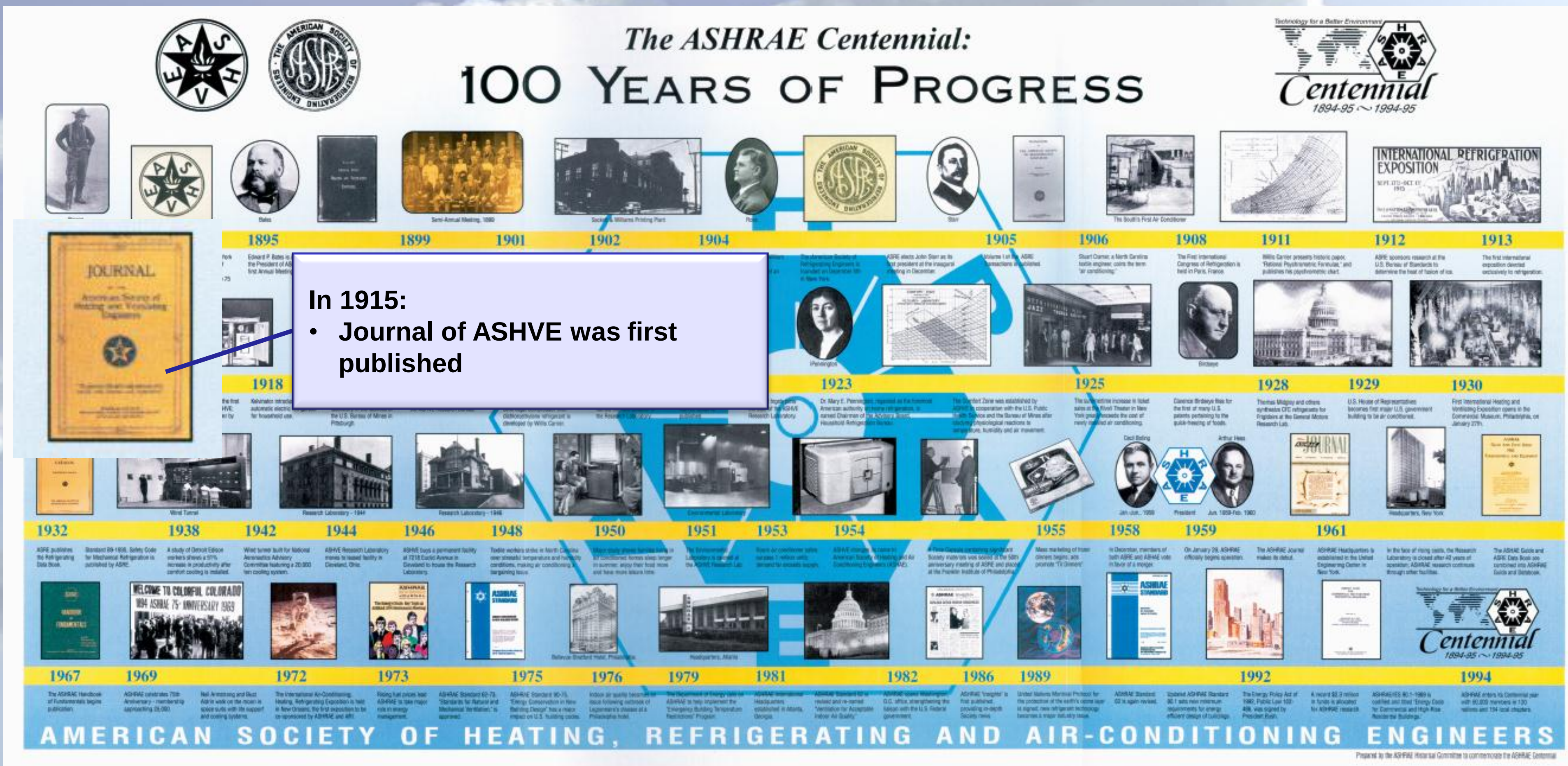
In 1905:

- **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



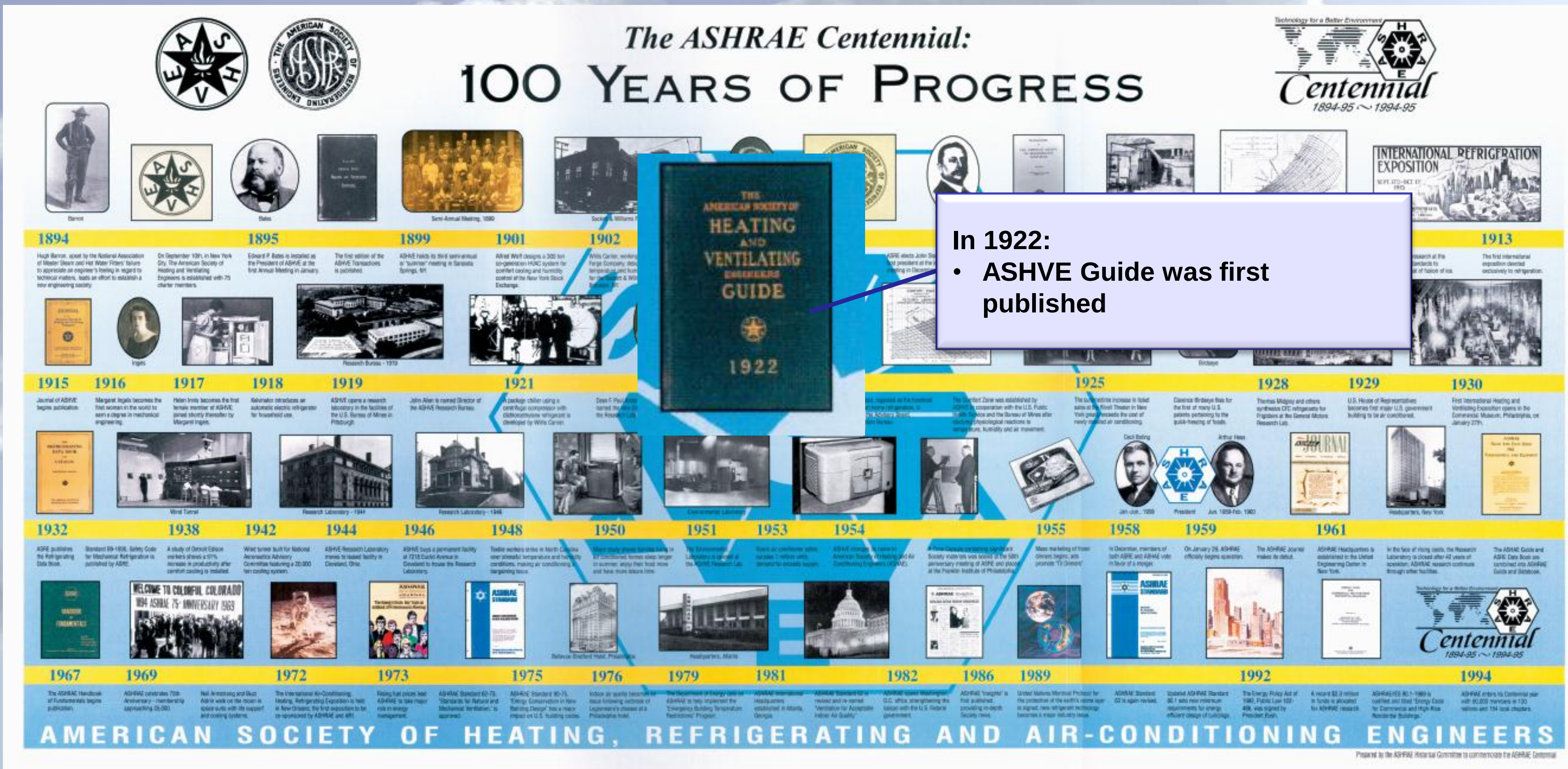
In 1915:

- **Journal of ASHVE was first published**

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

History of ASHVE, ASRE, ASHAE, ASHRAE

American Society of Heating, Refrigerating and Air-Conditioning Engineers



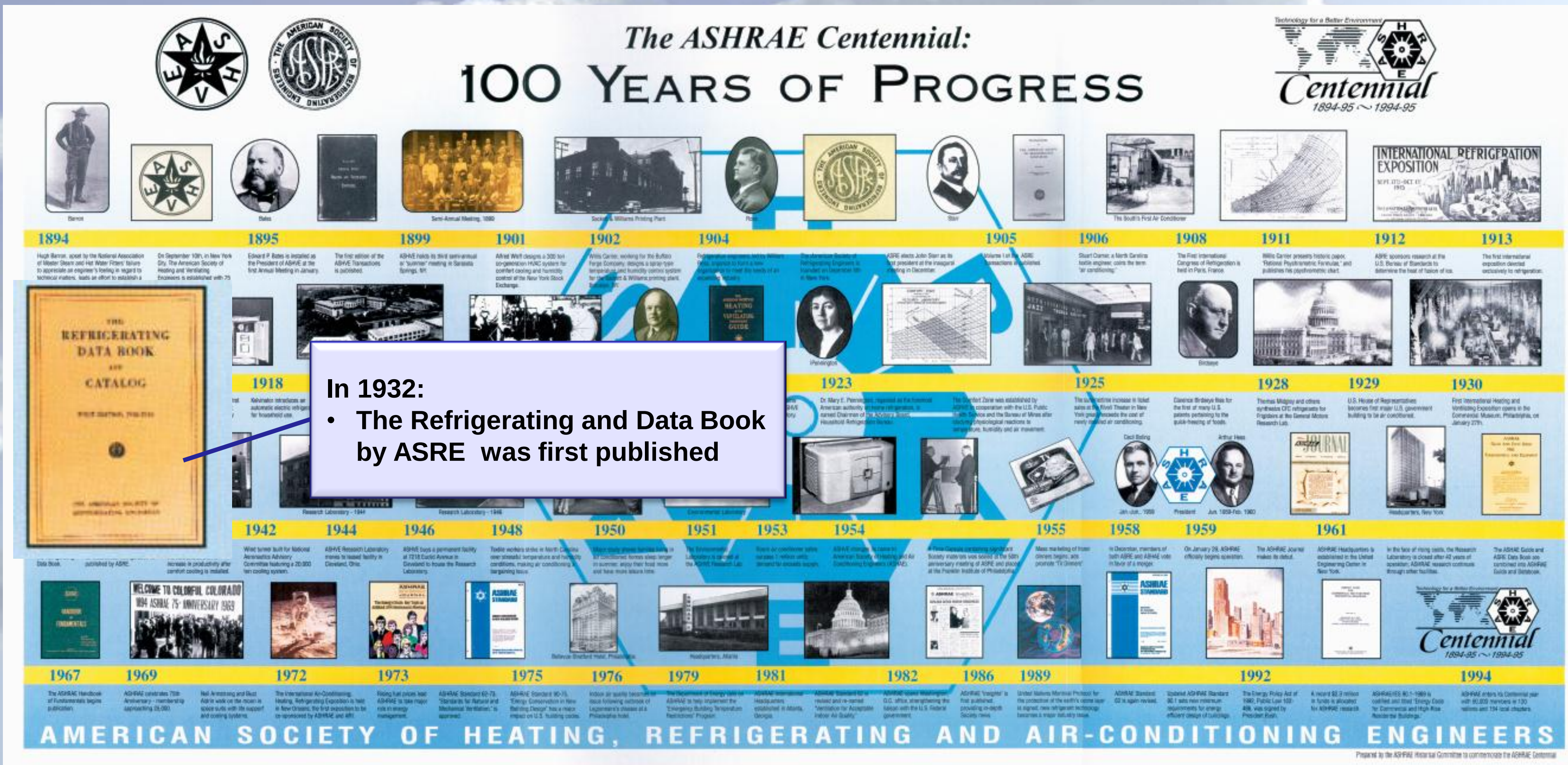
In 1922:

- **ASHVE Guide 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



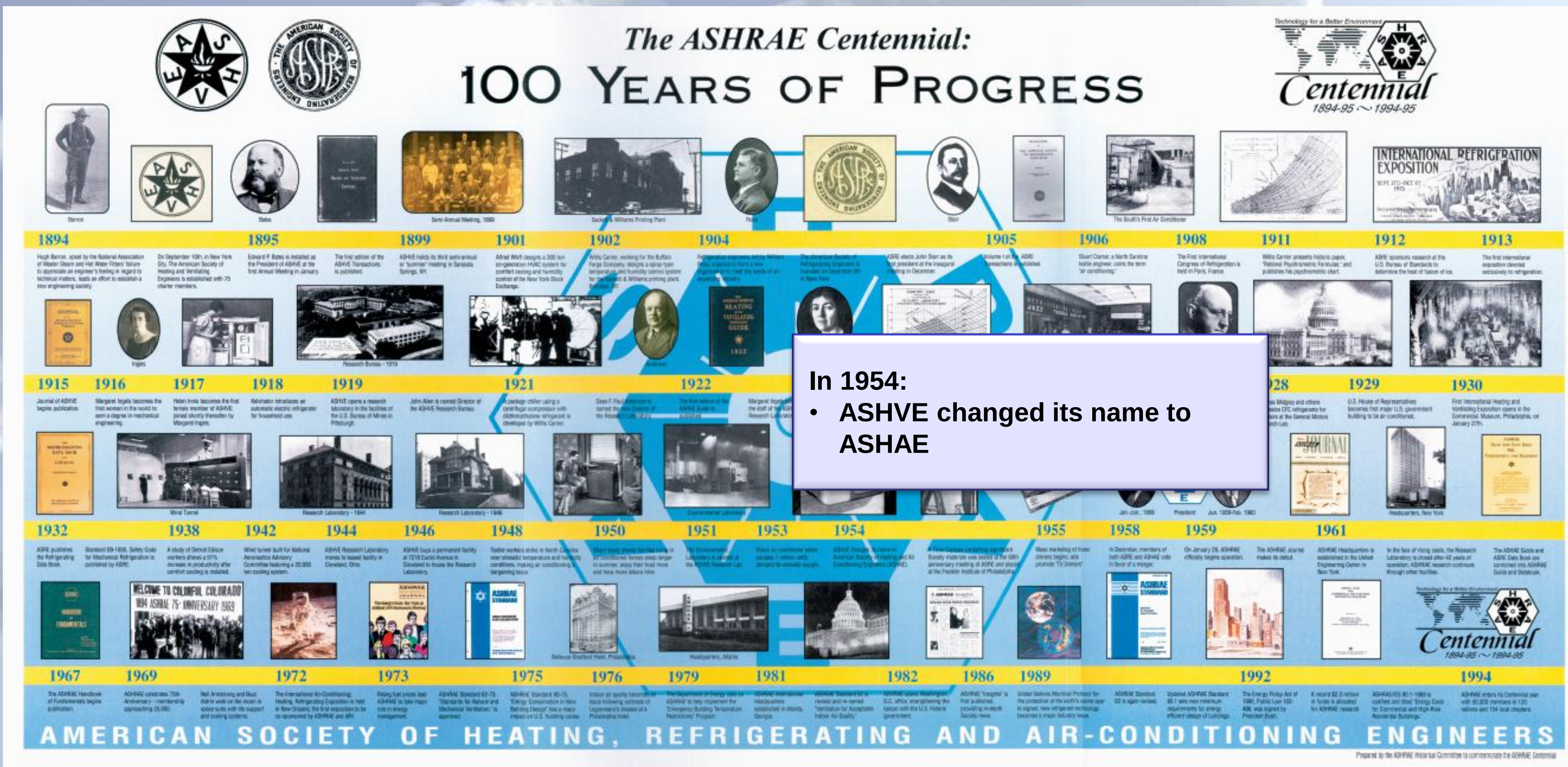
In 1932:

- **The Refrigerating and Data Book by ASRE 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

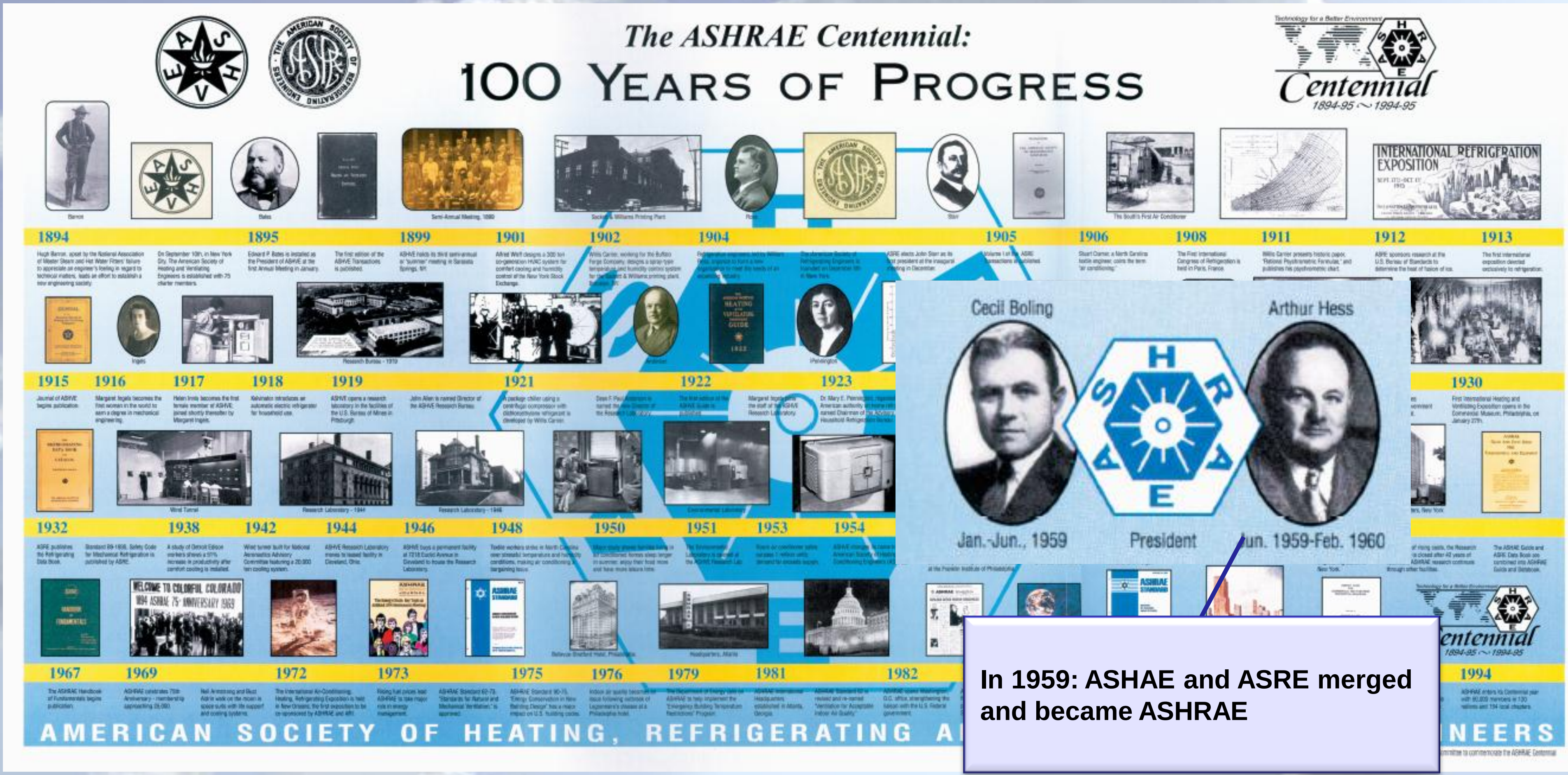


In 1954:
- **ASHVE changed its name to ASHAE**

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

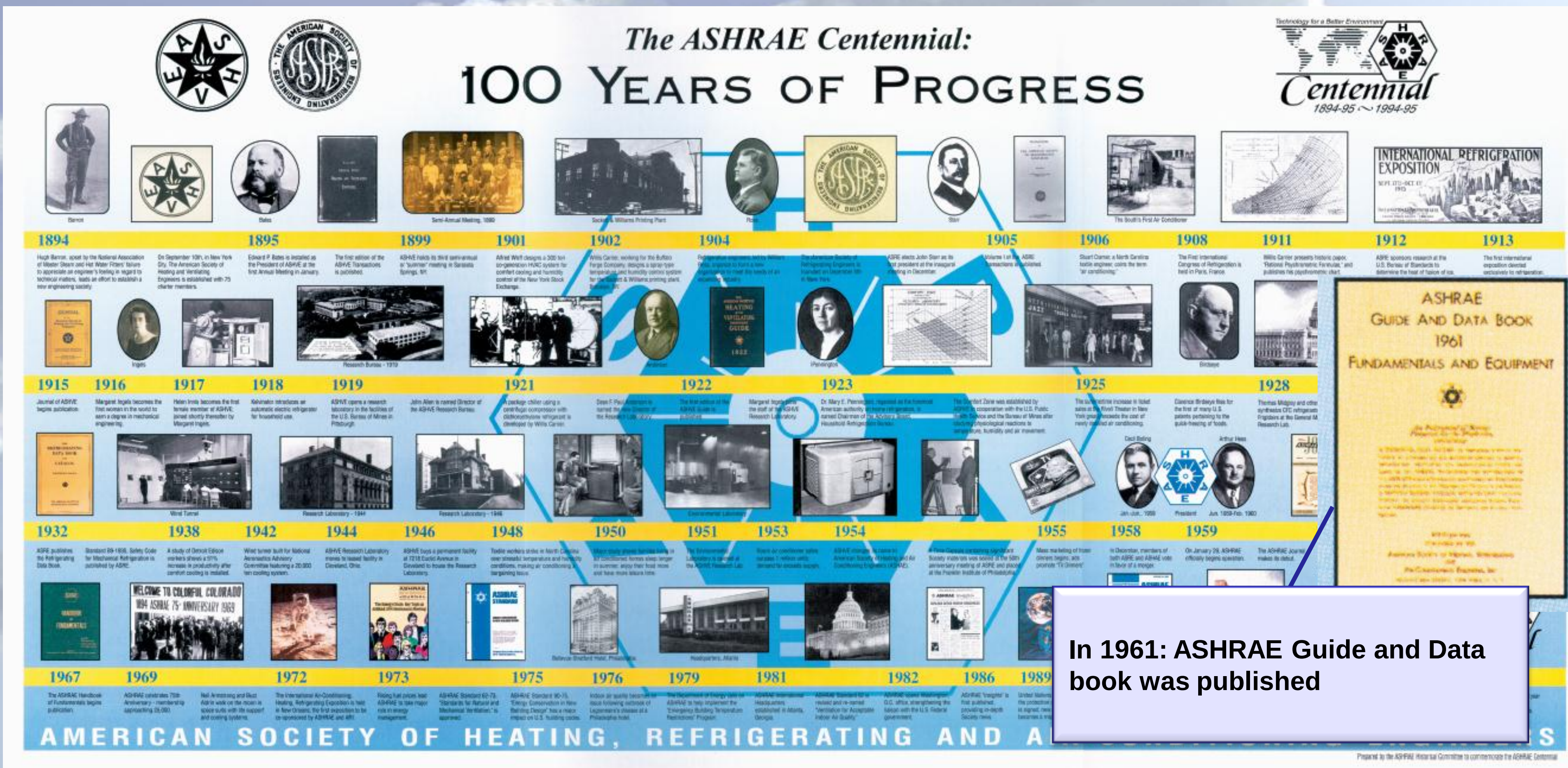


In 1959: ASHAE and ASRE merged and became ASHRAE

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

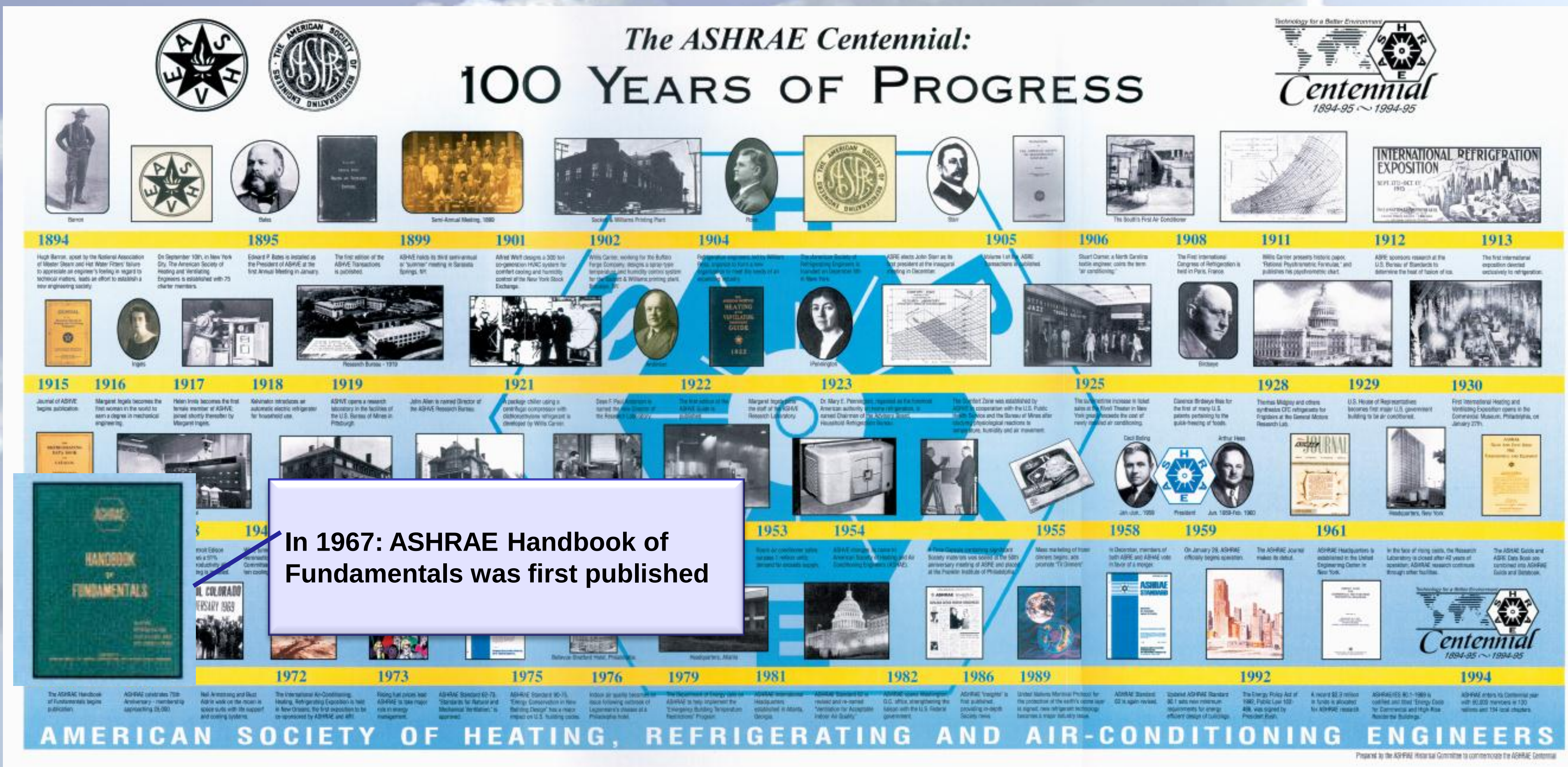


In 1961: ASHRAE Guide and Data book was published

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

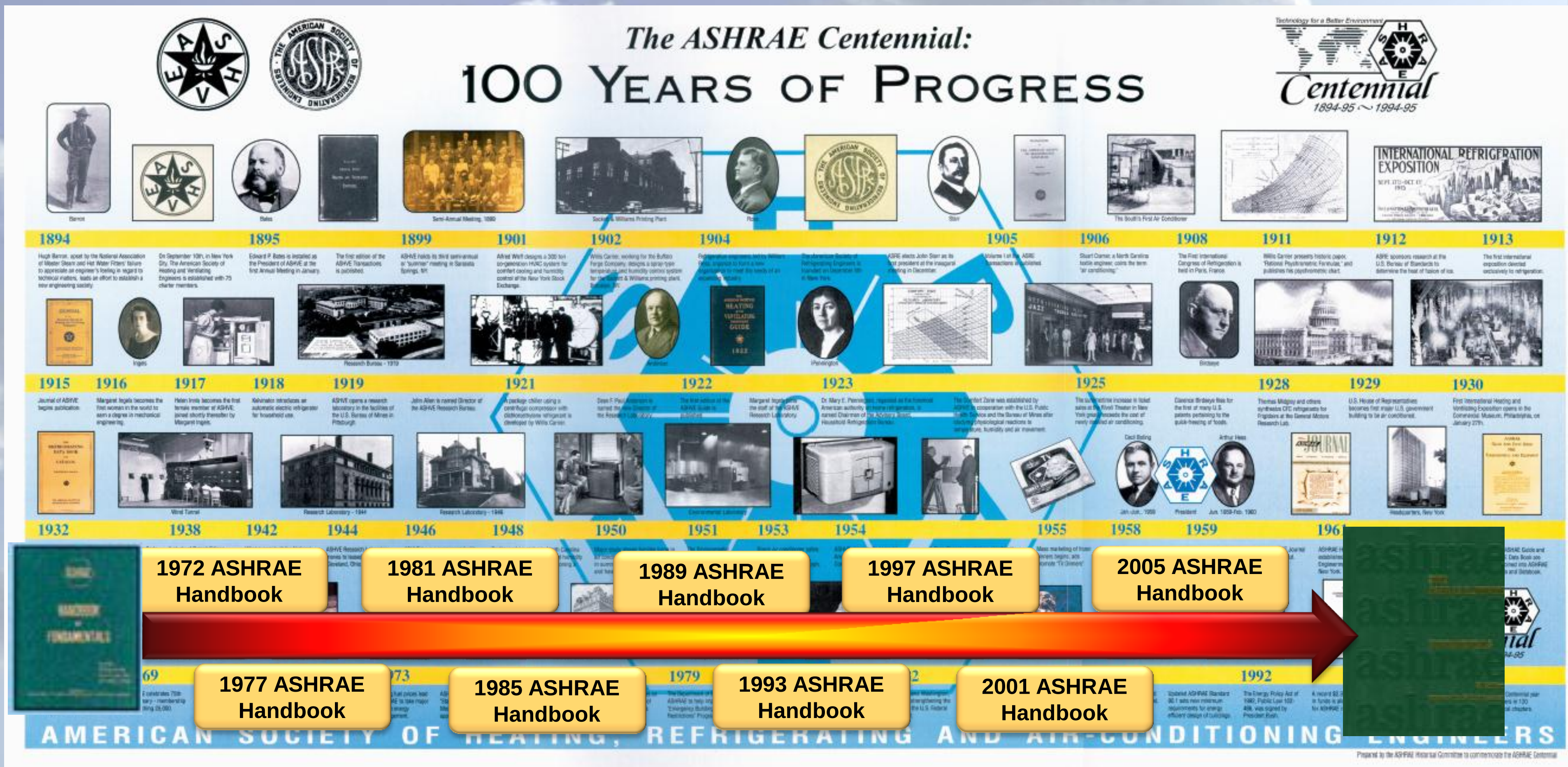


In 1967: ASHRAE Handbook of Fundamentals was first published

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

History of ASHVE, ASRE, ASHAE, ASHRAE

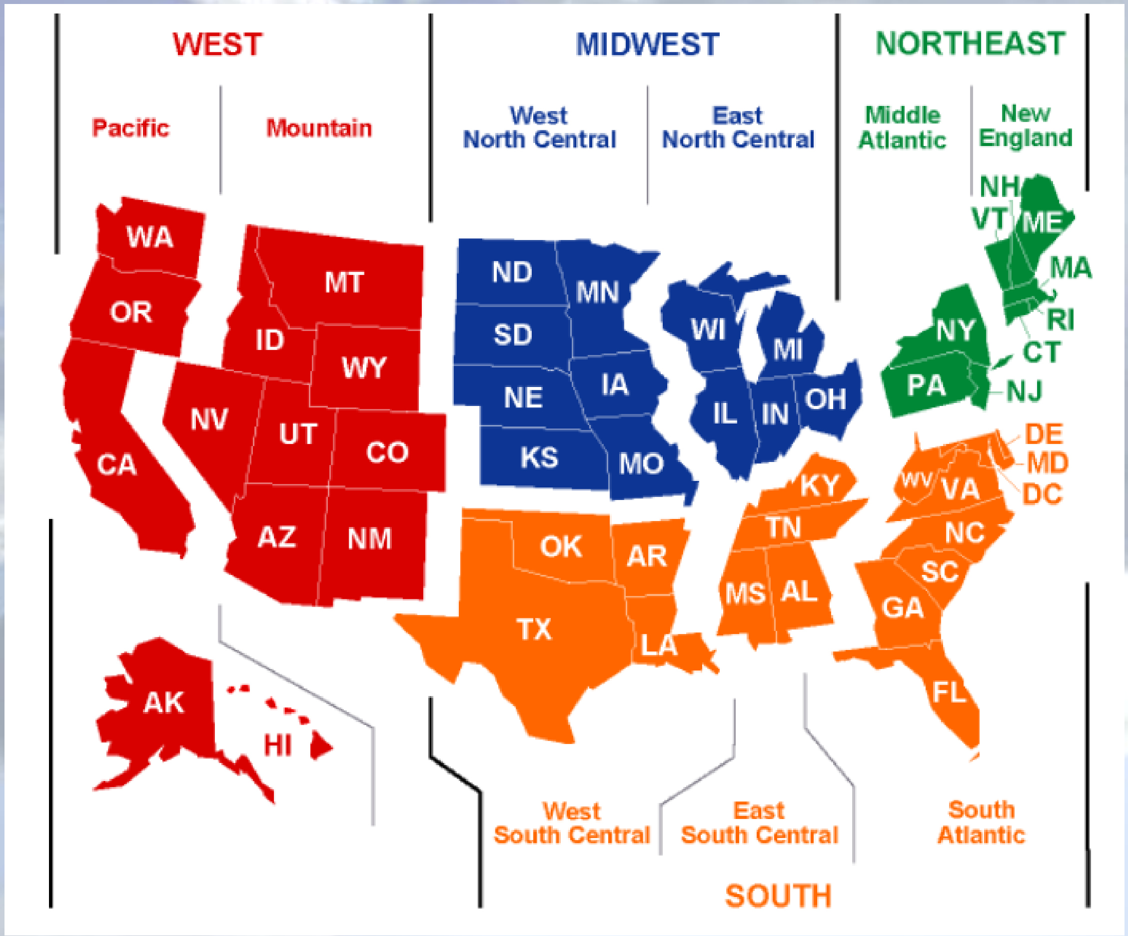
American Society of Heating, Refrigerating and Air-Conditioning Engineers



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

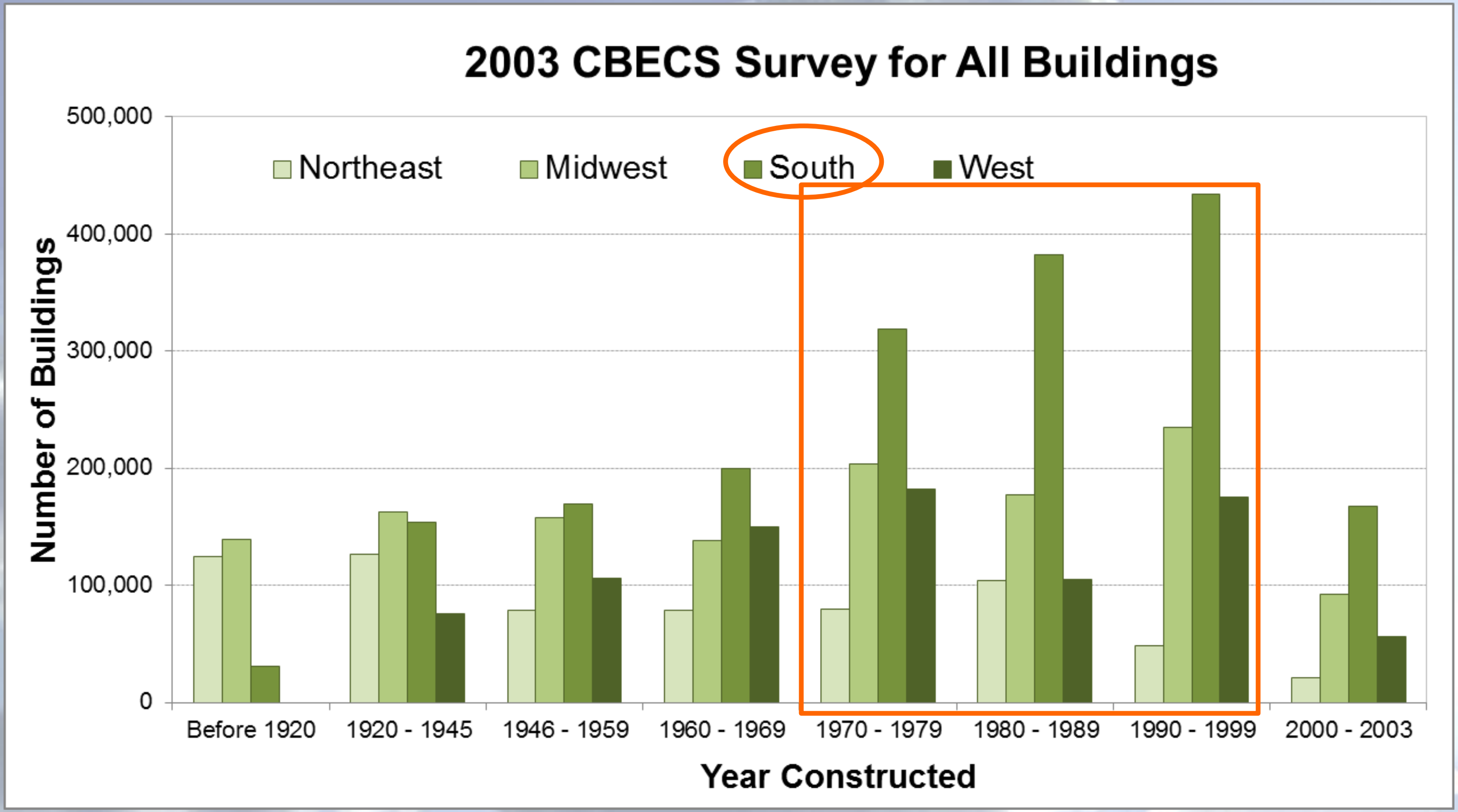
Distribution/Age of U.S. Commercial Buildings

CBECS Survey: U.S. Census Regions and Divisions



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

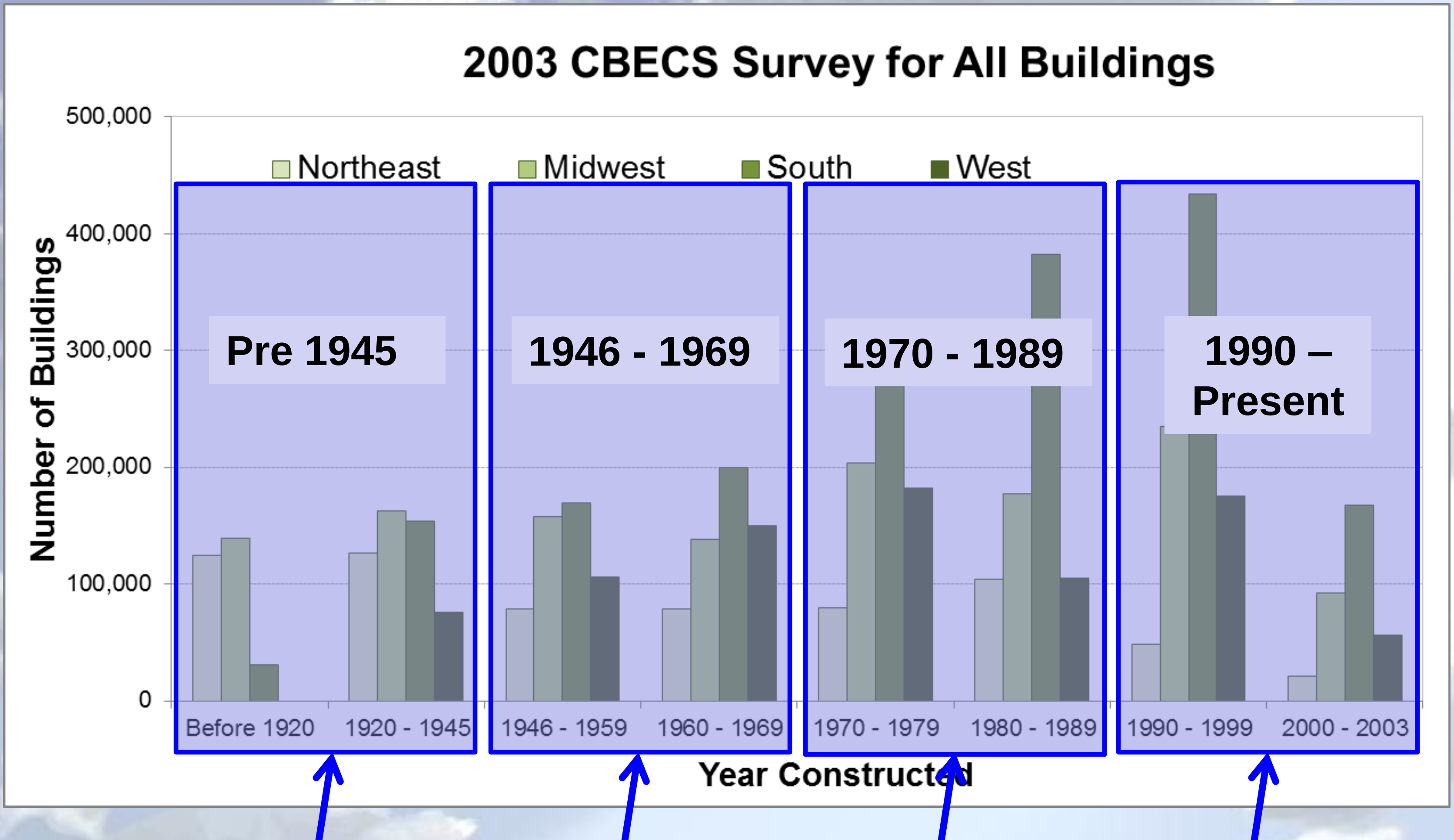
Distribution/Age of U.S. Commercial Buildings



Observations:

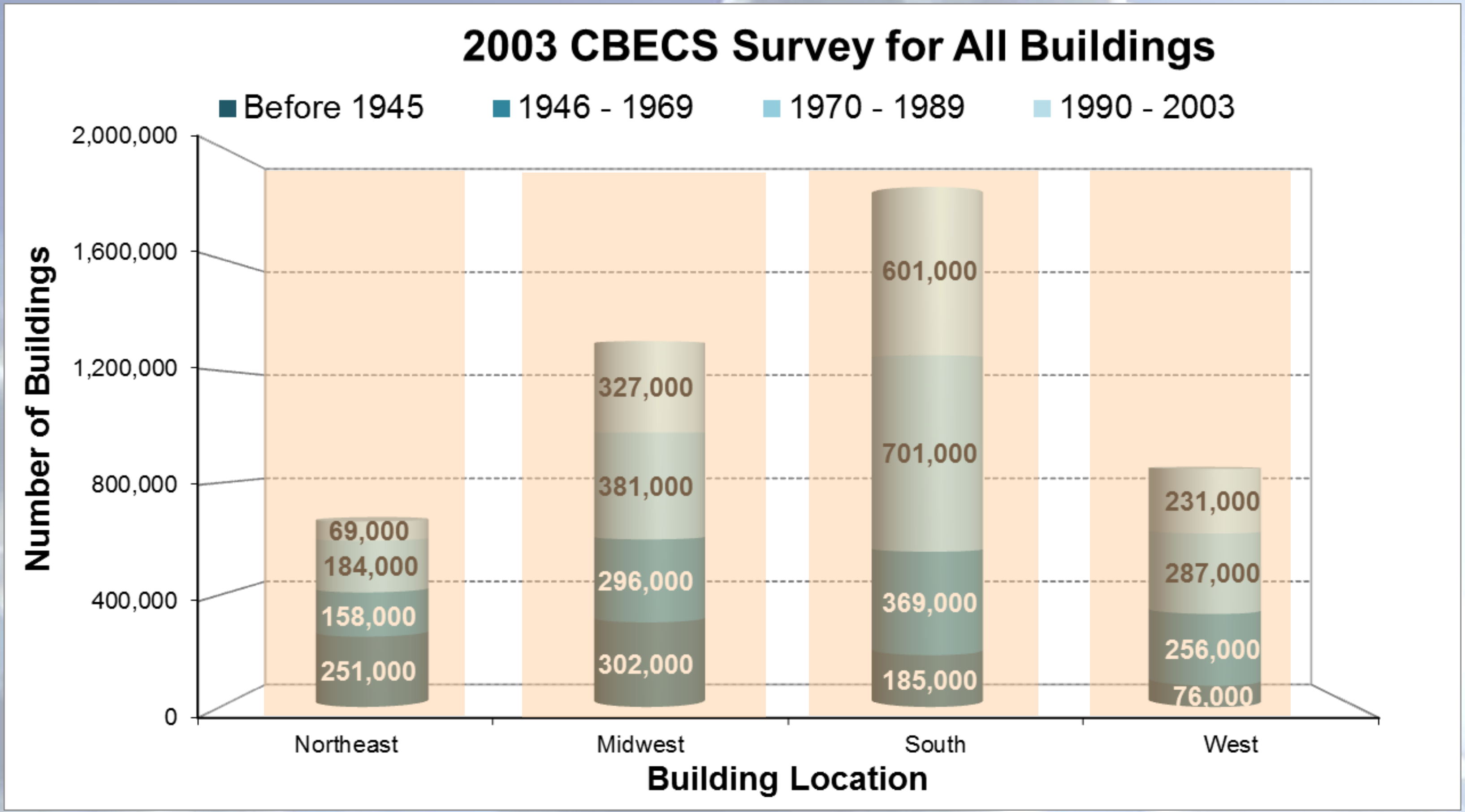
- 52.3% of the buildings were built from1970 to1999
- 39.7% of the buildings were built in South

Distribution/Age of U.S. Commercial Buildings



Pre WW II | **WW II – Pre Computer** | **Early Computer** | **Present**

Distribution/Age of U.S. Commercial Buildings

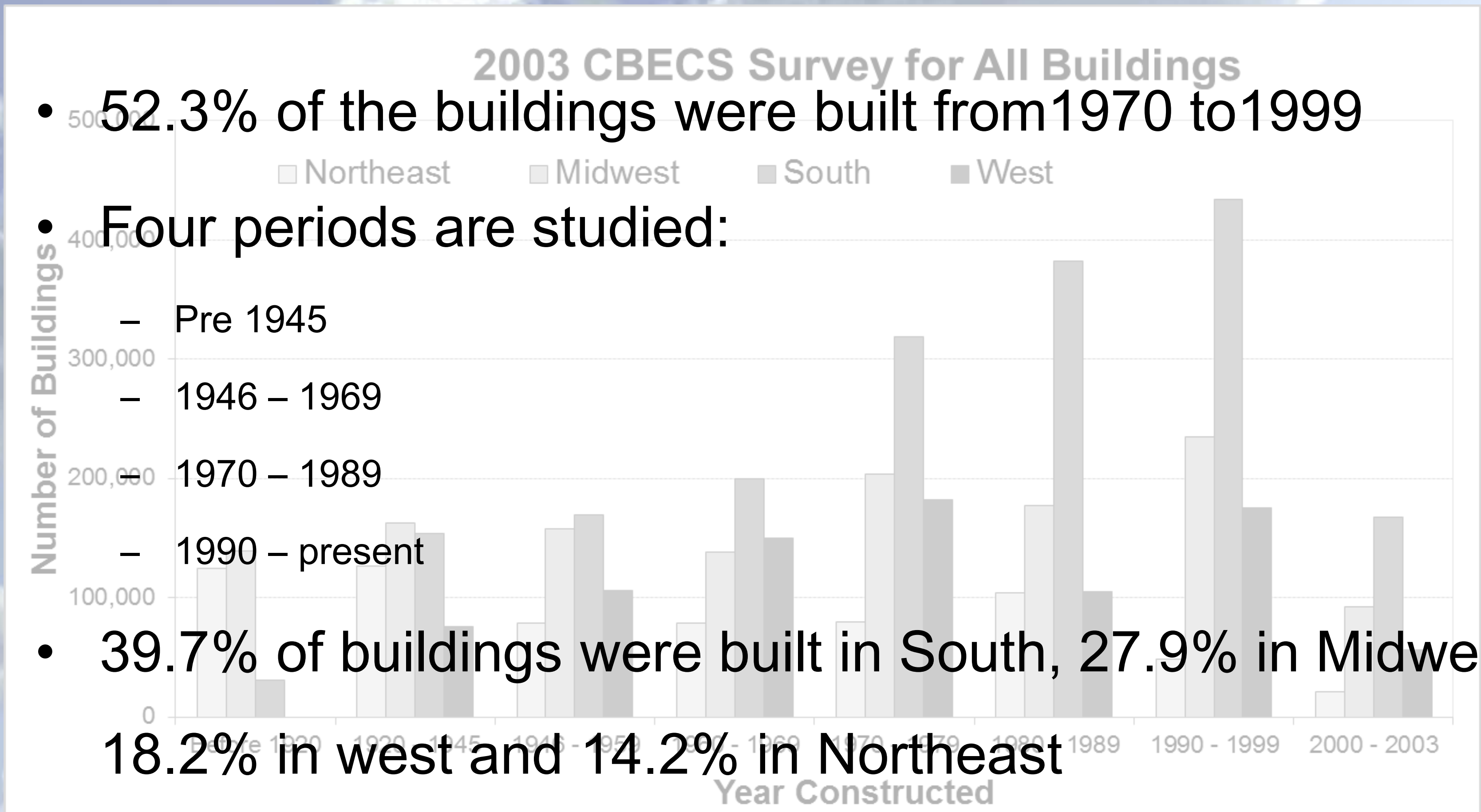


Observations:

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

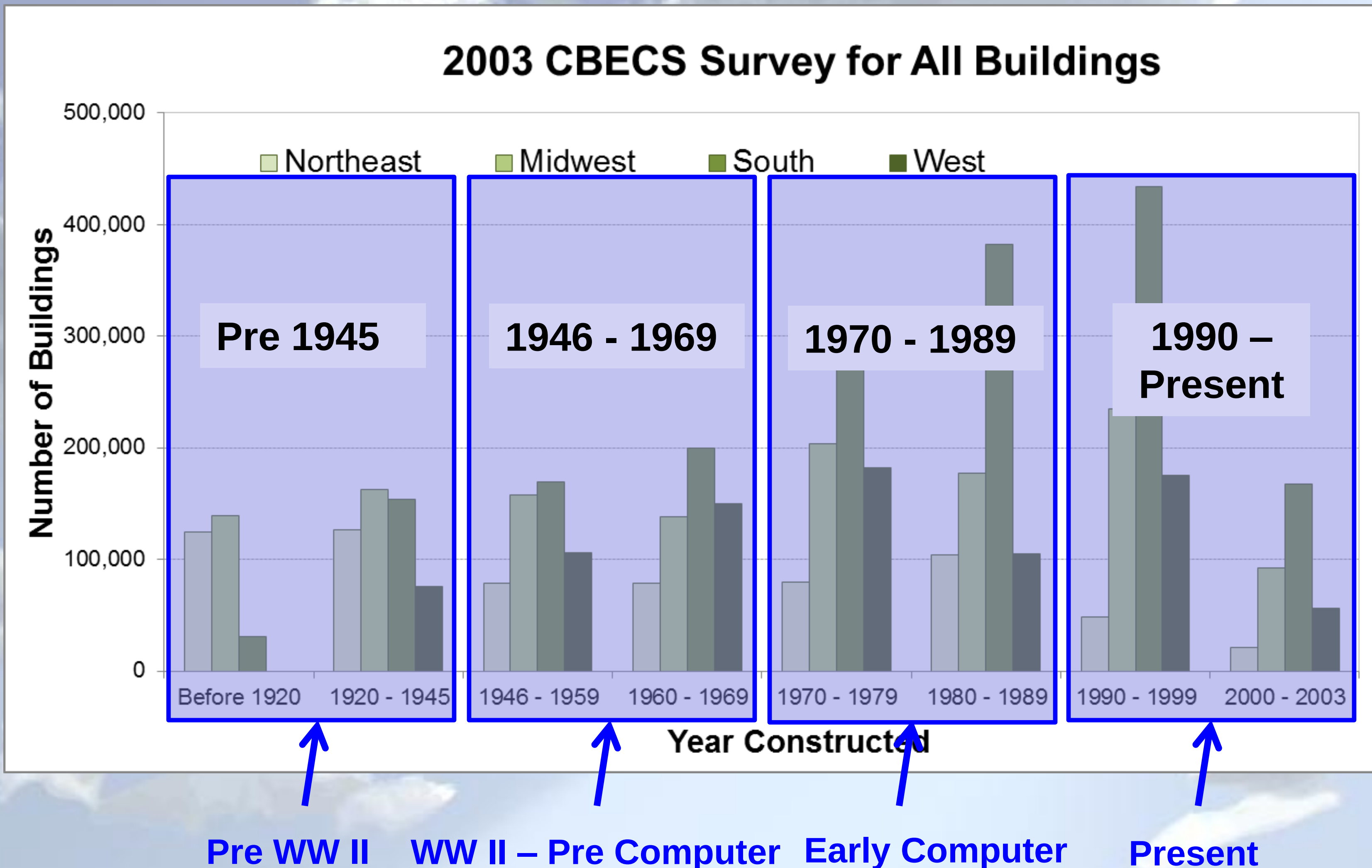
Distribution/Age of U.S. Commercial Buildings

CBECS Survey Summary

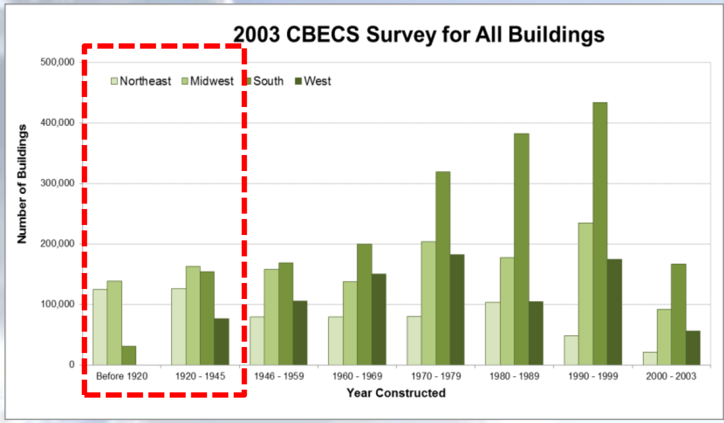


- 52.3% of the buildings were built from1970 to1999
- Four periods are studied:
  - Pre 1945
  - 1946 – 1969
  - 1970 – 1989
  - 1990 – present
- 39.7% of buildings were built in South, 27.9% in Midwest, 18.2% in west and 14.2% in Northeast

History: Building Energy Load Calculation Methods



History: Pre 1945 – Guide Books



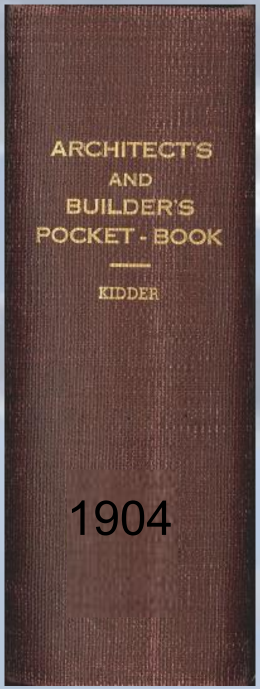
Guide Books:

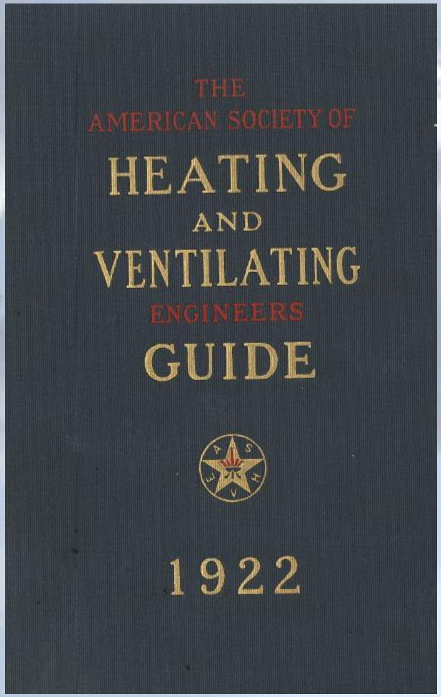
1904 Frank E. *Kidder Architect's and Builder's Handbook*

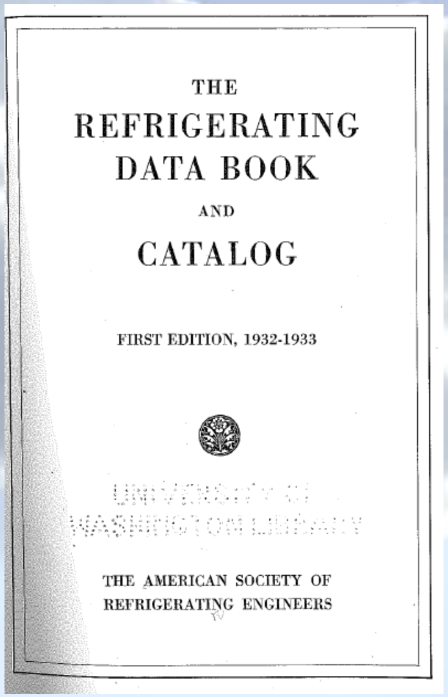
1922 *ASHVE Guide*

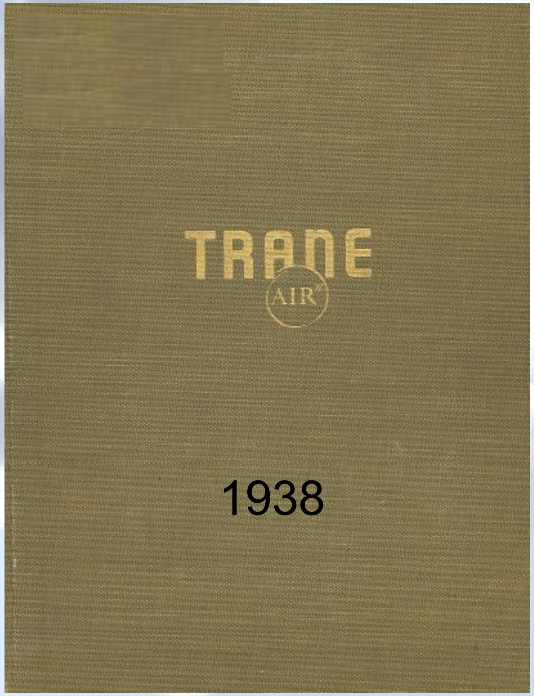
1932 *The Refrigerating Data Book* by ASRE

1938 *Trane Air Conditioning Manual*



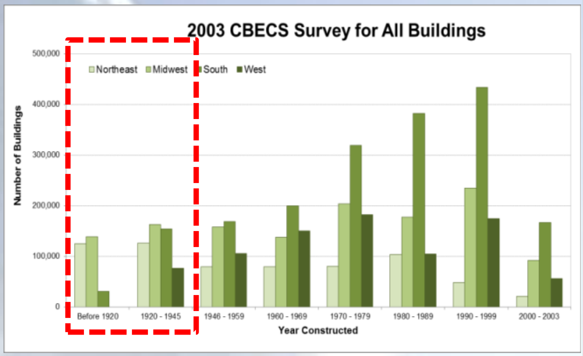






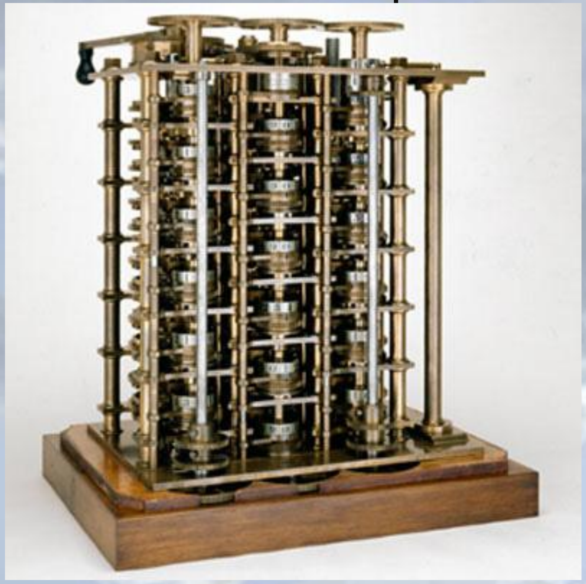
History: Pre 1945 – Guide Books

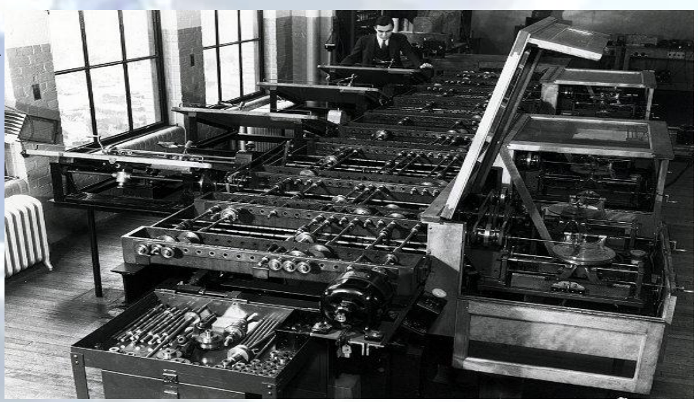
Computer Development:

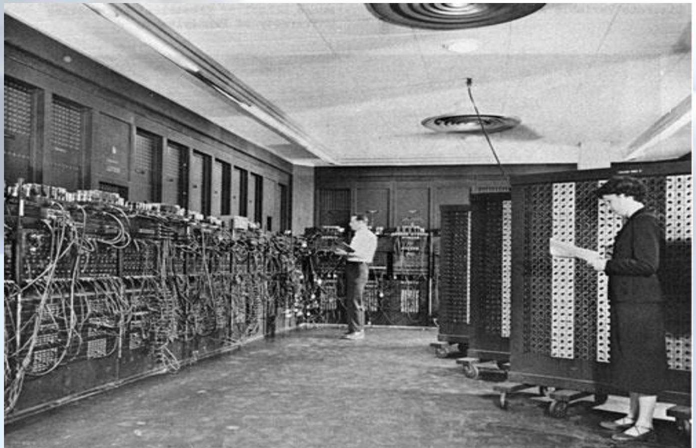


- 1822 - 1832 Charles Babbage and Joseph Clement

  Produced the first Difference Engine
- 1815-1852: first computer programmer: Ada Lovelace
- In 1930, differential analyzer available
- In 1946, first large scale electronic digita 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”

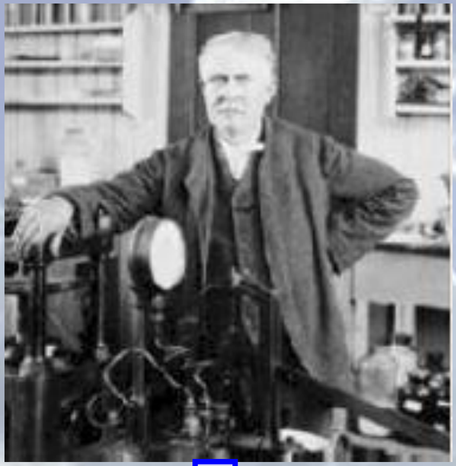
Figure 3: A model of Gorrie’s ice machine from the John Gorrie Museum in Apalachicola, Fla.

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

History: Pre 1945 – Important Developments

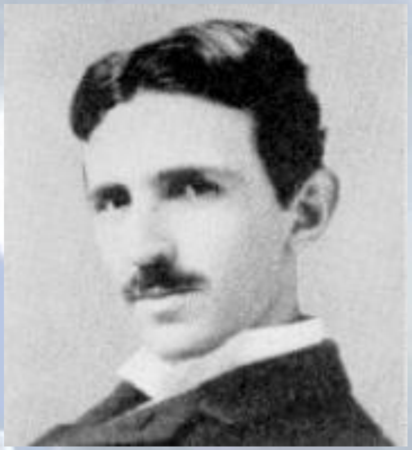
In the late 1880s, "War of the Currents" began between Edison and Tesla

Thomas Edison

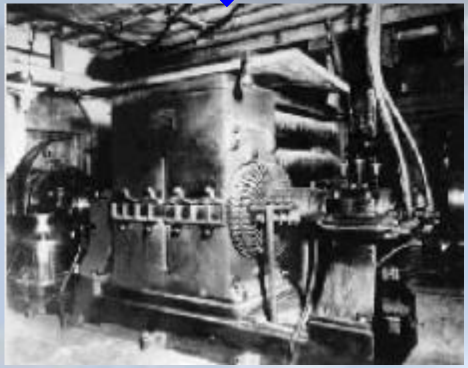


V.S.

Nikola Tesla



DC motor



AC motor

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

History: Pre 1945 – Important Developments

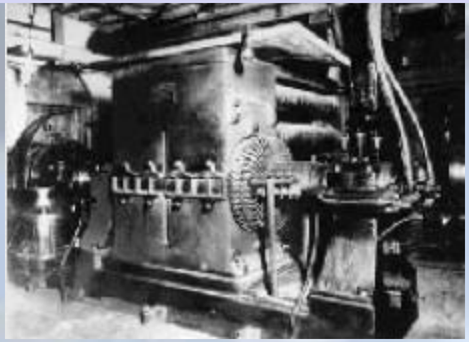
In the late 1880s, "War of the Currents" began between Edison and Tesla

Thomas Edison

V.S.

Nikola Tesla

Before that, air handling systems were steam-driven!



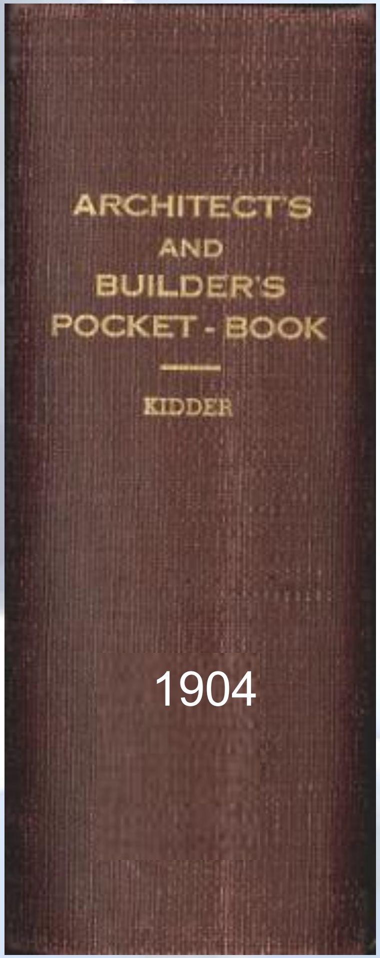
Source: http://staff.fcps.net/rroyster/war.htm

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……"



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

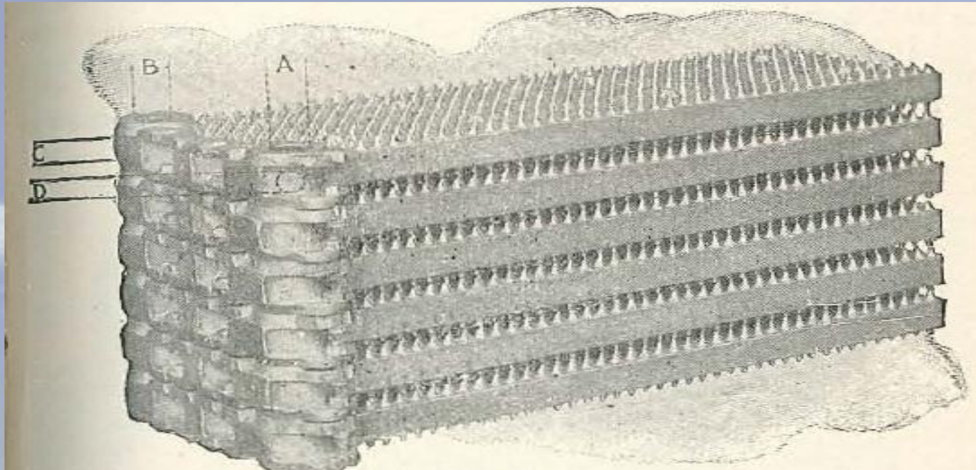


Fig. 10
Perfection Pin, Extra Large, Flange and Bolt.

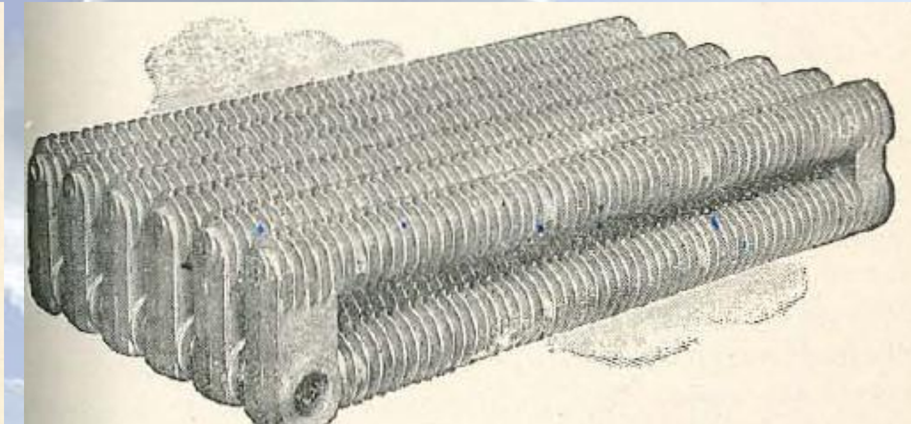


Fig. 11
Excelsior Steam Indirect Radiator.

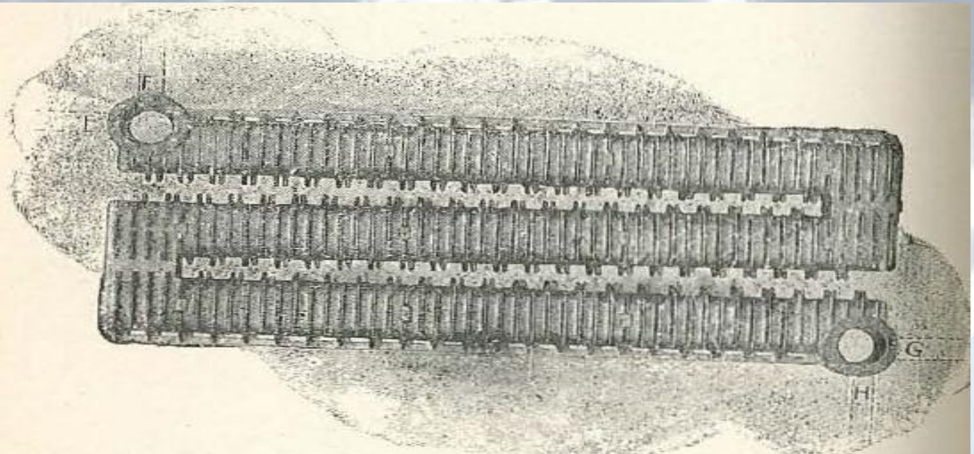
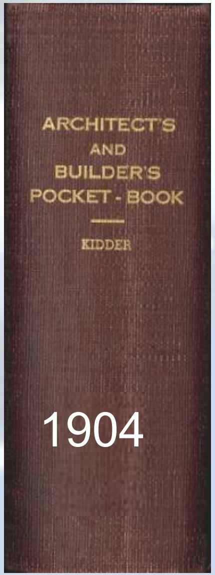


Fig. 12
Sterling Indirect Radiator.



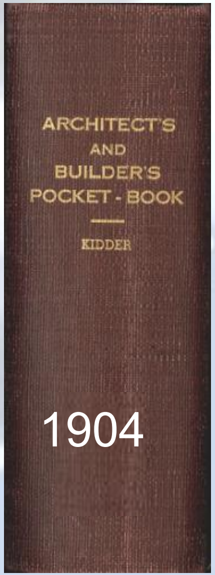
Source: Architect's and Builder's Handbook in 1904 by Frank E. Kidder

History: Pre 1945 – Heating Load Calculation

Radiators

DATA FOR EXCELSIOR INDIRECT STEAM-RADIATORS.

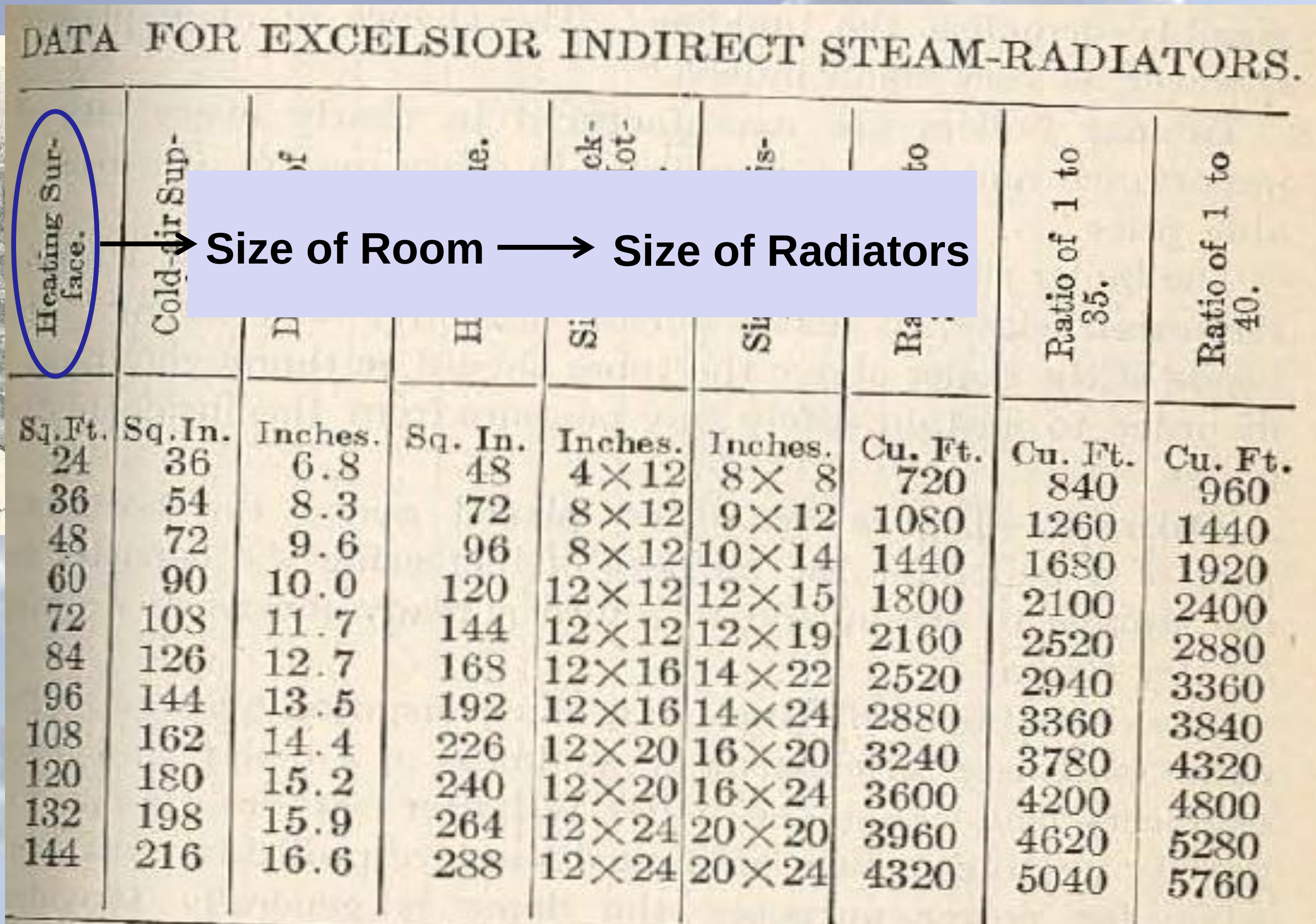
Heating Surface.	Cold-air Supply.	Diameter of Duct if Round.	Hot-air Flue.	Size for Brick-work if Hot-air Flues.	Size of Register.	Ratio of 1 to 30.	Ratio of 1 to 35.	Ratio of 1 to 40.
Sq.Ft.	Sq.In.	Inches.	Sq. In.	Inches.	Inches.	Cu. Ft.	Cu. Ft.	Cu. Ft.
24	36	6.8	48	4×12	8× 8	720	840	960
36	54	8.3	72	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



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

History: Pre 1945 – Heating Load Calculation

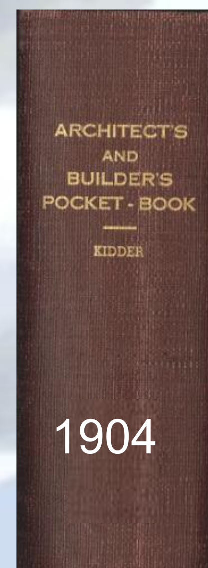
Radiators



DATA FOR EXCELSIOR INDIRECT STEAM-RADIATORS.

Heating Surface.	Cold-air Sup-	D... of	H...e.	Si...ck-...lot-	Si...is-	Ra...to	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.



1904

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

History: Pre 1945 – Heating Load Calculation

Boilers

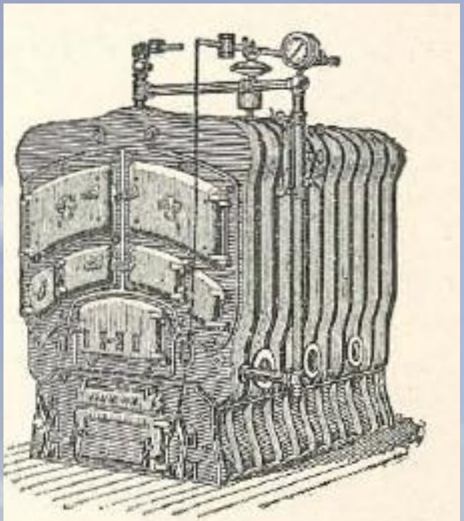


Fig. 15
"Ideal" Sectional Steam Boiler.

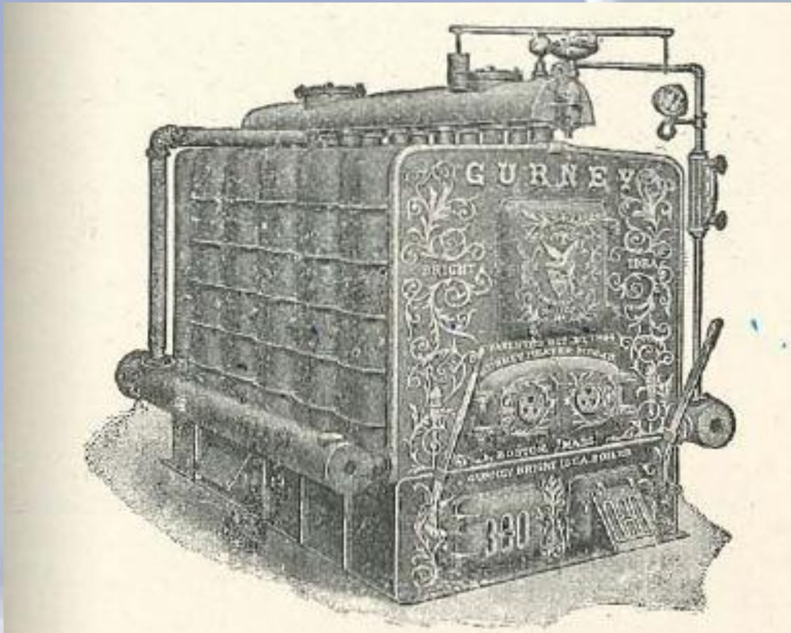


Fig. 16
Gurney Bright Idea Boiler, 1200 Series—Screw-nipple Type.

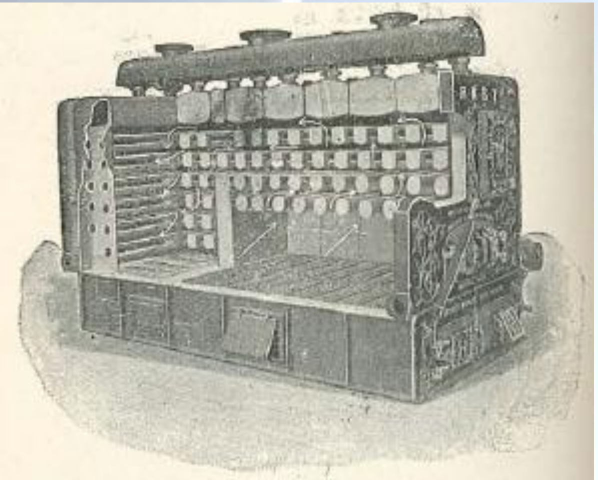
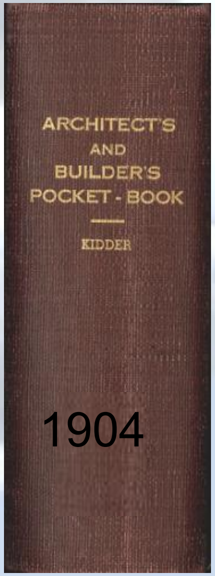


Fig. 17
Sectional View of Gurney Boiler.

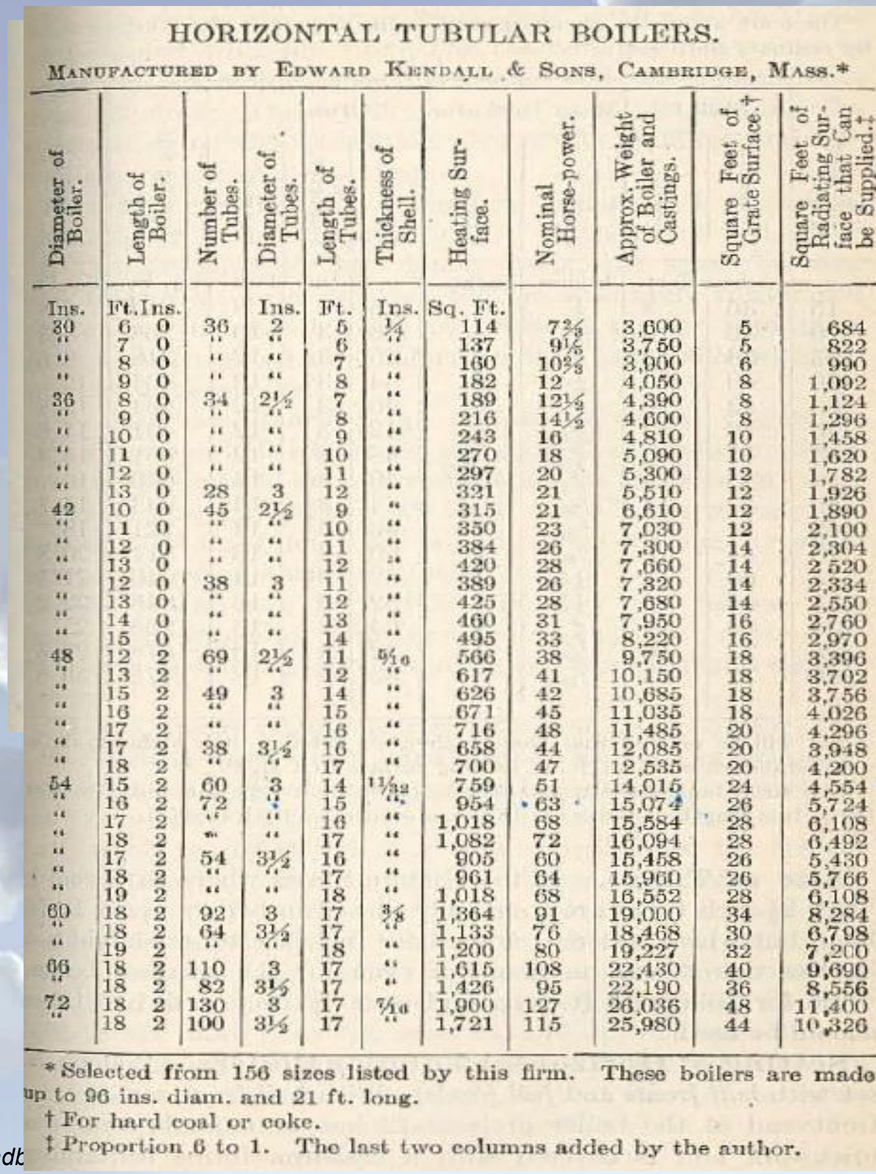


1904

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

History: Pre 1945 – Heating Load Calculation

Boilers



HORIZONTAL TUBULAR BOILERS.

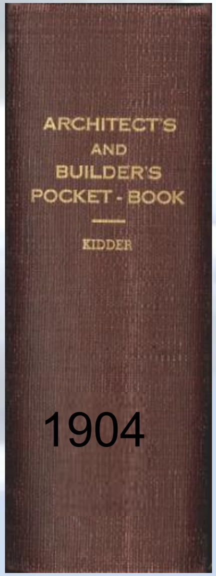
MANUFACTURED BY EDWARD KENDALL & SONS, CAMBRIDGE, MASS.*

Diameter of Boiler.	Length of Boiler.		Number of Tubes.	Diameter of Tubes.	Length of Tubes.	Thickness of Shell.	Heating Surface.	Nominal Horse-power.	Approx. Weight of Boiler and Castings.	Square Feet of Grate Surface.†	Square Feet of Radiating Surface that Can be Supplied.‡
Ins.	Ft.	Ins.		Ins.	Ft.	Ins.	Sq. Ft.				
30	6	0	36	2	5	¼	114	7⅔	3,600	5	684
"	7	0	"	"	6	"	137	9⅓	3,750	5	822
"	8	0	"	"	7	"	160	10⅔	3,900	6	990
"	9	0	"	"	8	"	182	12	4,050	8	1,092
36	8	0	34	2½	7	"	189	12½	4,390	8	1,124
"	9	0	"	"	8	"	216	14½	4,600	8	1,296
"	10	0	"	"	9	"	243	16	4,810	10	1,458
"	11	0	"	"	10	"	270	18	5,090	10	1,620
"	12	0	"	"	11	"	297	20	5,300	12	1,782
"	13	0	28	3	12	"	321	21	5,510	12	1,926
42	10	0	45	2½	9	"	315	21	6,610	12	1,890
"	11	0	"	"	10	"	350	23	7,030	12	2,100
"	12	0	"	"	11	"	384	26	7,300	14	2,304
"	13	0	"	"	12	"	420	28	7,660	14	2 520
"	12	0	38	3	11	"	389	26	7,320	14	2,334
"	13	0	"	"	12	"	425	28	7,680	14	2,550
"	14	0	"	"	13	"	460	31	7,950	16	2,760
"	15	0	"	"	14	"	495	33	8,220	16	2,970
48	12	2	69	2½	11	5/16	566	38	9,750	18	3,396
"	13	2	"	"	12	"	617	41	10,150	18	3,702
"	15	2	49	3	14	"	626	42	10,685	18	3,756
"	16	2	"	"	15	"	671	45	11,035	18	4,026
"	17	2	"	"	16	"	716	48	11,485	20	4,296
"	17	2	38	3½	16	"	658	44	12,085	20	3,948
"	18	2	"	"	17	"	700	47	12,535	20	4,200
54	15	2	60	3	14	11/32	759	51	14,015	24	4,554
"	16	2	72	"	15	"	954	63	15,074	26	5,724
"	17	2	"	"	16	"	1,018	68	15,584	28	6,108
"	18	2	"	"	17	"	1,082	72	16,094	28	6,492
"	17	2	54	3½	16	"	905	60	15,458	26	5,430
"	18	2	"	"	17	"	961	64	15,960	26	5,766
"	19	2	"	"	18	"	1,018	68	16,552	28	6,108
60	18	2	92	3	17	⅜	1,364	91	19,000	34	8,284
"	18	2	64	3½	17	"	1,133	76	18,468	30	6,798
"	19	2	"	"	18	"	1,200	80	19,227	32	7,200
66	18	2	110	3	17	"	1,615	108	22,430	40	9,690
"	18	2	82	3½	17	"	1,426	95	22,190	36	8,556
72	18	2	130	3	17	7/16	1,900	127	26,036	48	11,400
"	18	2	100	3½	17	"	1,721	115	25,980	44	10,326

* Selected from 156 sizes listed by this firm. These boilers are made up to 96 ins. diam. and 21 ft. long.

† For hard coal or coke.

‡ Proportion .6 to 1. The last two columns added by the author.



Source: Architect's and Builder's Handb

History: Pre 1945 – Heating Load Calculation

Boilers

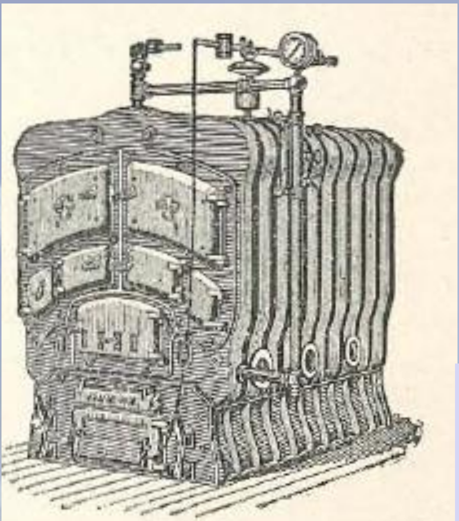


Fig. 15
"Ideal" Sectional Steam Boiler.

HORIZONTAL TUBULAR BOILERS.

MANUFACTURED BY EDWARD KENDALL & SONS, CAMBRIDGE, MASS.*

Diameter of Boiler.	Length of Boiler.		Number of Tubes.	Diameter of Tubes.	Length of Tubes.	Thickness of Shell.	Heating Surface.	Nominal Horse-power.	Approx. Weight of Boiler and Castings.	Square Feet of Grate Surface.†	Square Feet of Radiating Surface that Can be Supplied.‡
Ins.	Ft.	Ins.		Ins.	Ft.	Ins.	Sq. Ft.				
30	6	0	36	2	5	¼	114	7⅗	3,600	5	684
"	7	0	"	"	6	"	137	9⅕	3,750	5	822
"	8	0	"	"	7	"	160	10⅗	3,90[illegible]	6	990
"	9	0	"	"	8	"	182	12	4,0[illegible]	8	1,092
"	13	0	"	"	12	"	420	28	7,660	14	2 520
"	12	0	38	3	11	"	389	26	7,320	14	2,334
"	13	0	"	"	12	"	425	28	7,680	14	2,550
"	14	0	"	"	13	"	460	31	7,950	16	2,760
"	15	0	"	"	14	"	495	33	8,220	16	2,970
48	12	2	69	2½	11	5/16	566	38	9,750	18	3,396
"	13	2	"	"	12	"	617	41	10,150	18	3,702
"	15	2	49	3	14	"	626	42	10,685	18	3,756
"	16	2	"	"	15	"	671	45	11,035	18	4,026
"	17	2	"	"	16	"	716	48	11,485	20	4,296
"	17	2	38	3½	16	"	658	44	12,085	20	3,948
"	18	2	"	"	17	"	700	47	12,535	20	4,200
54	15	2	60	3	14	11/32	759	51	14,015	24	4,554
"	16	2	72	"	15	"	954	63	15,074	26	5,724
"	17	2	"	"	16	"	1,018	68	15,584	28	6,108
"	18	2	"	"	17	"	1,082	72	16,094	28	6,492
"	17	2	54	3½	16	"	905	60	15,458	26	5,430
"	18	2	"	"	17	"	961	64	15,960	26	5,766
"	19	2	"	"	18	"	1,018	68	16,552	28	6,108
60	18	2	92	3	17	⅜	1,364	91	19,000	34	8,284
"	18	2	64	3½	17	"	1,133	76	18,468	30	6,798
"	19	2	"	"	18	"	1,200	80	19,227	32	7,200
66	18	2	110	3	17	"	1,615	108	22,430	40	9,690
"	18	2	82	3½	17	"	1,426	95	22,190	36	8,556
72	18	2	130	3	17	7/16	1,900	127	26,036	48	11,400
"	18	2	100	3½	17	"	1,721	115	25,980	44	10,326

* Selected from 156 sizes listed by this firm. These boilers are made up to 96 ins. diam. and 21 ft. long.

† For hard coal or coke.

‡ Proportion 6 to 1. The last two columns added by the author.

No. of Radiators ⟶ Size of Boilers

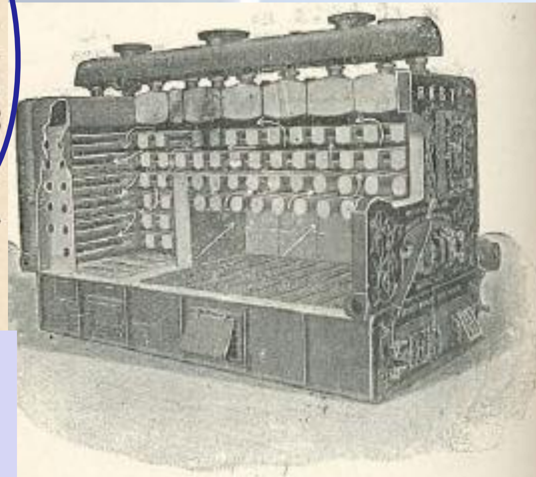
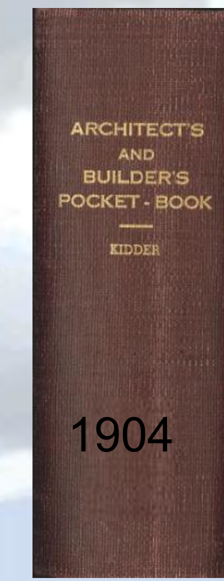


Fig. 17
Sectional View of Gurney Boiler.



1904

Source: Architect's and Builder's Handb

History: Pre 1945 – Heating Load Calculation

Boilers

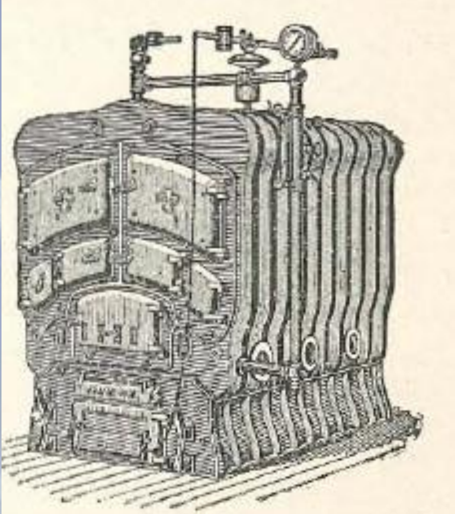
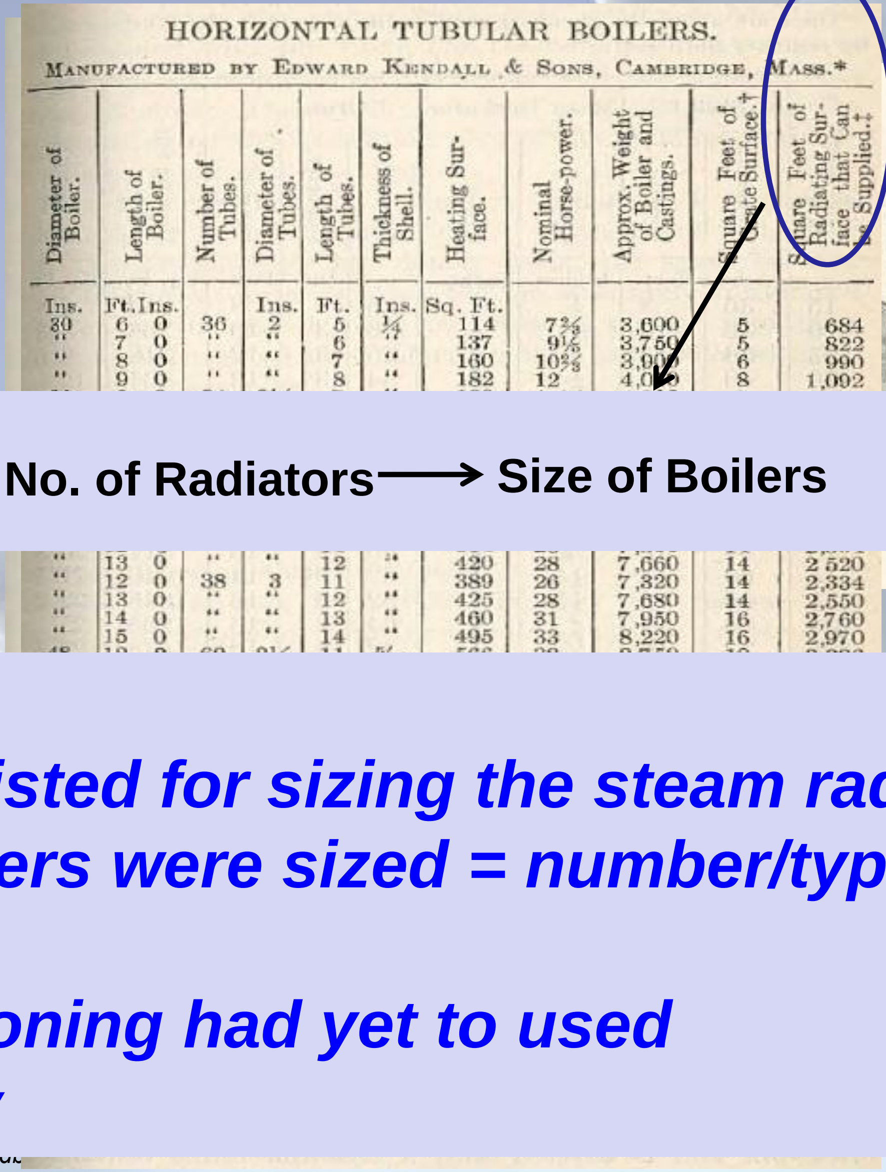


Fig. 15
"Ideal" Sectional Steam Boiler.



HORIZONTAL TUBULAR BOILERS.

MANUFACTURED BY EDWARD KENDALL & SONS, CAMBRIDGE, MASS.*

Diameter of Boiler.	Length of Boiler.	Number of Tubes.	Diameter of Tubes.	Length of Tubes.	Thickness of Shell.	Heating Surface.	Nominal Horse-power.	Approx. Weight of Boiler and Castings.	Square Feet of Grate Surface.†	Square Feet of Radiating Surface that Can be Supplied.‡
Ins.	Ft. Ins.		Ins.	Ft.	Ins.	Sq. Ft.				
30	6 0	36	2	5	1/4	114	7 3/4	3,600	5	684
"	7 0	"	"	6	"	137	9 1/8	3,750	5	822
"	8 0	"	"	7	"	160	10 5/8	3,900	6	990
"	9 0	"	"	8	"	182	12	4,0[illegible]	8	1,092
"	13 0	"	"	12	"	420	28	7,660	14	2,520
"	12 0	38	3	11	"	389	26	7,320	14	2,334
"	13 0	"	"	12	"	425	28	7,680	14	2,550
"	14 0	"	"	13	"	460	31	7,950	16	2,760
"	15 0	"	"	14	"	495	33	8,220	16	2,970

No. of Radiators ⟶ Size of Boilers

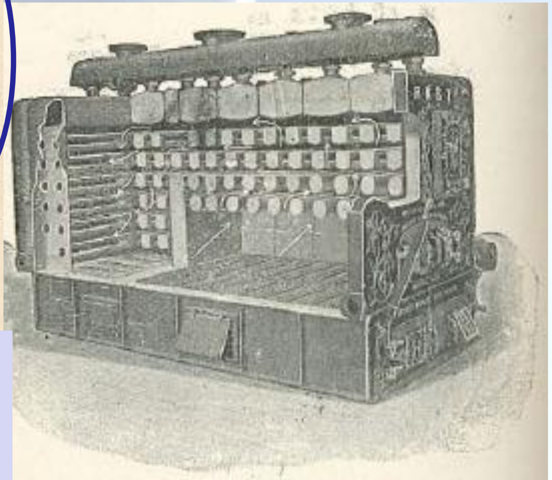
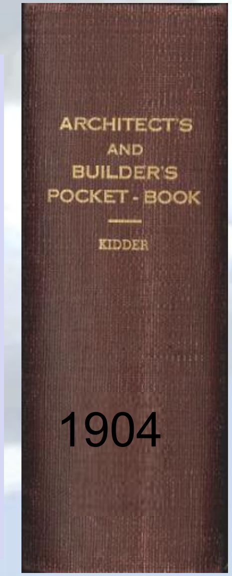


Fig. 17
Sectional View of Gurney Boiler.

1904:

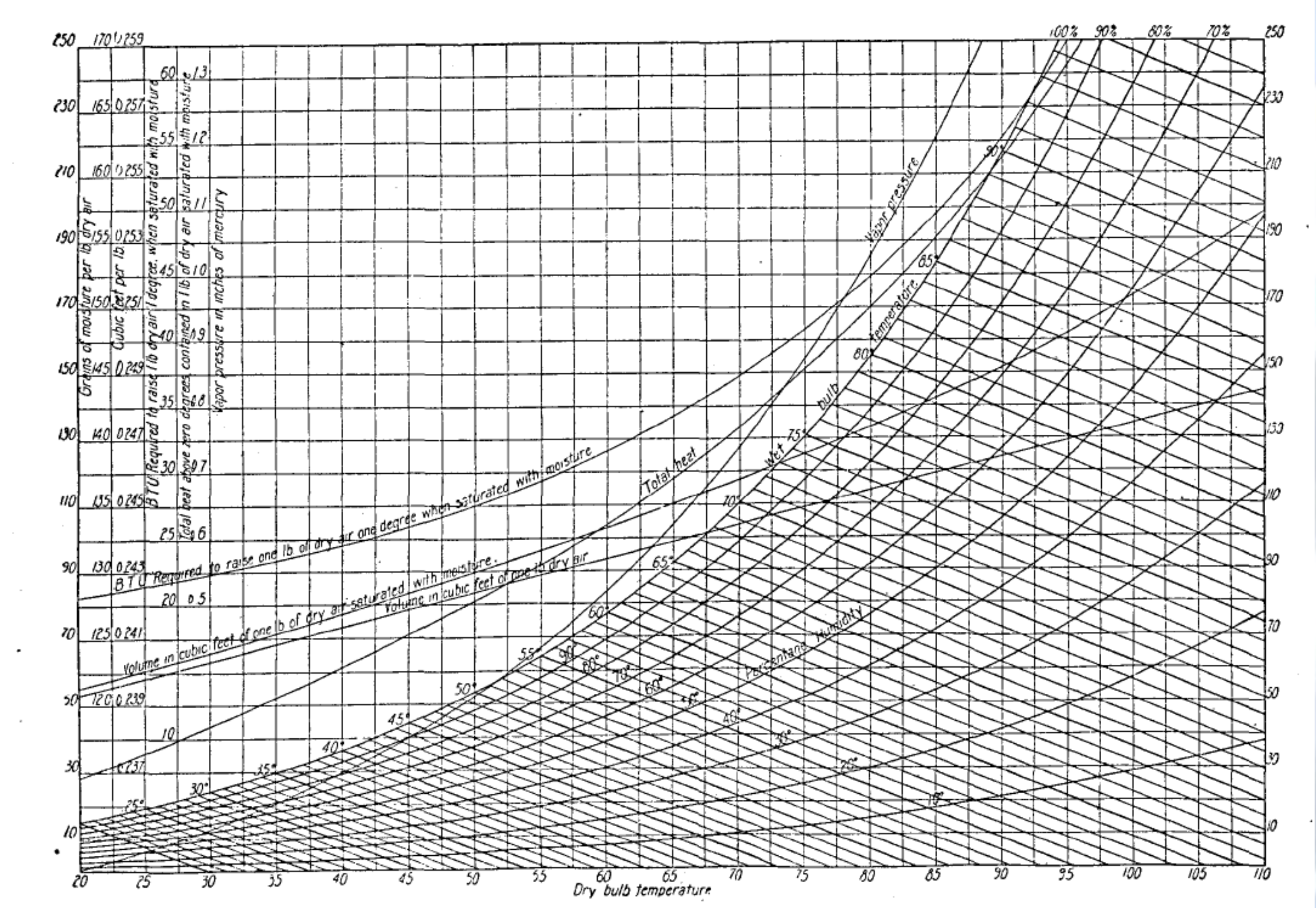
- ***Method existed for sizing the steam radiator***
- ***Steam boilers were sized = number/type of radiators***
- ***Air conditioning had yet to used commercially***



Source: Architect's and Builder's Handb

History: Pre 1945 – Heating Load Calculation

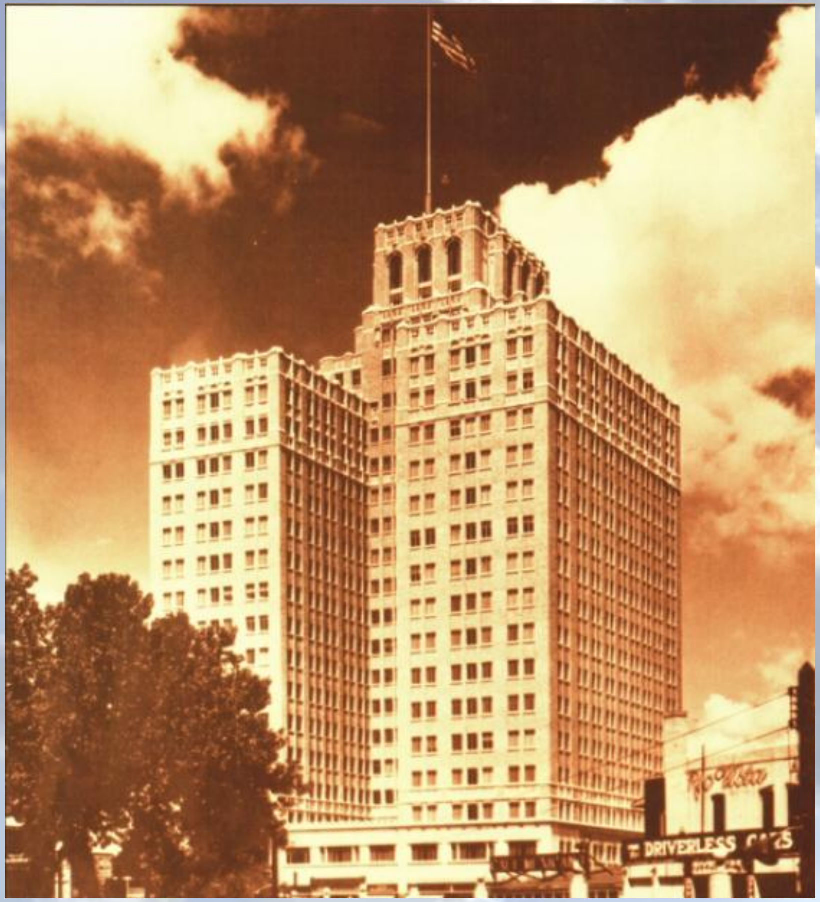
In 1911, Willis Carrier developed his ***Psychrometric chart***



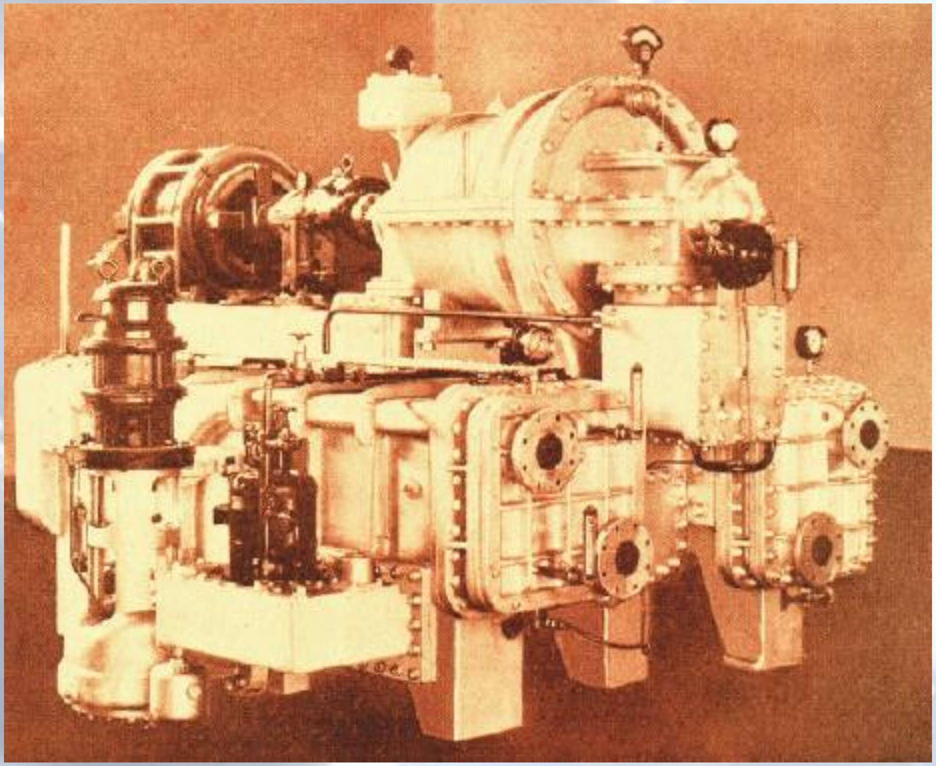
Source: Carrier, W., 1911. Rational Psychrometric Formulae: their relation to the problems of meteorology and of air conditioning. ASME Transactions, Vol.33

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

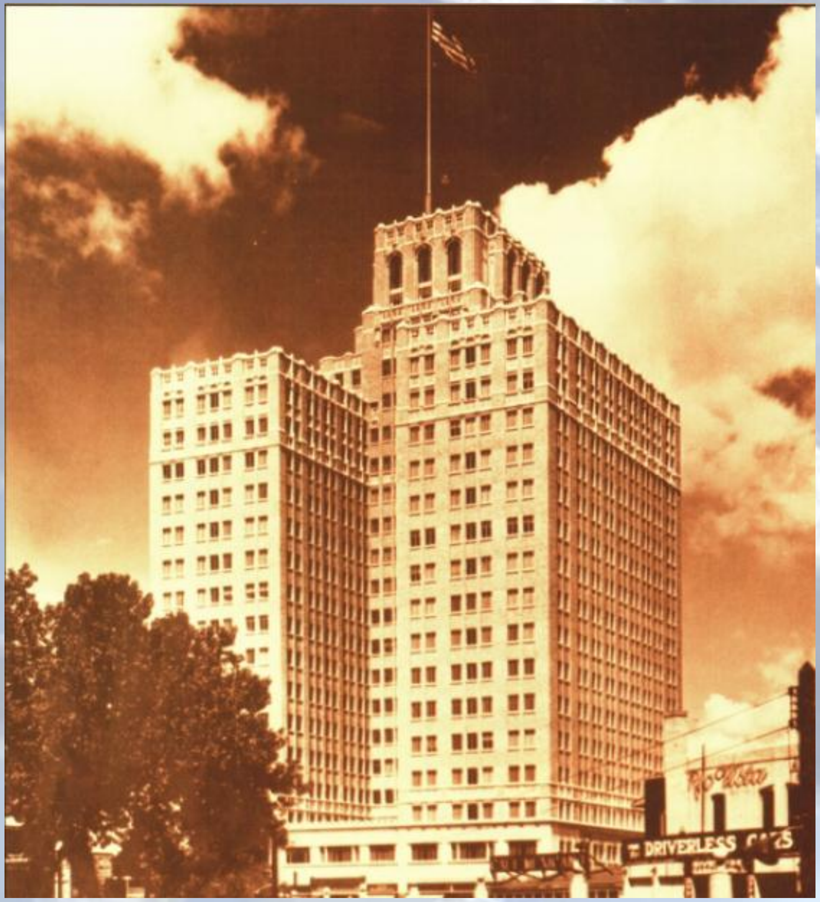


Original Carrier Centrifugal Refrigeration Unit

*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”



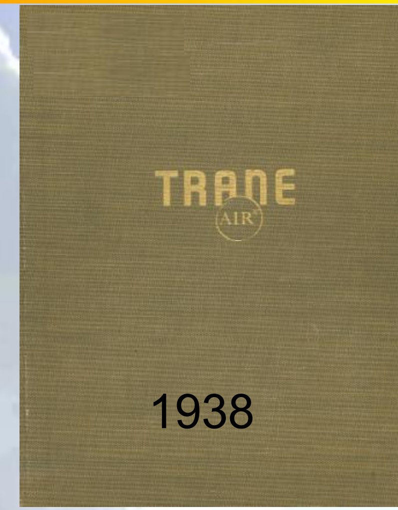
The Milam Building

- 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 damprs were Added to Solve the Problem

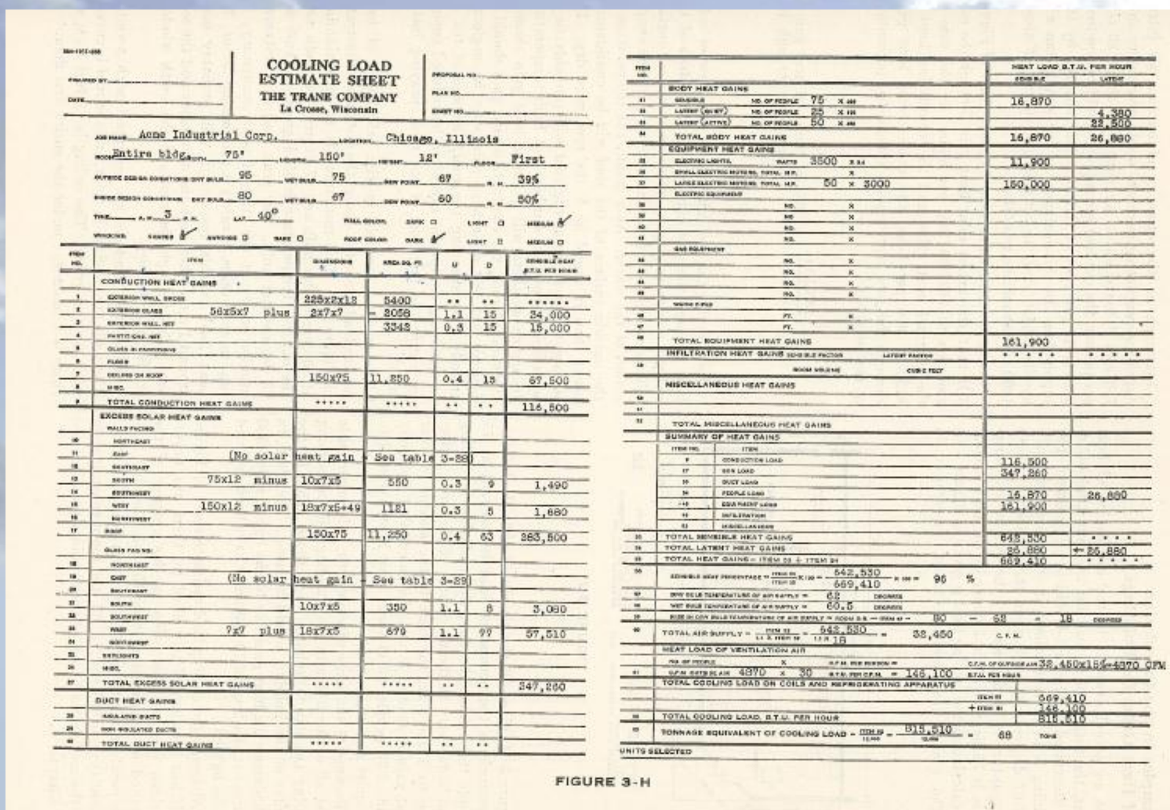
*Source:www.alamoashrae.org/database/articles/**Milam_Building**_Report.pdf*

History: Pre 1945 – Cooling Load Calculation

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.



1938



COOLING LOAD ESTIMATE SHEET
THE TRANE COMPANY
La Crosse, Wisconsin

PREPARED BY ____ DATE ____ PROPOSAL NO. ____ PLAN NO. ____ SHEET NO. ____

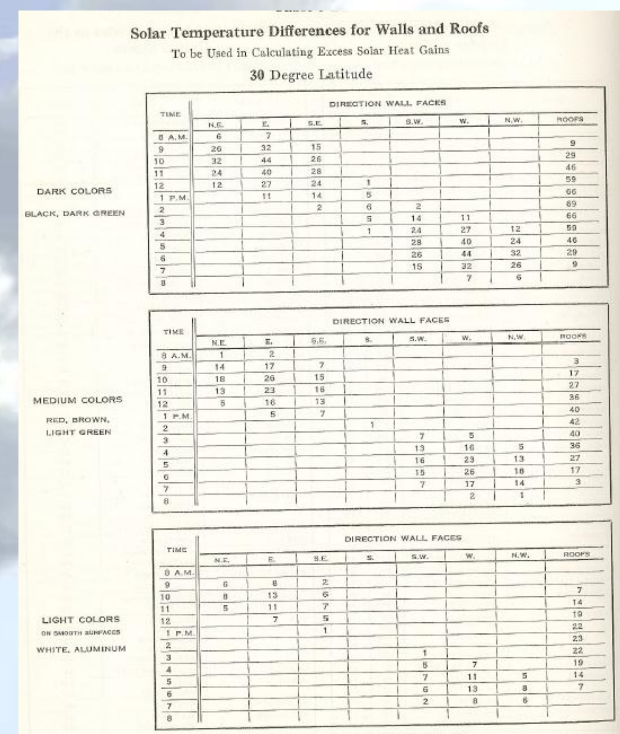
JOB NAME Acme Industrial Corp. LOCATION Chicago, Illinois
ROOM Entire bldg. WIDTH 75' LENGTH 150' HEIGHT 12' FLOOR First
OUTSIDE DESIGN CONDITIONS DRY BULB 95 WET BULB 75 DEW POINT 67 R. H. 39%
INSIDE DESIGN CONDITIONS DRY BULB 80 WET BULB 67 DEW POINT 60 R. H. 50%
TIME ____ A. M. 3 P. M. LAT. 40°
WALL COLOR: DARK ☐ LIGHT ☐ MEDIUM ✓
WINDOWS: SHADES ✓ AWNINGS ☐ BARE ☐ ROOF COLOR: DARK ✓ LIGHT ☐ MEDIUM ☐

ITEM NO.	ITEM		DIMENSIONS	AREA SQ. FT.	U	D	SENSIBLE HEAT B.T.U. PER HOUR
	CONDUCTION HEAT GAINS						
1	EXTERIOR WALL, GROSS		225x2x12	5400	**	**	******
2	EXTERIOR GLASS	56x5x7 plus	2x7x7	- 2058	1.1	15	34,000
3	EXTERIOR WALL, NET			3342	0.3	15	15,000
4	PARTITIONS, NET						
5	GLASS IN PARTITIONS						
6	FLOOR						
7	CEILING OR ROOF		150x75	11,250	0.4	15	67,500
8	MISC.						
9	TOTAL CONDUCTION HEAT GAINS		*****	*****	**	**	116,500
	EXCESS SOLAR HEAT GAINS						
	WALLS FACING						
10	NORTHEAST						
11	EAST	(No solar	heat gain -	See table	3-38)		
12	SOUTHEAST						
13	SOUTH	75x12 minus	10x7x5	550	0.3	9	1,490
14	SOUTHWEST						
15	WEST	150x12 minus	18x7x5+49	1181	0.3	5	1,880
16	NORTHWEST						
17	ROOF		150x75	11,250	0.4	63	283,500
	GLASS FACING						
18	NORTHEAST						
19	EAST	(No solar	heat gain -	See table	3-39)		
20	SOUTHEAST						
21	SOUTH		10x7x5	350	1.1	8	3,080
22	SOUTHWEST						
23	WEST	7x7 plus	18x7x5	679	1.1	77	57,510
24	NORTHWEST						
25	SKYLIGHTS						
26	MISC.						
27	TOTAL EXCESS SOLAR HEAT GAINS		*****	*****	**	**	347,260
	DUCT HEAT GAINS						
28	INSULATED DUCTS						
29	NON INSULATED DUCTS						
30	TOTAL DUCT HEAT GAINS		*****	*****	**	**	

ITEM NO.		HEAT LOAD B.T.U. PER HOUR SENSIBLE	LATENT
	BODY HEAT GAINS		
31	SENSIBLE NO. OF PEOPLE 75 x 225	16,870	
32	LATENT (QUIET) NO. OF PEOPLE 25 x 175		4,380
33	LATENT (ACTIVE) NO. OF PEOPLE 50 x 450		22,500
34	TOTAL BODY HEAT GAINS	16,870	26,880
	EQUIPMENT HEAT GAINS		
35	ELECTRIC LIGHTS, WATTS 3500 x 3.4	11,900	
36	SMALL ELECTRIC MOTORS, TOTAL H.P. x		
37	LARGE ELECTRIC MOTORS, TOTAL H.P. 50 x 3000	150,000	
	ELECTRIC EQUIPMENT		
38	NO. x		
39	NO. x		
40	NO. x		
41	NO. x		
	GAS EQUIPMENT		
42	NO. x		
43	NO. x		
44	NO. x		
45	NO. x		
	STEAM PIPES		
46	FT. x		
47	FT. x		
48	TOTAL EQUIPMENT HEAT GAINS	161,900	
	INFILTRATION HEAT GAINS SENSIBLE FACTOR LATENT FACTOR	*****	*****
49	ROOM VOLUME CUBIC FEET		
	MISCELLANEOUS HEAT GAINS		
50			
51			
52	TOTAL MISCELLANEOUS HEAT GAINS		
	SUMMARY OF HEAT GAINS (ITEM NO. / ITEM)		
	9 CONDUCTION LOAD	116,500	
	27 SUN LOAD	347,260	
	30 DUCT LOAD		
	34 PEOPLE LOAD	16,870	26,880
	48 EQUIPMENT LOAD	161,900	
	49 INFILTRATION		
	52 MISCELLANEOUS		
53	TOTAL SENSIBLE HEAT GAINS	642,530	****
54	TOTAL LATENT HEAT GAINS	26,880	← 26,880
55	TOTAL HEAT GAINS = ITEM 53 + ITEM 54	669,410	*****

56 SENSIBLE HEAT PERCENTAGE = ITEM 53 / ITEM 55 x 100 = 642,530 / 669,410 x 100 = 96 %
57 DRY BULB TEMPERATURE OF AIR SUPPLY = 62 DEGREES
58 WET BULB TEMPERATURE OF AIR SUPPLY = 60.5 DEGREES
59 RISE IN DRY BULB TEMPERATURE OF AIR SUPPLY = ROOM D.B. — ITEM 57 = 80 — 62 = 18 DEGREES
60 TOTAL AIR SUPPLY = ITEM 53 / 1.1 x ITEM 59 = 642,530 / 1.1 x 18 = 32,450 C. F. M.
HEAT LOAD OF VENTILATION AIR
NO. OF PEOPLE x C.F.M. PER PERSON = C.F.M. OF OUTSIDE AIR 32,450x15%=4870 CFM
61 C.F.M. OUTSIDE AIR 4870 x 30 B.T.U. PER C.F.M. = 146,100 B.T.U. PER HOUR
TOTAL COOLING LOAD ON COILS AND REFRIGERATING APPARATUS
ITEM 55 669,410
+ ITEM 61 146,100
62 TOTAL COOLING LOAD, B.T.U. PER HOUR 815,510
63 TONNAGE EQUIVALENT OF COOLING LOAD = ITEM 62 / 12,000 = 815,510 / 12,000 = 68 TONS
UNITS SELECTED

FIGURE 3-H



Solar Temperature Differences for Walls and Roofs
To be Used in Calculating Excess Solar Heat Gains
30 Degree Latitude

DARK COLORS
BLACK, DARK GREEN

TIME	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	ROOFS
8 A.M.	6	7						
9	26	32	15					9
10	32	44	26					29
11	24	40	28					46
12	12	27	24	1				59
1 P.M.		11	14	5				66
2			2	6	2			69
3				5	14	11		66
4				1	24	27	12	59
5					28	40	24	46
6					26	44	32	29
7					15	32	26	9
8						7	6	

MEDIUM COLORS
RED, BROWN, LIGHT GREEN

TIME	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	ROOFS
8 A.M.	1	2						
9	14	17	7					3
10	18	26	15					17
11	13	23	16					27
12	5	16	13					36
1 P.M.		5	7					40
2				1				42
3					7	5		40
4					13	16	5	36
5					16	29	13	27
6					15	26	18	17
7					7	17	14	3
8						2	1	

LIGHT COLORS ON SMOOTH SURFACES
WHITE, ALUMINUM

TIME	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	ROOFS
8 A.M.								
9	6	8	2					
10	8	13	6					7
11	5	11	7					14
12		7	5					19
1 P.M.			1					22
2								23
3					1			22
4					5	7		19
5					7	11	5	14
6					6	13	8	7
7					2	8	6	
8								

Source: 1938 TRANE Air Conditioning Manual

History: Pre 1945 – Load Estimate Sheet

TRANE Air-Conditioning Manual

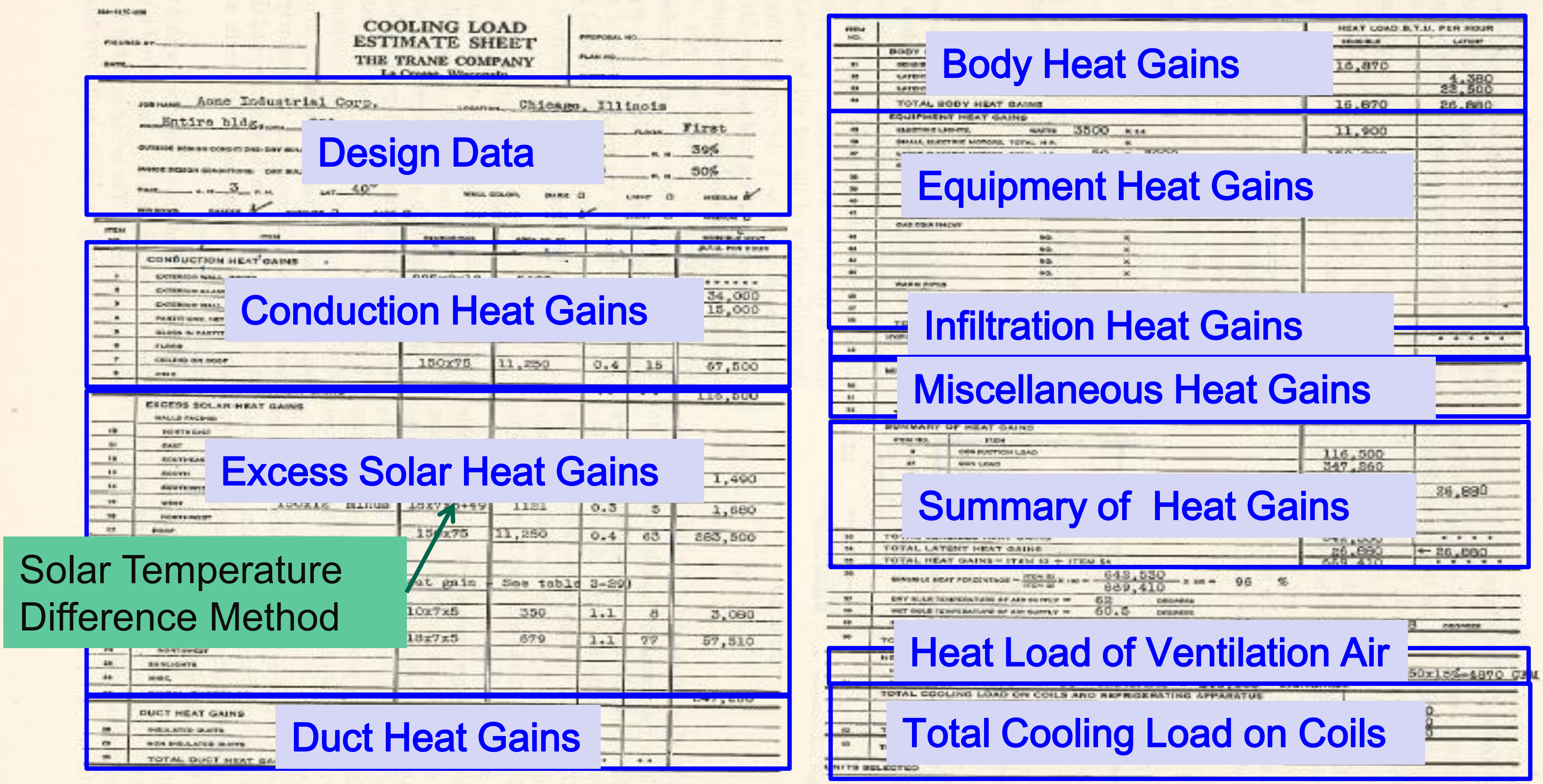
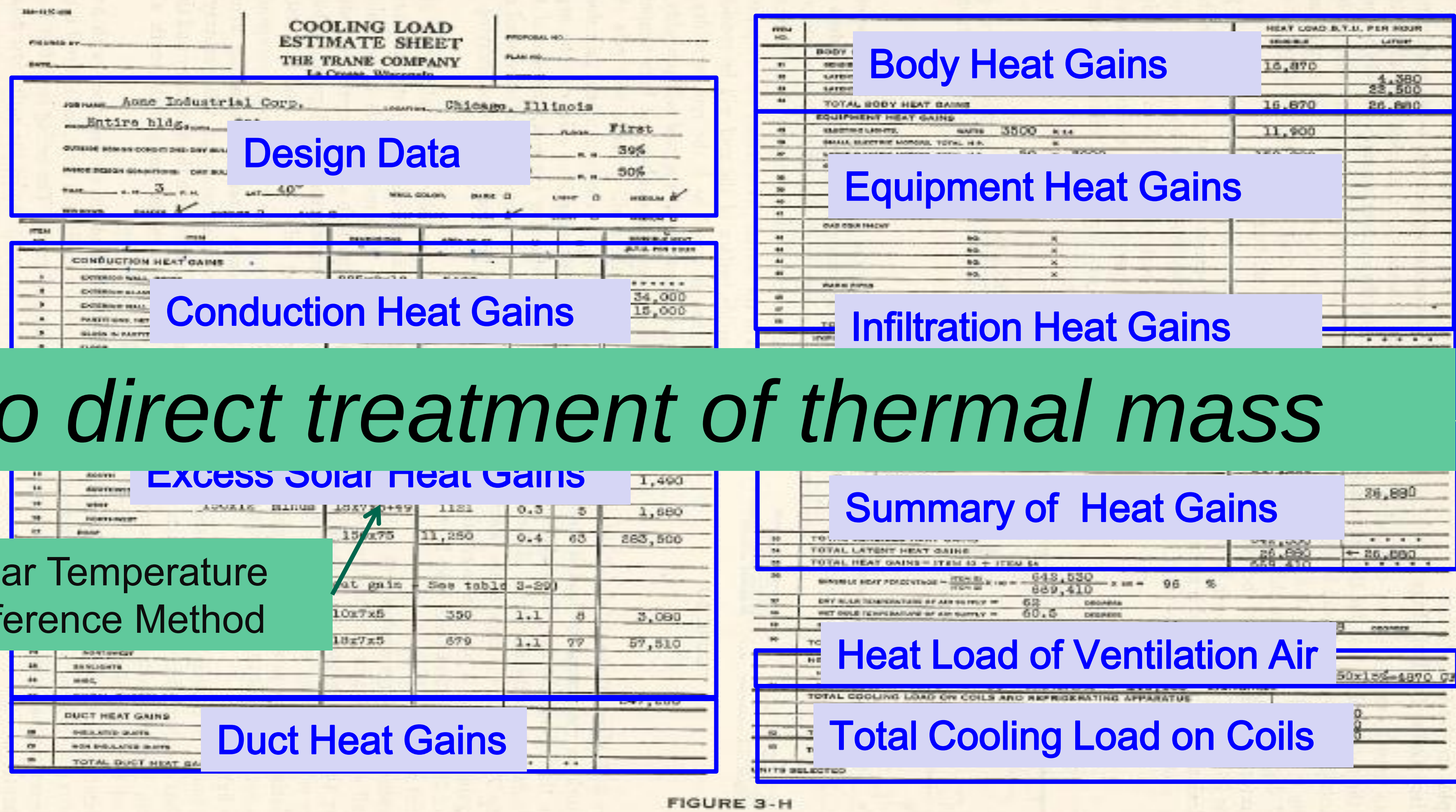


FIGURE 3-H

History: Pre 1945 – Load Estimate Sheet

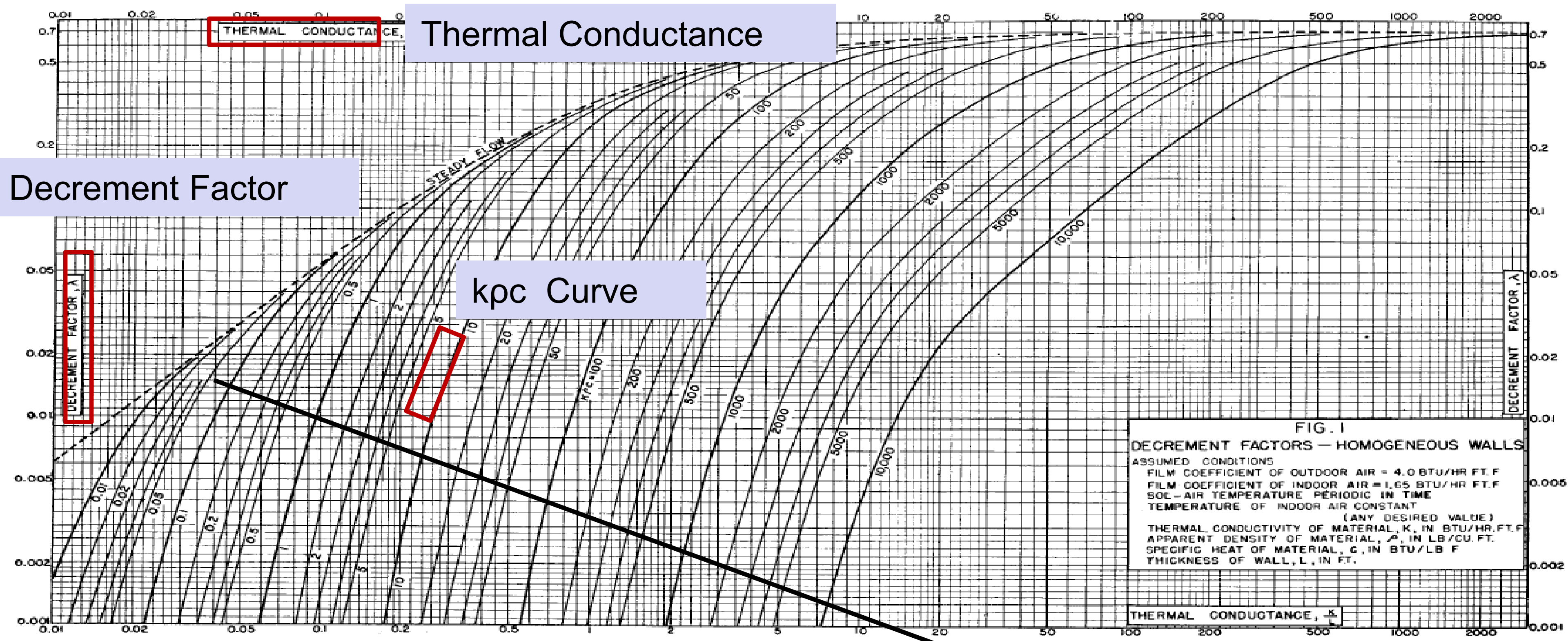
TRANE Air-Conditioning Manual



No direct treatment of thermal mass

History: Pre 1945 – Cooling Load Calculation

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



Inside Surface Temperature

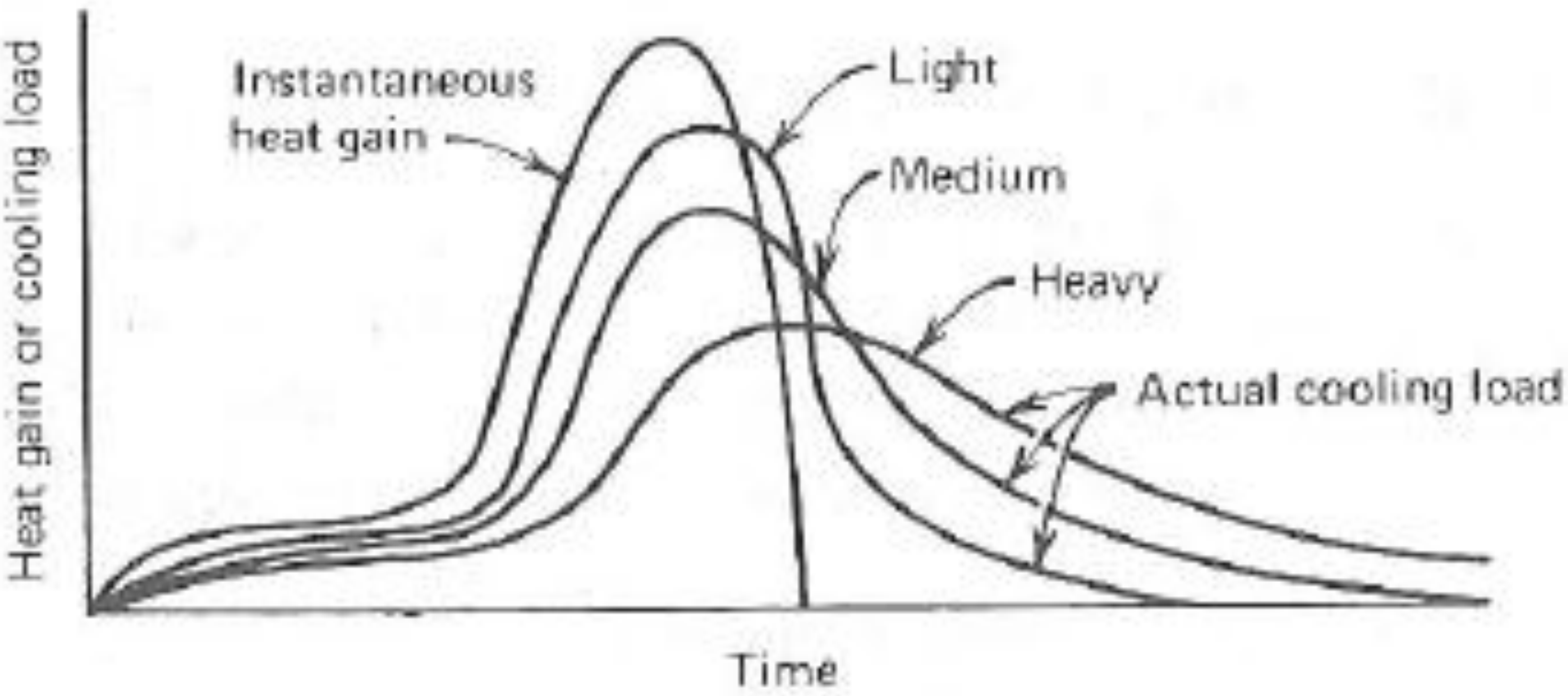
$$t_o = t_i + \frac{0.606(t_m - t_i)}{0.856 + L/k} + \sum_{n=1}^{\infty} \lambda_n t_n \cos(15n\theta - \alpha_n - \phi_n)$$

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

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

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



Inside Surface Temperature

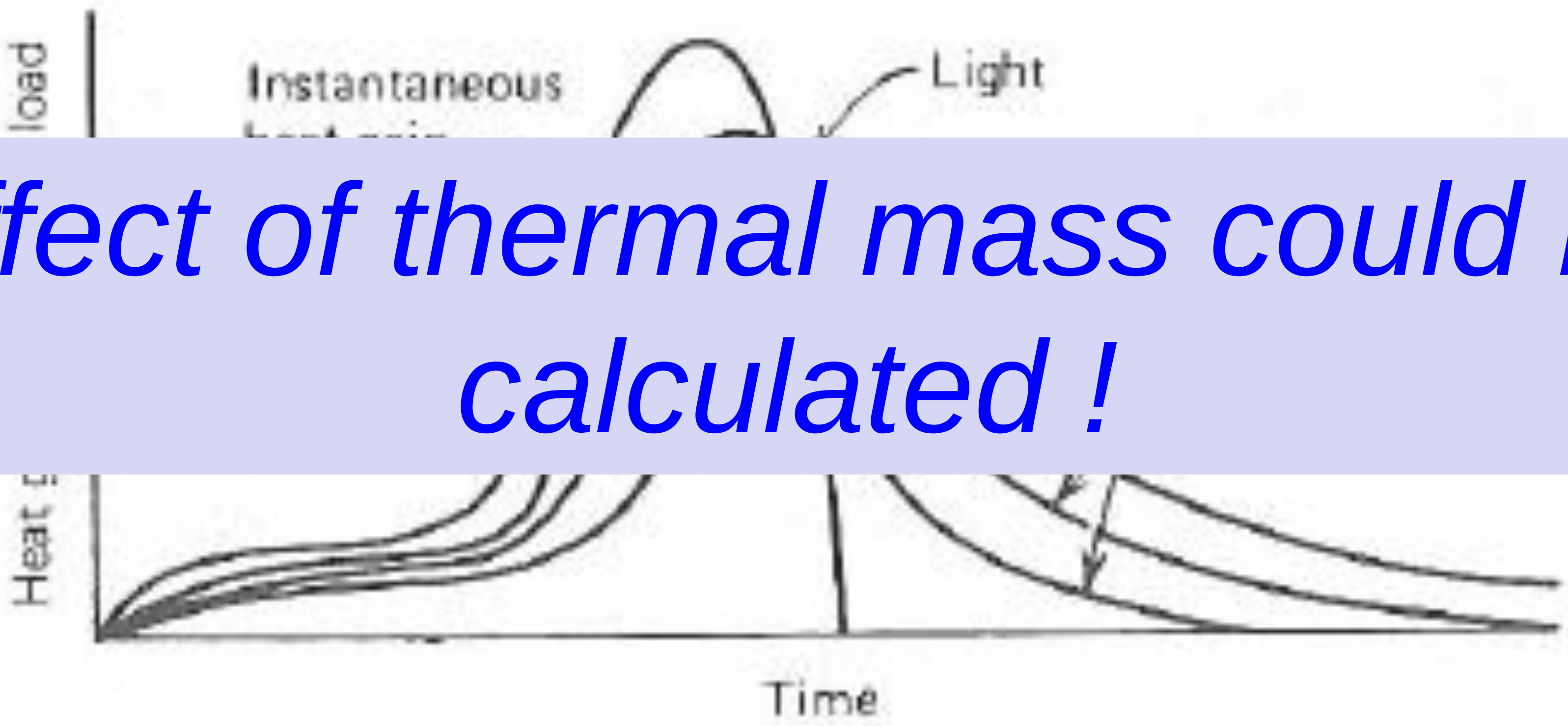
$$t_o = t_i + \frac{0.606(t_m - t_i)}{0.856 + L/k} + \sum_{n=1}^{\infty} \lambda_n t_n \cos(15n\theta - \alpha_n - \phi_n)$$

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

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

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.

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 in 1961, sol-air temperature method was tabulated in the ***ASHRAE Guide and Data Book – Fundamentals and Equipment***

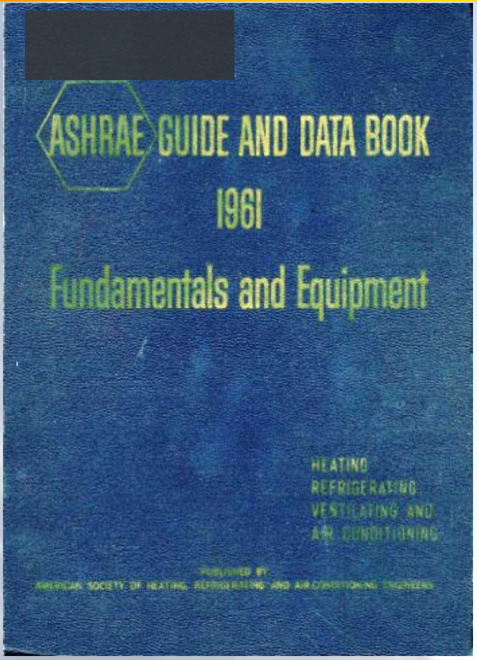


Table 8 . . . . Summer Design Sol-Air Temperatures Used for Tables 9 and 10

Mean Sun Time	Sol-Air Temperature t_e, Fahrenheit Degrees: Any Surface[b]	Horiz.	North	East		South		West	
Ratio[a]: $\frac{\alpha}{f_{co}}$	0	0.225	0	0.225	0.125	0.225	0.125	0.225	0.125
12 Midnight	77	77	77	77	77	77	77	77	77
1 AM	76	76	76	76	76	76	76	76	76
2	76	76	76	76	76	76	76	76	76
3	75	75	75	75	75	75	75	75	75
4	74	74	74	74	74	74	74	74	74
5	74	74	74	75	80	74	74	74	74
6	74	76	74	110	93	74	74	74	74
7	75	91	75	123	100	75	75	75	75
8	77	106	77	126	103	82	78	77	77
9	80	119	80	125	104	93	86	80	80
10	83	129	83	117	100	102	93	83	83
11	87	137	87	108	96	110	99	89	87
12 Noon	90	142	90	92	92	114	104	96	92
1 PM	93	144	93	93	93	115	105	110	102
2	94	140	94	95	94	111	104	124	111
3	95	132	95	95	95	104	100	135	119
4	94	120	94	94	94	99	96	141	120
5	93	107	93	93	93	95	94	139	118
6	91	96	91	91	91	91	91	125	111
7	87	90	87	87	87	88	87	103	94
8	85	85	85	85	85	85	85	85	85
9	83	83	83	83	83	83	83	83	83
10	81	81	81	81	81	81	81	81	81
11	79	79	79	79	79	79	79	79	79
24 Hr Avg. t_m	83.1	100.5	83.1	93.0	88.4	89.0	86.2	93.0	88.4

[a] α = surface absorptivity, dimensionless, roof = 0.9; dark walls = 0.9, and light walls = 0.5. f_{co} = unit convective conductance = 4.0 Btu per (hr) (F deg).

[b] Values in this column are magnitudes of t_o, the outdoor air temperature.

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

History: Pre 1945 – Cooling Load Calculation

1961 ASHRAE Guide and Data Book – Fundamentals and Equipment – Total Equivalent Temperature Difference tabulated in the Handbook

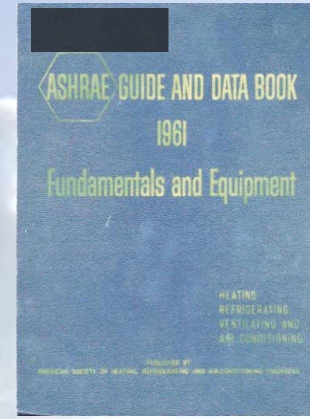
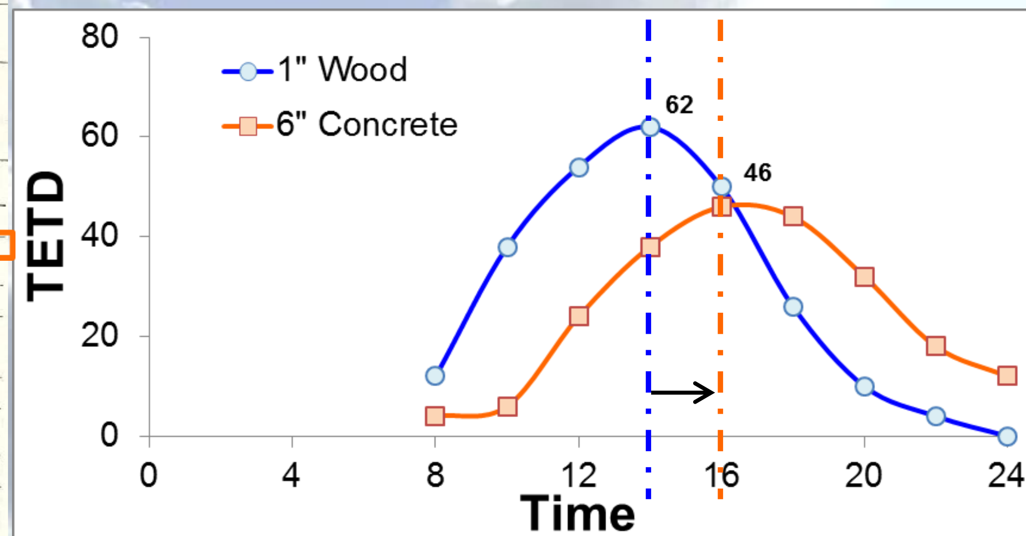


Table 9. . . . Total Equivalent Temperature Differentials for Calculating Heat Gain Through Sunlit and Shaded Roofs

Description of Roof Construction[a]	Sun Time A.M. 8	10	12	P.M. 2	4	6	8	10	12
Light Construction Roofs—Exposed to Sun									
1" Wood[b] or 1" Wood[b] + 1" or 2" insulation	12	38	54	62	50	26	10	4	0
Medium Construction Roofs—Exposed to Sun									
2" Concrete or 2" Concrete + 1" or 2" insulation or 2" Wood[b]	6	30	48	58	50	32	14	6	2
2" Gypsum or 2" Gypsum + 1" insulation; 1" Wood[b] or 2" Wood[b] or 2" Concrete or 2" Gypsum + 4" rock wool in furred ceiling	0	20	40	52	54	42	20	10	6
4" Concrete or 4" Concrete with 2" insulation	0	20	38	50	52	40	22	12	6
Heavy Construction Roofs—Exposed to Sun									
6" Concrete	4	6	24	38	46	44	32	18	12
6" Concrete + 2" insulation	[illegible]	[illegible]	20	34	42	44	34	20	14
Roofs Covered with Water—Exposed to Sun									
Light construction roof with 1" water	0	4	16	22	18	14	10	2	0
Heavy construction roof with 1" water	−2	−2	−4	10	14	16	14	10	6
Any roof with 6" water	−2	0	0	6	10	10	8	4	0
Roofs with Roof Sprays—Exposed to Sun									
Light construction	0	4	12	18	16	14	10	2	0
Heavy construction	−2	−2	2	8	12	14	12	10	6
Roofs in Shade									
Light construction	−4	0	6	12	14	12	8	2	0
Medium construction	−4	−2	2	8	12	12	10	6	2
Heavy construction	−2	−2	0	4	8	10	10	8	4

[a] Includes ¾ in. felt roofing with ...



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

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

History: Pre 1945 – Cooling Load Calculation

1961 ASHRAE Guide and Data Book – Fundamentals and Equipment – Total Equivalent Temperature Difference tabulated in the Handbook

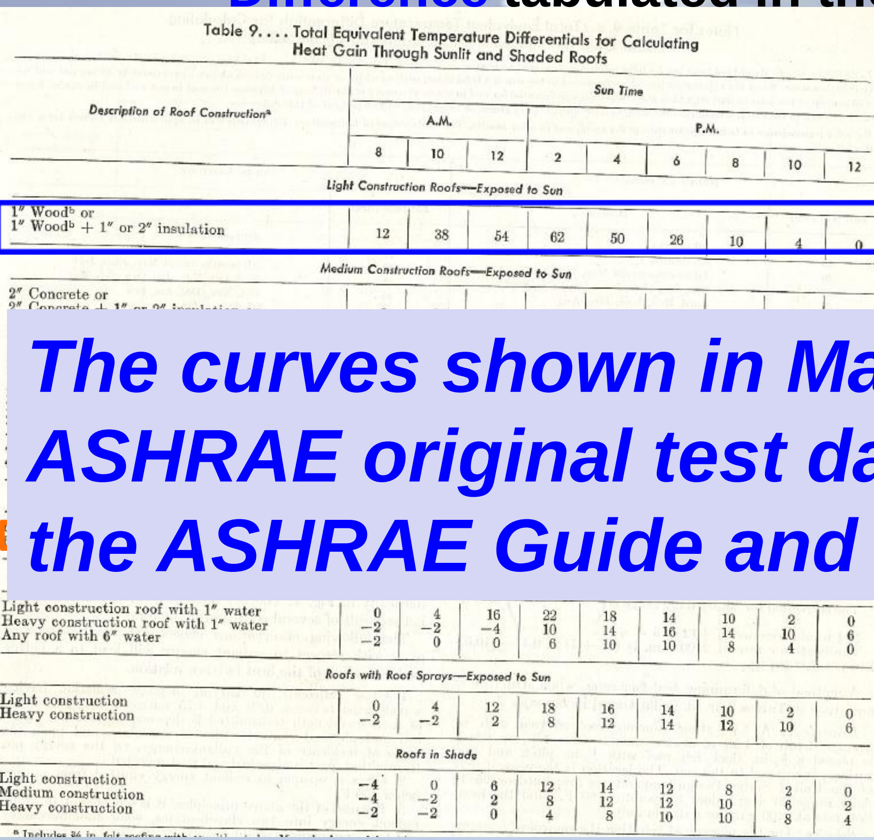
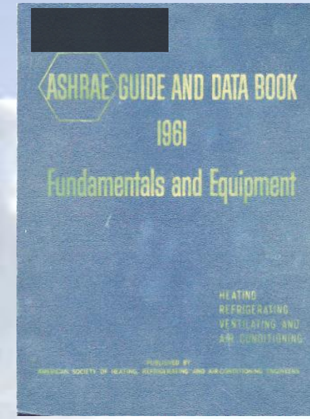


Table 9. . . . Total Equivalent Temperature Differentials for Calculating Heat Gain Through Sunlit and Shaded Roofs

Description of Roof Construction[a]	Sun Time A.M. 8	10	12	P.M. 2	4	6	8	10	12
Light Construction Roofs—Exposed to Sun									
1″ Wood[b] or 1″ Wood[b] + 1″ or 2″ insulation	12	38	54	62	50	26	10	4	0
Medium Construction Roofs—Exposed to Sun									
2″ Concrete or 2″ Concrete + 1″ or 2″ insulation [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Light construction roof with 1″ water Heavy construction roof with 1″ water Any roof with 6″ water	0 −2 −2	4 −2 0	16 −4 0	22 10 6	18 14 10	14 16 10	10 14 8	2 10 4	0 6 0
Roofs with Roof Sprays—Exposed to Sun									
Light construction Heavy construction	0 −2	4 −2	12 2	18 8	16 12	14 14	10 12	2 10	0 6
Roofs in Shade									
Light construction Medium construction Heavy construction	−4 −4 −2	0 −2 −2	6 2 0	12 8 4	14 12 8	12 12 10	8 10 10	2 6 8	0 2 4

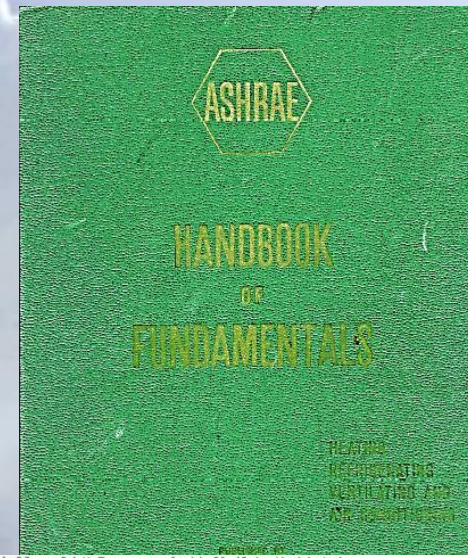


The curves shown in Mackey and Wright and ASHRAE original test data were finally tabulated in the ASHRAE Guide and Data Book

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

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

History: Pre 1945 – Cooling Load Calculation



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,

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

Table 25 . . . . Sol-Air Temperatures for July 21, 40 deg North Latitude

Time	Air Temp, F	N	NE	E	SE	S	SW	W	NW	HOR
		$\alpha/h_o = 0.15$								
1	76	76	76	76	76	76	76	76	76	69
2	76	76	76	76	76	76	76	76	76	69
3	75	75	75	75	75	75	75	75	75	68
4	74	74	74	74	74	74	74	74	74	67
5	74	74	74	74	74	74	74	74	74	67
6	74	82	95	97	86	75	75	75	75	74
						78	78	78	78	85
						83	81	81	81	96
						92	85	85	85	106
						100	89	89	89	115
						108	96	93	93	123
						112	107	97	96	127
						114	117	110	100	129
						111	123	121	107	126
						107	125	129	116	121
						100	122	131	120	113
						96	115	127	121	103
						92	103	114	112	91
						87	87	87	87	80
						85	85	85	85	78
						83	83	83	83	76
						81	81	81	81	74
						79	79	79	79	72
						77	77	77	77	70
						89	90	91	89	91
						76	76	76	76	69
						76	76	76	76	69
						75	75	75	75	68
						74	74	74	74	67
						74	74	74	74	67
						77	77	77	77	81
						82	82	82	82	102
						89	86	86	86	122
						105	91	91	91	140
						118	96	95	95	155
						129	105	100	100	166
						134	125	104	103	172
						135	142	128	107	172
						129	152	148	120	166
						120	156	163	137	155
						106	151	168	147	139
						100	138	162	149	120
						94	116	138	134	98
						87	87	87	87	80
						85	85	85	85	78
						83	83	83	83	76
						81	81	81	81	74
						79	79	79	79	72
						77	77	77	77	70
						95	99	100	95	107

Table 26 . . . . Total Equivalent Temperature Differentials for Calculating Heat Gain Through Roofs

Description of Roof Construction[a]	Sun Time A.M. 2	4	6	8	10	12	P.M. 2	4	6	8	10	12	λ	
Light Construction Roofs—Exposed to Sun														
1" Wood[b]	−5	−6	−6	16	52	81	94	84	56	20	5	−4	0.95	2
2" Insulating board + 1" wood[b]	2	−3	−6	−1	20	50	75	85	77	53	26	7	0.82	4
2" Concrete or 2" gypsum Plank	−2	−5	−6	11	41	69	85	83	63	32	13	1	0.83	3
2" Wood[b]	1	−3	−6	1	24	54	77	85	75	48	23	6	0.82	3
Medium Construction Roofs—Exposed to Sun														
2" Insulating board + 2" concrete or 2" gypsum plank	10	3	−1	−1	13	36	60	75	75	60	38	19	0.69	5
2" Gypsum or 2" concrete + 4" rock wool + ½" plaster	13	5	0	−1	9	30	54	71	75	64	43	22	0.66	5
2" Wood[b] + 4" rock wool + ½" plaster	29	19	12	6	7	16	32	49	61	63	54	39	0.48	7
Heavy Construction Roofs—Exposed to Sun														
" Concrete	9	3	−1	5	23	46	65	74	68	49	31	15	0.64	4
" Concrete	20	12	7	6	16	32	49	61	63	54	40	26	0.48	5
" Insulating board + 4" concrete	27	19	14	10	14	25	39	51	57	54	45	32	0.38	6
" Insulating board + 6" concrete	32	27	22	18	17	23	31	41	47	48	44	35	0.26	7

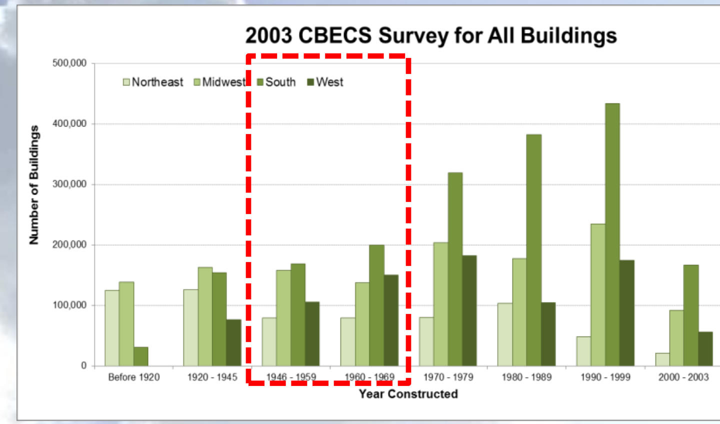
Roofs Covered with Water—Exposed to Sun

	Outside Air Dew Point (F)	Water Layer Thickness (in.)	2	4	6	8	10	12	2	4	6	8	10	12
ight Construction	60	6	3	−1	−4	−6	−6	−1	6	13	17	17	13	7
		1	−6	−9	−11	−12	−6	4	15	21	22	17	8	0
		0	−8	−10	−12	−12	−4	7	17	23	22	16	5	−3
	70	6	7	4	1	−1	0	4	11	18	21	21	17	12
		1	0	−3	−5	−5	0	10	19	25	26	21	12	5
		0	−2	−4	−6	−5	2	12	21	26	26	19	9	2
eavy Construction	60	6	6	3	−1	−3	−4	−1	4	9	13	15	13	10
		1	1	−3	−6	−8	−6	1	8	15	18	17	11	6
		0	−1	−5	−7	−9	−5	2	10	16	19	16	10	4
	70	6	11	8	5	2	2	4	9	14	18	20	18	15
		1	6	3	0	−2	0	6	14	20	23	21	16	11
		0	5	1	−1	−2	1	8	16	21	23	21	15	9

[a] Includes 3/8 in. felt roofing with or without slag. May also be used for shingle roof. [b] Nominal thickness of the wood.

Source: 1967 ASHRAE Handbook of Fundamentals

History: 1946 – 1969   Guide Books



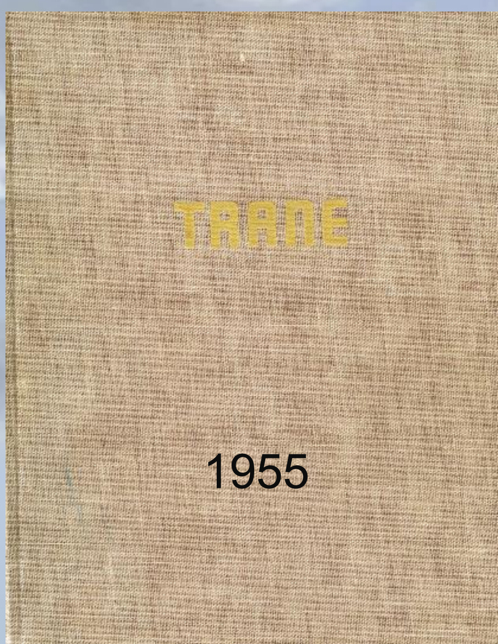
Guide Books:

1955 *TRANE Air Conditioning Design Manual*

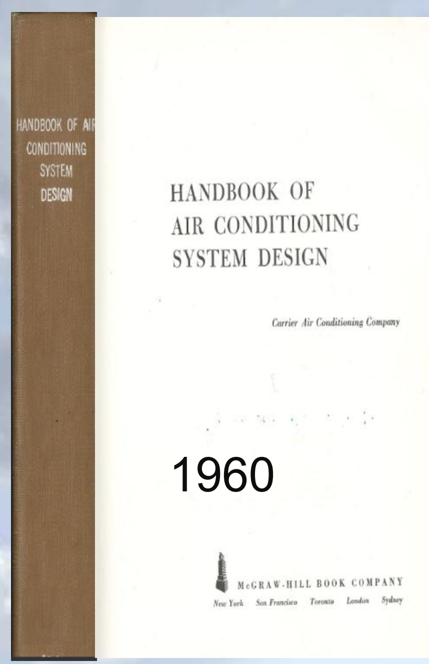
1960 *Handbook of Air Conditioning System Design by Carrier*

1961 *ASHRAE Guide and Data Book*

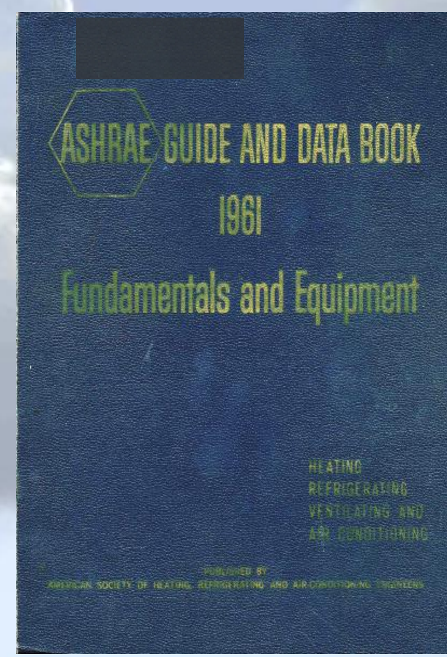
1967 *ASHRAE Handbook of Fundamentals*

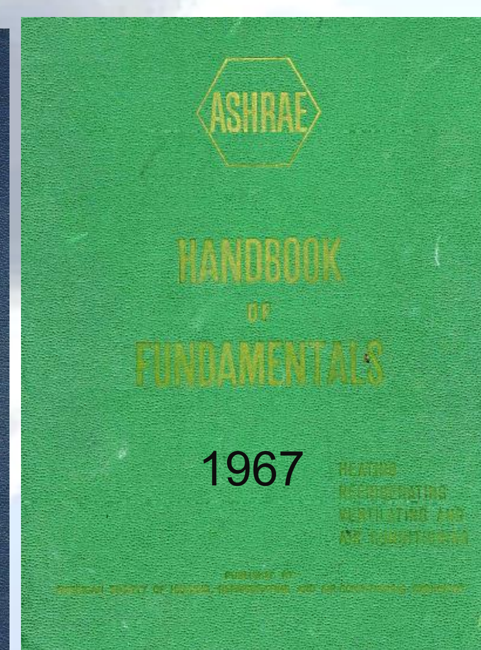


1955



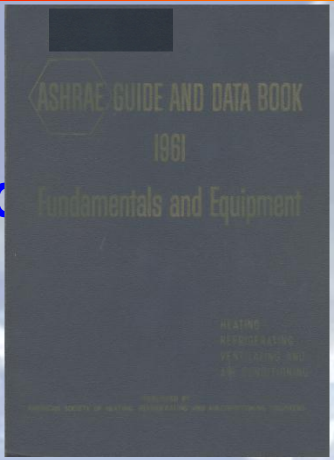
1960

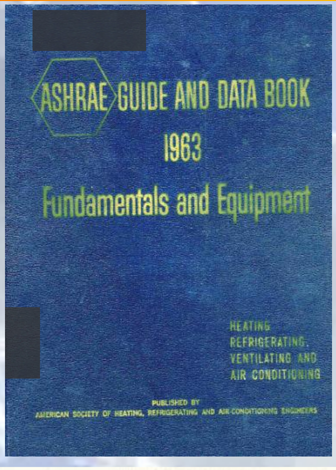


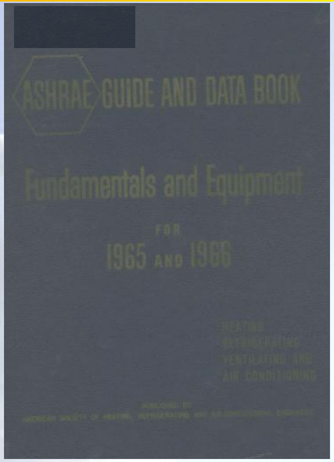


1967

History: 1946 – 1969 Cooling Load Calculation







Peak Cooling Load Calculation

- ❑ 1961 TETD/TA Method:
  - ✓ **T**otal **E**quivalent **T**emperature **D**ifference/**T**ime **A**veraging 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:

$$q = UA(TETD)$$

↑

Thermal mass is in the TETD

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

Table 9. . . . Total Equivalent Temperature Differentials for Calculating Heat Gain Through Sunlit and Shaded Roofs

Description of Roof Construction[a]	Sun Time A.M. 8	10	12	P.M. 2	4	6	8	10	12
Light Construction Roofs—Exposed to Sun									
1" Wood[b] or 1" Wood[b] + 1" or 2" insulation	12	38	54	62	50	26	10	4	0
Medium Construction Roofs—Exposed to Sun									
2" Concrete or 2" Concrete + 1" or 2" insulation or 2" Wood[b]	6	30	48	58	50	32	14	6	2
2" Gypsum or 2" Gypsum + 1" insulation 1" Wood[b] or 2" Wood[b] or 2" Concrete or 2" Gypsum } + 4" rock wool in furred ceiling	0	20	40	52	54	42	20	10	6
4" Concrete or 4" Concrete with 2" insulation	0	20	38	50	52	40	22	12	6
Heavy Construction Roofs—Exposed to Sun									
6" Concrete 6" Concrete + 2" insulation	4 6	6 6	24 20	38 34	46 42	44 44	32 34	18 20	12 14
Roofs Covered with Water—Exposed to Sun									
Light construction roof with 1" water Heavy construction roof with 1" water Any roof with 6" water	0 −2 −2	4 −2 0	16 −4 0	22 10 6	18 14 10	14 16 10	10 14 8	2 10 4	0 6 0
Roofs with Roof Sprays—Exposed to Sun									
Light construction Heavy construction	0 −2	4 −2	12 2	18 8	16 12	14 14	10 12	2 10	0 6
Roofs in Shade									
Light construction Medium construction Heavy construction	−4 −4 −2	0 −2 −2	6 2 0	12 8 4	14 12 8	12 12 10	8 10 10	2 6 8	0 2 4

[a] Includes ⅜ in. felt roofing with or without slag. May also be used for shingle roof.
[b] Nominal thickness of the wood.

Notes for Table 9

Explanation: {Total heat transmission from solar radiation and temperature difference between outdoor and room air. Btu per (hr) (sq ft) of roof area} = {Equivalent temperature differential from above table} × {Heat transmission coefficient for summer Btu per (hr) (sq ft) (F deg)}

1. *Source.* Calculated by Mackey and Wright method (see reference list) and adjusted after studying ASHRAE original test data. Estimated for about August 1 in 40 deg north latitude. (For sol-air temperatures used in calculations see Table 8.) For typical design day where the maximum outdoor temperature is 95 F and minimum temperature at night is approximately 75 F (daily range of temperature, 20 F) mean 24 hr temperature 84 F for a room temperature of 80 F. All roofs have been assumed a dark color which absorbs 90 percent of solar radiation, and reflects only 10 percent.

2. *Application.* These values may be used for all normal air conditioning estimates; usually without correction, in latitude 0 deg to 50 deg north or south when the load is calculated for the hottest weather. Note 5 explains how to adjust the temperature differential for other room and outdoor temperatures.

3. *Peaked Roofs.* If the roof is peaked and the heat gain is primarily due to solar radiation, use for the area of the roof, the area projected on a horizontal plane.

4. *Attics.* If the ceiling is insulated and if a fan is used in the attic for positive ventilation, the total temperature differential for a roof exposed to the sun may be decreased 25 percent.

5. *Corrections. For temperature difference when outdoor maximum design temperature minus room is different from 15 deg.* If the outdoor design temperature minus room temperature is different from the base of 15 deg, correct as follows: When the difference is greater (or less) than 15 deg add the excess to (or subtract the deficiency from) the above differentials.

For outdoor daily range of temperature other than 20 deg. If the daily range of temperature is less than 20 deg, add 1 deg for every 2 deg lower daily range; if the daily range is greater than 20 deg, subtract 1 deg for every 2 deg higher daily range. For example, the daily range in Miami, Florida is 12 deg or 8 deg less than 20 deg, therefore, the correction is +4 deg at all hours of the day.

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***

Table 1 Procedure for Calculating Space Design Cooling Load—Summary of Load Sources and Equations

Load Source	Equation	Reference, Table, Description
External		
Roof	$q = U \times A \times CLTD$	Chapter 22-Design Heat Transfer Coefficients—Table 3 and 4 Area Calculated from Architectural Plans Table 5—Cooling Load Temperature Difference at Base Conditions for Roofs Note 4—Correction for Color of Exterior Surface Note 2—Correction for Outside Dry Bulb Temperature and Daily Range Note 2—Correction for Inside Dry Bulb Temperature Note 1 & 5—Application for Latitude and Month
Walls	$q = U \times A \times CLTD$	Chapter 22—Design Heat Transmission Coefficients—Tables 3 and 4 Area Calculated from Architectural Plans Table 6—Wall Construction Group Description Table 7—Cooling Load Temperature Difference at Base Conditions for Wall Group Note 3—Correction for Color of Exterior Surface Note 2—Correction for Outside Dry Bulb Temperature and Daily Range Note 2—Correction for Inside Dry Bulb Temperature Note 1 & 4 Application for Latitude and Month
Glass		Chapter 22 or Chapter 26-Type of Glass and Interior Shading if Used
Conduction	$q = U \times A \times CLTD$	Area—Net Glass Area Calculated from Plans Table 9—Cooling Load Temperature Difference for Conduction Load Through Glass Note 1—Correction for Outside Dry Bulb Temperature and Daily Range Note 1—Correction for Inside Dry Bulb Temperature
Solar	$q = A \times SC \times SHGF \times CLF$	Area—Net Glass Area Calculated from Plans Chapter 26—Tables 28, 33, 34, 35, 36, 38, and 40 Shading Coefficients for Combination of Type of Glass and Type of Shading Table 10—Maximum Solar Heat Gain Factor for Specific Orientation of Surface, Latitude and Month Table 11—Cooling Load Factor with No Interior Shading Table 12—Cooling Load Factor if Interior Shading is Used
Partitions, Ceilings, Floors	$q = U \times A \times TD$	Chapter 22—Design Heat Transmission Coefficients—Tables 3 and 4 Area Calculated from Architectural Plans Section 5.0—Design Temperature Difference
Internal Lights	$q = INPUT \times CLF$	Input Rating from Electrical Plans or Lighting Fixture Data Tables 13 & 14—Coefficients "a" and classification "b" for Type of Fixture, Installation, Air Supply and Return and Room Furnishings and Construction Table 15—Cooling Load Factor Based on Total Hours of Operation and Time Note 1—Correction for Schedule of Operation of Cooling System
People		Number of People in Space
Sensible	$q_s = No \times Sens.\ H.G. \times CLF$	Table 16 or Chapter 8—Sensible Heat Gain from Occupants Table 17—Cooling Load Factor for People—Based on Duration of Occupancy and Time from Entry Note 1—Correction for Density of Occupants
Latent	$q_l = No \times Lat.\ H.G.$	Table 16 or Chapter 8—Latent Heat Gain from Occupants
Appliances		
Sensible	$q_s = HEAT\ GAIN \times CLF$	Tables 18 & 19—Recommended Rate of Heat Gain-Sensible Heat Table 20—For Use with Hood Table 21—For Use without Hood
Latent	$q_l = HEAT\ GAIN$	Tables 18 & 19—Recommended Rate of Heat Gain—Latent Heat (Without Hood) Set Equal to Zero When Hood is Used Over Appliances
Power	$q = HEAT\ GAIN \times CLF$	Eq 21, 22, or 23 using Tables 22 and 23 or Manufacturer's Data Table 21
Ventilation & Infiltration Air		Ventilation and Infiltration Air, Standard CFM Inside-Outside Air Temperature Difference, deg F
Sensible	$q_s = 1.10 \times CFM \times \Delta t$	
Latent	$q_l = 4840 \times CFM \times \Delta W$	Inside-Outside Air Humidity Ratio Difference, lb H_2O/lb Dry Air
Total	$q = 4.5 \times CFM \times \Delta h$	Inside-Outside Air Enthalpy Difference, Btu/lb of Dry Air
Adjustment Factor	$F_c = 1 - 0.02 K_t$	Fraction of Input Energy Lost to the Surroundings; Applied to all External and Internal Loads Except Ventilation and Infiltration Air. Eq 31

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

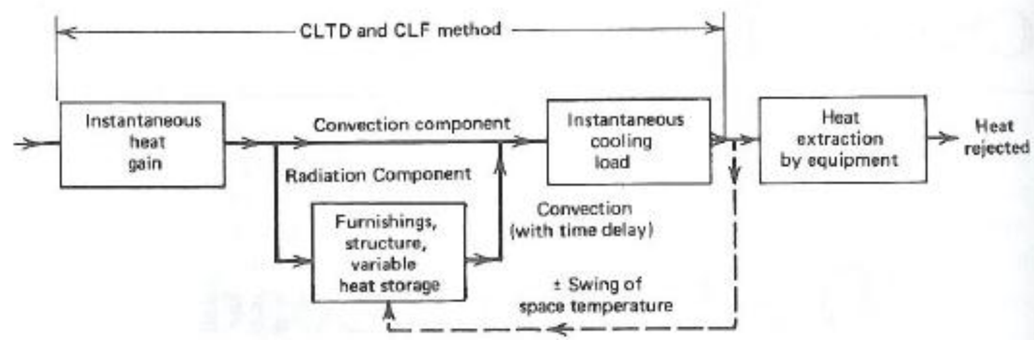


Figure 8-1 Schematic relation of heat gain to cooling load.

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

CLTD

North Latitude Wall Facing	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Hr of Maximum CLTD	Minimum CLTD	Maximum CLTD	Difference CLTD
Group A Walls																												
N	14	14	14	13	13	13	12	12	11	11	10	10	10	10	10	10	11	11										
NE	19	19	19	18	17	17	16	15	15	15	15	15	16	16	17	18	18	18										
E	24	24	23	23	22	21	20	19	19	18	19	19	20	21	22	23	24	24										
SE	24	23	23	22	21	20	20	19	18	18	18	18	18	19	20	21	22	23										
S	20	20	19	19	18	18	17	16	16	15	14	14	14	14	14	15	16	17										
SW	25	25	25	24	24	23	22	21	20	19	19	18	17	17	17	17	18	19										
W	27	27	26	26	25	24	24	23	22	21	20	19	19	18	18	18	18	19										
NW	21	21	21	20	20	19	19	18	17	16	16	15	15	14	14	14	15	15										
Group B Walls																												
N	15	14	14	13	12	11	11	10	9	9	9	8	9	9	9	10	11	12										
NE	19	18	17	16	15	14	13	12	12	13	14	15	16	17	18	19	19	20										
E	23	22	21	20	18	17	16	15	15	15	17	19	21	22	24	25	26	26										
SE	23	22	21	20	18	17	16	15	14	14	15	16	18	20	21	23	24	25										
S	21	20	19	18	17	15	14	13	12	11	11	11	11	12	14	15	17	19										
SW	27	26	25	24	22	21	19	18	16	15	14	14	13	13	14	15	17	20										
W	29	28	27	26	24	23	21	19	18	17	16	15	14	14	14	15	17	19										
NW	23	22	21	20	19	18	17	15	14	13	12	12	12	11	12	12	13	15										
Group C Walls																												
N	15	14	13	12	11	10	9	8	8	7	7	8	8	9	10	12	13	14										
NE	19	17	16	14	13	11	10	10	11	13	15	17	19	20	21	22	22	23										
E	22	21	19	17	15	14	12	12	14	16	19	22	25	27	29	29	30	30										
SE	22	21	19	17	15	14	12	12	12	13	16	19	22	24	26	28	29	29										
S	21	19	18	16	15	13	12	10	9	9	9	10	11	14	17	20	22	24										
SW	29	27	25	22	20	18	16	15	13	12	11	11	11	13	15	18	22	26										
W	31	29	27	25	22	20	18	16	14	13	12	12	12	13	14	16	20	24										
NW	25	23	21	20	18	16	14	13	11	10	10	10	10	11	12	13	15	18										
Group D Walls																												
N	15	13	12	10	9	7	6	6	6	6	6	7	8	10	12	13	15	17										
NE	17	15	13	11	10	8	7	8	10	14	17	20	22	23	23	24	24	25										
E	19	17	15	13	11	9	8	9	12	17	22	27	30	32	33	33	32	32										
SE	20	17	15	13	11	10	8	8	10	13	17	22	26	29	31	32	32	32										
S	19	17	15	13	11	9	8	7	6	6	7	9	12	16	20	24	27	29										
SW	28	25	22	19	16	14	12	10	9	8	8	8	10	12	16	21	27	32										
W	31	27	24	21	18	15	13	11	10	9	9	9	10	11	14	18	24	30										
NW	25	22	19	17	14	12	10	9	8	7	7	8	9	10	12	14	18	22										
Group E Walls																												
N	12	10	8	7	5	4	3	4	5	6	7	9	11	13	15	17	19	20	21	23	20	18	16	14	20	3	22	19
NE	13	11	9	7	6	4	5	9	15	20	24	25	25	26	26	26	26	26	25	24	22	19	17	15	16	4	26	22

Table 11 Cooling Load Factors for Glass without Interior Shading

CLF

N. Latitude Fenestration Facing	Room Construction	1	2	3	4	5	6	7	8	9	10	11	12	13
N	L	0.17	0.14	0.11	0.09	0.08	0.33	0.42	0.48	0.56	0.63	0.71	0.76	0.8
	M	0.23	0.20	0.18	0.16	0.14	0.34	0.41	0.46	0.52	0.59	0.65	0.70	0.7
	H	0.25	0.23	0.21	0.20	0.19	0.38	0.45	0.50	0.55	0.60	0.65	0.69	0.7
NE	L	0.04	0.04	0.03	0.02	0.02	0.23	0.41	0.51	0.51	0.45	0.39	0.36	0.3
	M	0.07	0.06	0.06	0.05	0.04	0.21	0.36	0.44	0.45	0.40	0.36	0.33	0.3
	H	0.09	0.08	0.08	0.07	0.07	0.23	0.37	0.44	0.44	0.39	0.34	0.31	0.2
E	L	0.04	0.04	0.03	0.02	0.02	0.19	0.37	0.51	0.57	0.57	0.51	0.42	0.3
	M	0.07	0.06	0.06	0.05	0.04	0.18	0.33	0.44	0.50	0.51	0.45	0.39	0.3
	H	0.09	0.09	0.08	0.08	0.07	0.21	0.34	0.45	0.50	0.49	0.43	0.36	0.3
SE	L	0.05	0.04	0.04	0.03	0.02	0.13	0.28	0.43	0.55	0.62	0.63	0.57	0.4
	M	0.09	0.08	0.07	0.06	0.05	0.14	0.26	0.38	0.48	0.54	0.55	0.51	0.4
	H	0.11	0.10	0.10	0.09	0.08	0.17	0.28	0.40	0.49	0.53	0.53	0.48	0.4
S	L	0.08	0.07	0.05	0.04	0.04	0.06	0.09	0.14	0.22	0.34	0.48	0.59	0.65
	M	0.12	0.11	0.09	0.08	0.07	0.08	0.11	0.14	0.21	0.31	0.42	0.52	0.57
	H	0.13	0.12	0.12	0.11	0.10	0.12	0.14	0.17	0.24	0.33	0.43	0.51	0.56
SW	L	0.12	0.10	0.08	0.06	0.05	0.06	0.08	0.10	0.12	0.14	0.16	0.24	0.36
	M	0.15	0.13	0.12	0.10	0.09	0.09	0.10	0.12	0.13	0.15	0.17	0.23	0.33
	H	0.15	0.14	0.13	0.12	0.11	0.12	0.13	0.14	0.16	0.17	0.19	0.25	0.34
W	L	0.12	0.10	0.08	0.07	0.05	0.06	0.07	0.08	0.10	0.11	0.13	0.14	0.20
	M	0.15	0.13	0.11	0.10	0.09	0.09	0.09	0.10	0.11	0.12	0.13	0.14	0.19
	H	0.14	0.13	0.12	0.11	0.10	0.11	0.12	0.13	0.13	0.14	0.15	0.16	0.21
NW	L	0.11	0.09	0.08	0.06	0.05	0.06	0.08	0.10	0.12	0.14	0.16	0.17	0.15
	M	0.14	0.12	0.11	0.09	0.08	0.09	0.10	0.11	0.13	0.14	0.16	0.17	0.18
	H	0.14	0.12	0.11	0.11	0.10	0.11	0.12	0.13	0.15	0.16	0.18	0.19	0.19
HOR	L	0.11	0.09	0.07	0.06	0.05	0.07	0.14	0.24	0.36	0.48	0.58	0.66	0.72
	M	0.16	0.14	0.12	0.11	0.09	0.11	0.16	0.24	0.33	0.43	0.52	0.59	0.64
	H	0.17	0.16	0.15	0.14	0.13	0.15	0.20	0.27	0.36	0.45	0.52	0.59	0.62

History: 1946 – 1969 Cooling Load Calculation

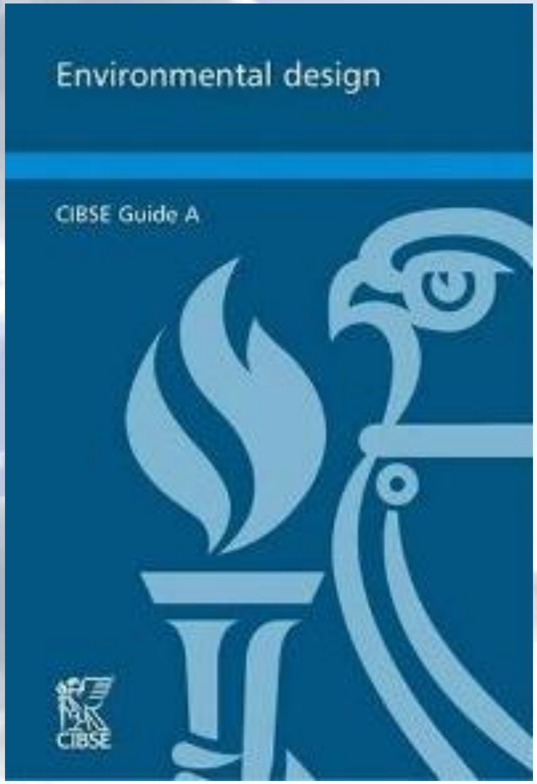
Other Developments:

Finite Difference /Finite Element Method **:**

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

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:

- ✓ Degree Days first used to predict snow melt.
- ✓ Manual method was adopted in mid 1960s
- ✓ Later appeared in ***1981 ASHRAE Handbook***

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*

Equivalent Full Load Hours Method :

- ✓ Manual method was adopted in the mid-1960s
- ✓ Cooling energy requirement calculation
- ✓ Later appeared in ***1981 ASHRAE Handbook***

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 was adopted in the mid-1960s
- ✓ Heating and Cooling
- ✓ Energy Calculation
- ✓ Later appeared in ***1981 ASHRAE Handbook***

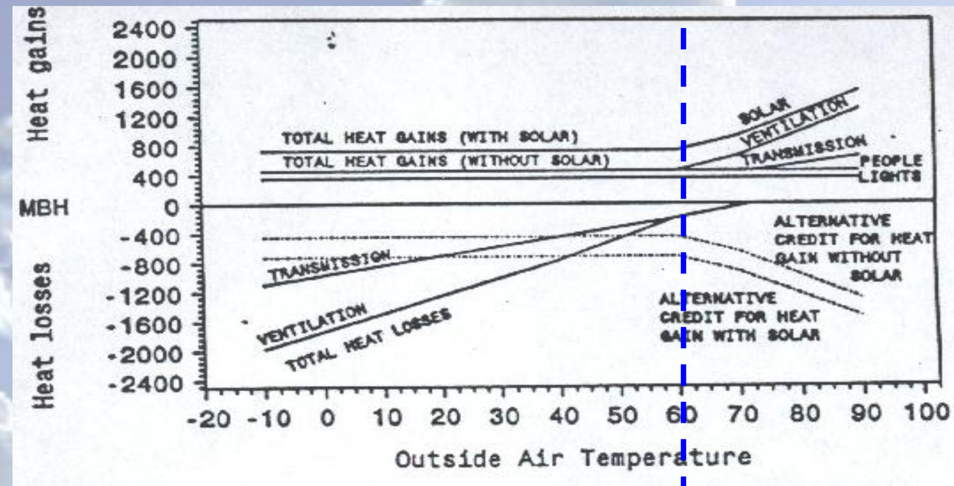
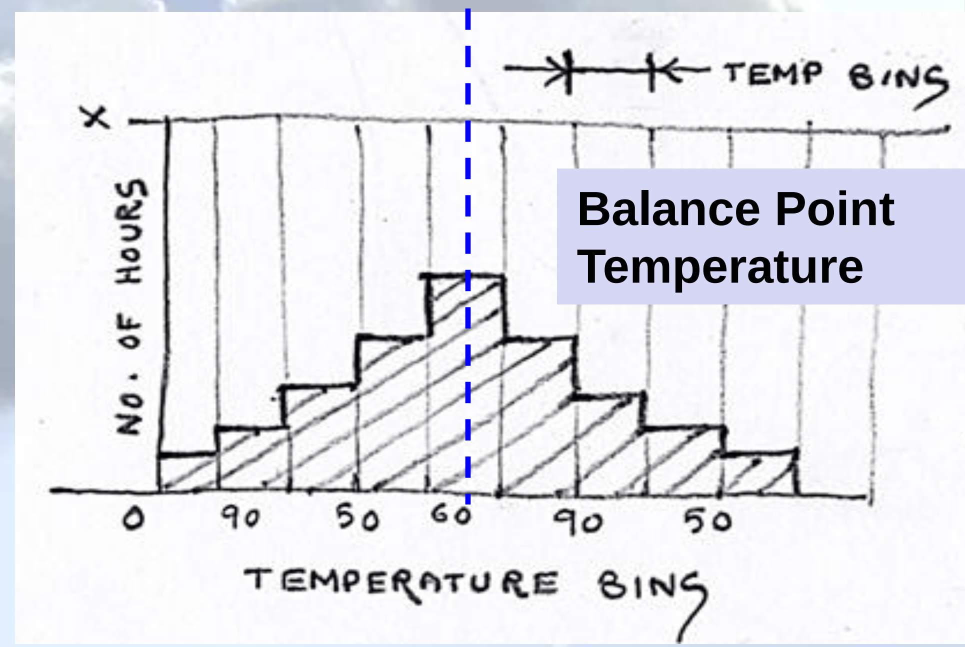
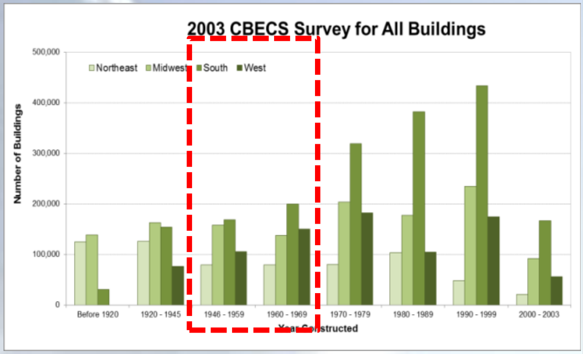


Figure 1 *Simplified building load analysis.*

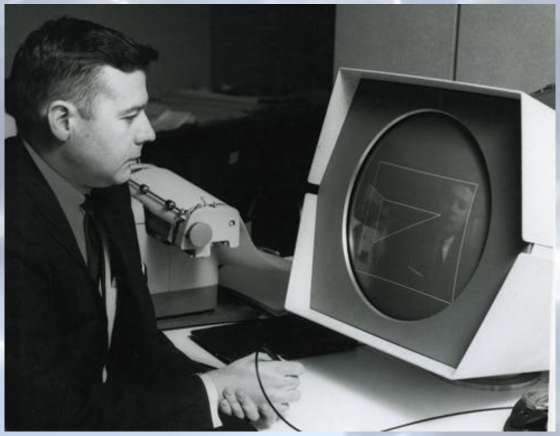


History : 1946 – 1969 Computer Developments

- 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 are 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

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***

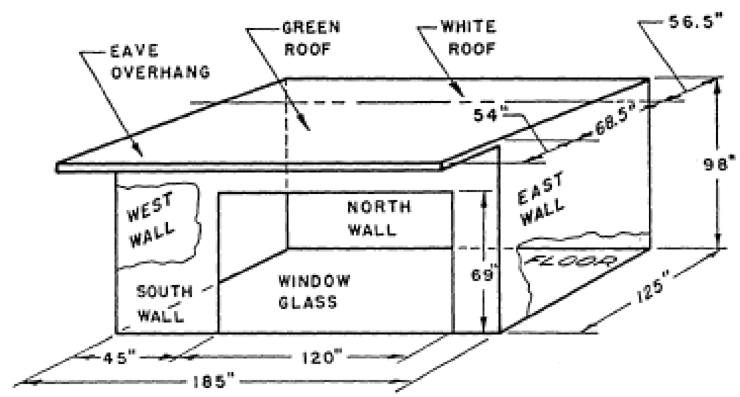


FIG. 1—SCHEMATIC DIAGRAM OF TEST HOUSE

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

History: 1946 – 1969 Annual Energy Use

Thermal Network Method:

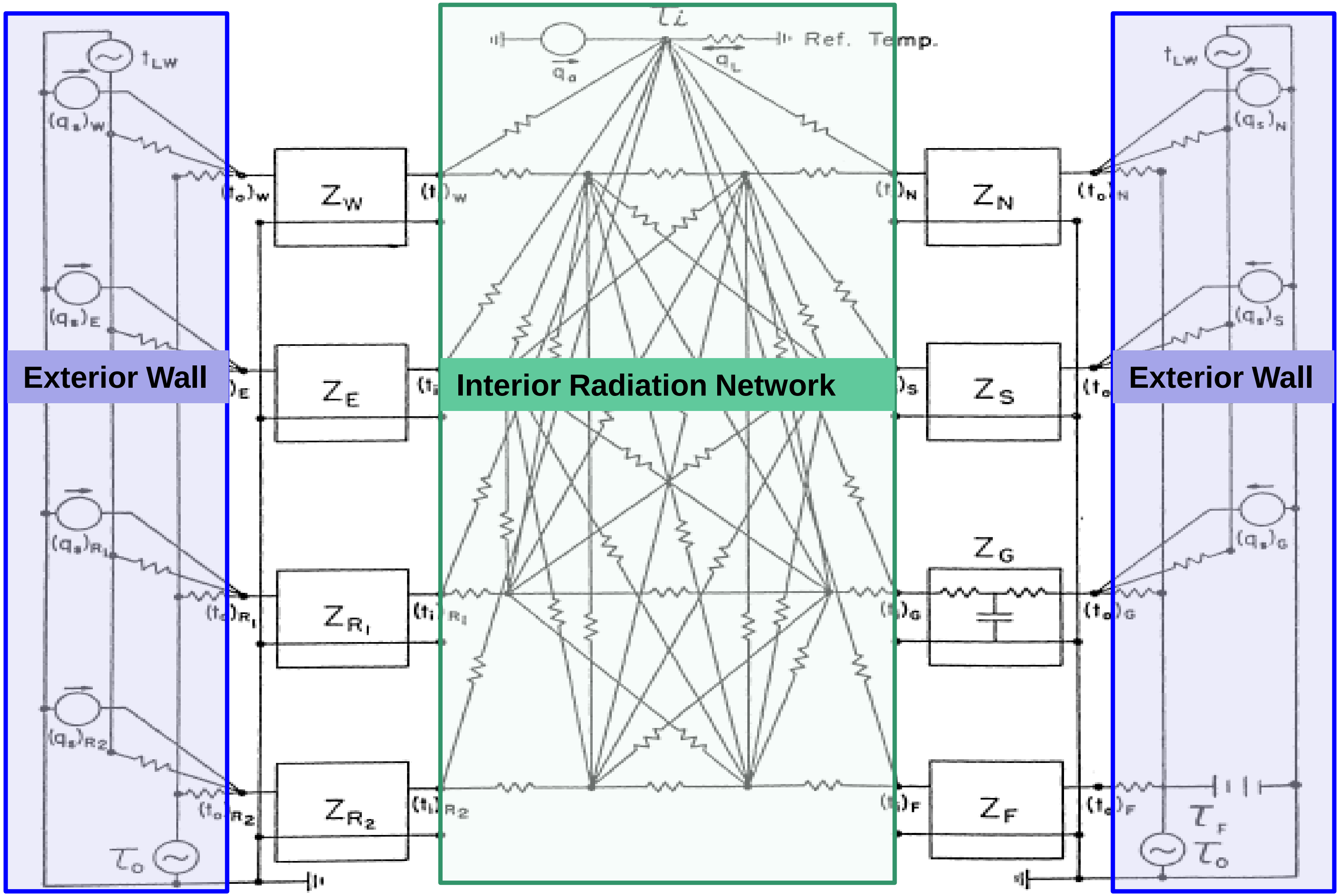


FIG. 2—BASIC THERMAL NETWORK REPRESENTING THE IDEALIZED TEST HOUSE

Source: Buch
Transactions

History: 1946 – 1969 Annual Energy Use

Thermal Network Method:

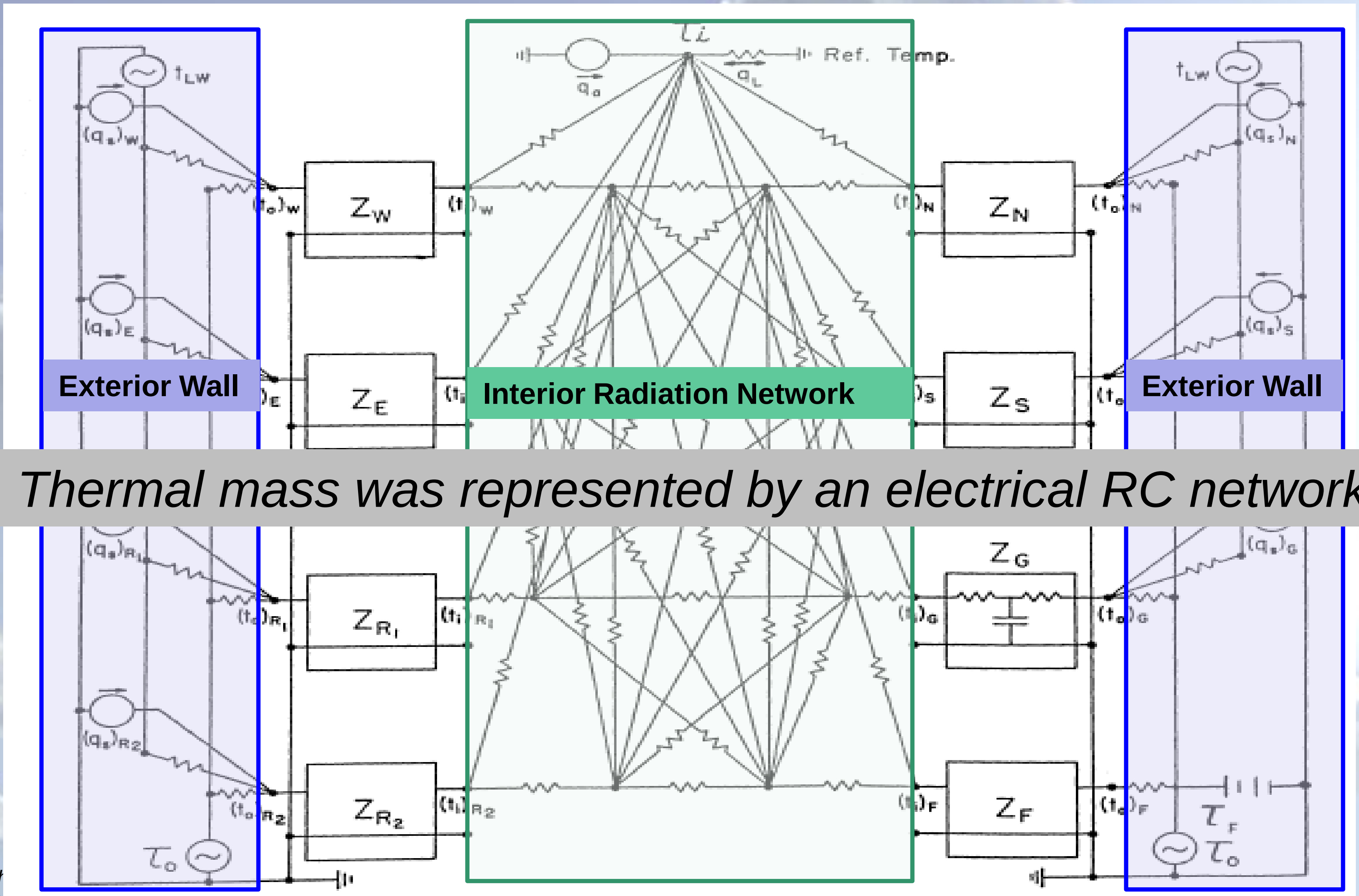


FIG. 2—BASIC THERMAL NETWORK REPRESENTING THE IDEALIZED TEST HOUSE

Thermal mass was represented by an electrical RC network

Source: Buch
Transactions

History: 1946 – 1969 Annual Energy Use

Thermal Network Method:

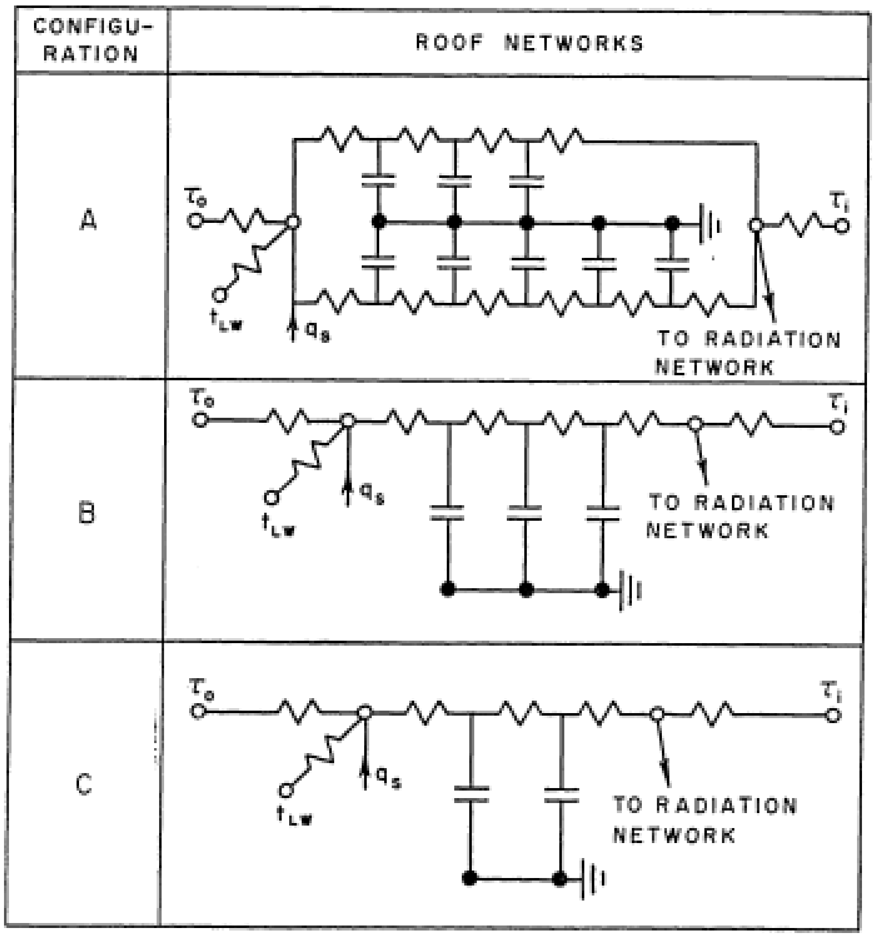


FIG. A-2—CONDUCTION PATH THERMAL NETWORK CONFIGURATIONS FOR ROOF SECTIONS

TABLE A—MAGNITUDE OF DECREMENT FACTORS

	λ_2	λ_1	ADD. TIME LAG
A. Solar radiation transmitted through north glass ref. D	0.54	0.95	3 hrs
B. Solar radiation transmitted through south glass ref. E 2 in. floor	0.66	1.00	1 hr, approx.
6 in. floor	0.47	1.00	1 hr, approx.
C. Southwest wall ref. F	0.93	0.92	0 hr
D. Roof problem	0.34	0.83	3 hr

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

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

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: $v_0, v_1, v_2, \cdots, w_1, w_{2,\dots}$

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: $g_0, g_1, g_2, \cdots, P_1, P_{2,\dots}$

History: 1946 – 1969 Annual Energy Use

Computer Algorithms:

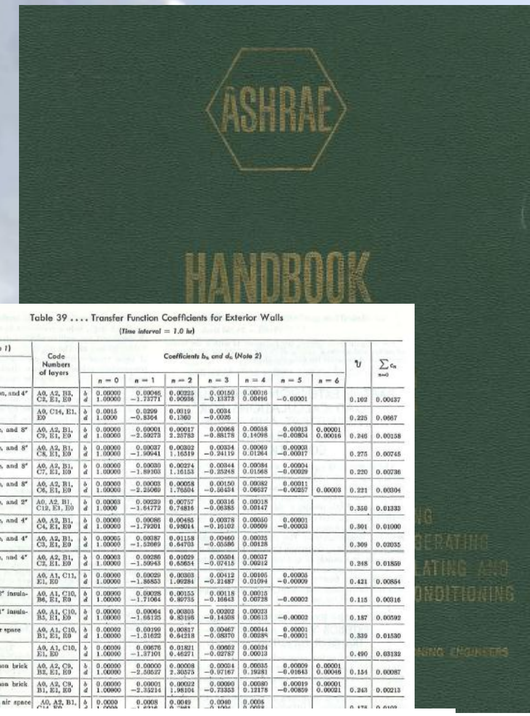


Table 39 .... Transfer Function Coefficients for Exterior Walls
(Time interval = 1.0 hr)

No.	Construction (Note 1) Description	Code Numbers of layers		Coefficients b_n and d_n (Note 2) n = 0	n = 1	n = 2	n = 3	n = 4	n = 5	n = 6	U	$\sum_{n=0} c_n$
1	4" face brick, 2" insulation, and 4" l.w. concrete block	A0, A2, B3, C2, E1, E0	b	0.00000	0.00046	0.00225	0.00150	0.00016				
			d	1.00000	−1.73771	0.90936	−0.13373	0.00496	−0.00001		0.102	0.00437
2	4" l.w. concrete	A0, C14, E1, E0	b	0.0015	0.0299	0.0319	0.0034					
			d	1.0000	−0.8364	0.1360	−0.0026				0.225	0.0667
3	4" face brick, air space, and 8" common brick	A0, A2, B1, C9, E1, E0	b	0.00000	0.00001	0.00017	0.00068	0.00058	0.00013	0.00001		
			d	1.00000	−2.50273	2.25783	−0.88178	0.14098	−0.00804	0.00016	0.246	0.00158
4	4" face brick, air space, and 8" h.w. concrete block	A0, A2, B1, C8, E1, E0	b	0.00000	0.00037	0.00302	0.00334	0.00060	0.00003			
			d	1.00000	−1.90941	1.16319	−0.24119	0.01264	−0.00017		0.275	0.00745
5	4" face brick, air space, and 8" l.w. concrete block	A0, A2, B1, C7, E1, E0	b	0.00000	0.00030	0.00274	0.00344	0.00084	0.00004			
			d	1.00000	−1.89103	1.16153	−0.25248	0.01568	−0.00029		0.220	0.00736
6	4" face brick, air space, and 8" clay tile	A0, A2, B1, C6, E1, E0	b	0.00000	0.00003	0.00058	0.00150	0.00082	0.00011			
			d	1.00000	−2.25060	1.76504	−0.56434	0.06527	−0.00257	0.00003	0.221	0.00304
7	4" face brick, air space, and 2" h.w. concrete	A0, A2, B1, C12, E1, E0	b	0.00003	0.00239	0.00757	0.00316	0.00018				
			d	1.0000	−1.64772	0.74816	−0.06385	0.00147			0.350	0.01333
8	4" face brick, air space, and 4" common brick	A0, A2, B1, C4, E1, E0	b	0.00000	0.00086	0.00485	0.00378	0.00050	0.00001			
			d	1.00000	−1.79201	0.98014	−0.16102	0.00609	−0.00003		0.301	0.01000
9	4" face brick, air space, and 4" h.w. concrete block	A0, A2, B1, C3, E1, E0	b	0.00005	0.00387	0.01158	0.00460	0.00025				
			d	1.00000	−1.52869	0.64703	−0.05586	0.00128			0.309	0.02035
10	4" face brick, air space, and 4" l.w. concrete block	A0, A2, B1, C2, E1, E0	b	0.00003	0.00286	0.01029	0.00504	0.00037				
			d	1.00000	−1.50943	0.65654	−0.07415	0.00212			0.248	0.01859
11	12" h.w. concrete	A0, A1, C11, E1, E0	b	0.00000	0.00029	0.00303	0.00412	0.00105	0.00005			
			d	1.00000	−1.86853	1.09284	−0.21487	0.01094	−0.00009		0.421	0.00854
12	8" h.w. concrete with 2" insulation	A0, A1, C10, B6, E1, E0	b	0.00000	0.00028	0.00155	0.00118	0.00015				
			d	1.00000	−1.71064	0.89735	−0.16643	0.00728	−0.00002		0.115	0.00316
13	8" h.w. concrete with 1" insulation	A0, A1, C10, B5, E1, E0	b	0.00000	0.00064	0.00303	0.00202	0.00023				
			d	1.00000	−1.66125	0.83196	−0.14508	0.00613	−0.00002		0.187	0.00592
14	8" h.w. concrete with air space	A0, A1, C10, B1, E1, E0	b	0.00002	0.00190	0.00817	0.00467	0.00044	0.00001			
			d	1.00000	−1.51622	0.64218	−0.08370	0.00288	−0.00001		0.339	0.01530
15	8" h.w. concrete	A0, A1, C10, E1, E0	b	0.00009	0.00676	0.01821	0.00602	0.00024				
			d	1.00000	−1.37101	0.46271	−0.02787	0.00013			0.490	0.03132
16	4" face brick, 8" common brick with 1" insulation	A0, A2, C9, B2, E1, E0	b	0.00000	0.00000	0.00008	0.00034	0.00035	0.00009	0.00001		
			d	1.00000	−2.50537	2.30575	−0.97167	0.19281	−0.01643	0.00046	0.154	0.00087
17	4" face brick, 8" common brick with air space	A0, A2, C9, B1, E1, E0	b	0.00000	0.00001	0.00022	0.00090	0.00080	0.00019	0.00001		
			d	1.00000	−2.35214	1.98104	−0.73353	0.12178	−0.00859	0.00021	0.243	0.00213
18	Wall with 4" face brick, air space and 4" l.w. block	A0, A2, B1, [illegible]	b	0.0000	0.0008	0.0049	0.0040	0.0006				
			d	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]

Thermal Mass: Transfer Function Method:

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

Heat gain through a wall or roof:

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

where,

$b_n \quad c_n \quad d_n$

Transfer function coefficients

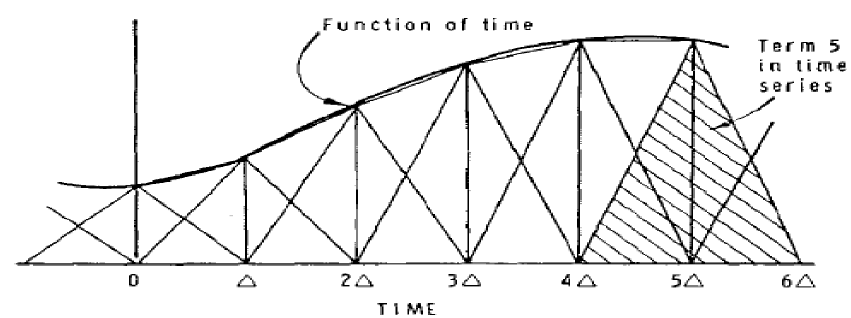


Fig. 1 Time-series representation of a continuous function

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

History: 1946 – 1969 Cooling Load Calculation

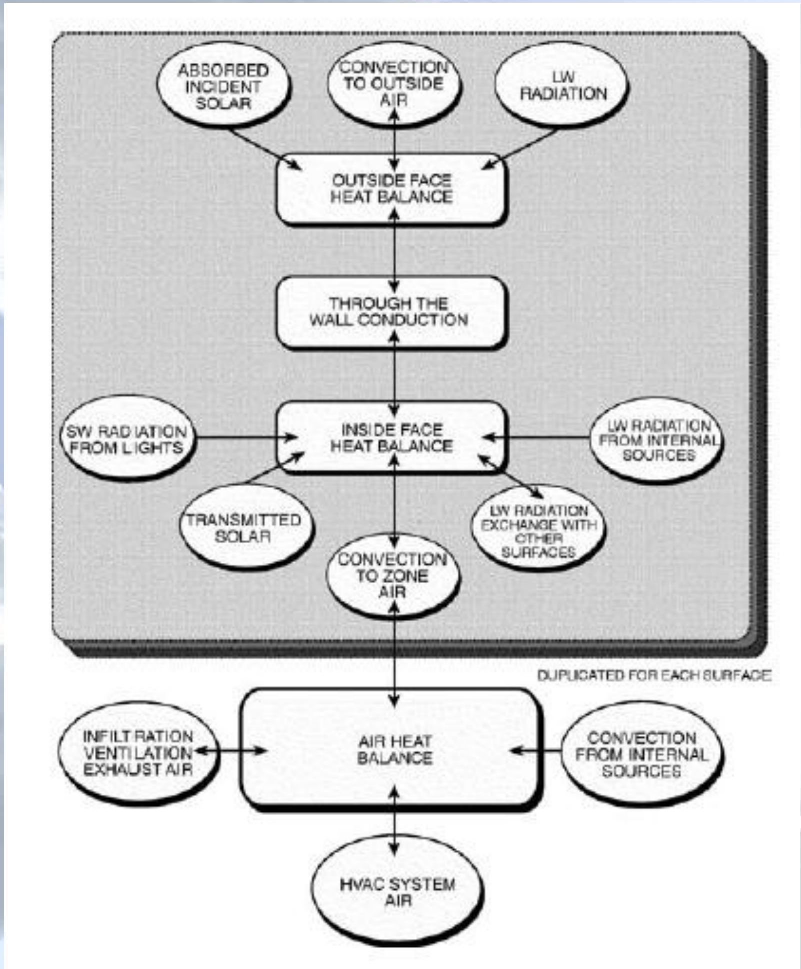
Computer Algorithms:

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: $q_{sys_j} = a + bt_{a_j}$

where, $$t_{a_j} = \frac{a + \sum_{i=1}^{N} A_i h_{ci} t_{si_{i,j}} + \rho c V_{infil_f} t_{o_j} + q_{c,\text{int}_j}}{-b + \sum_{i=1}^{N} A_i h_{ci} + \rho c V_{infil_j} + \rho c V_{vent_j}}$$

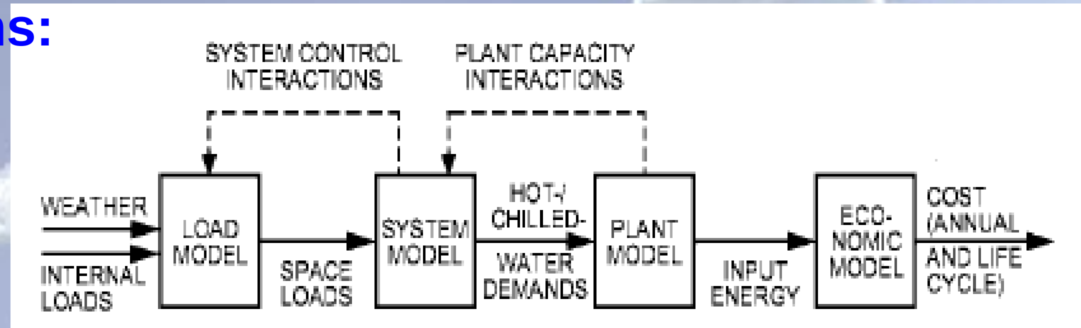


Schematic of Heat Balance Processes in Zone
(*Source: 2009 ASHRAE Handbook*)

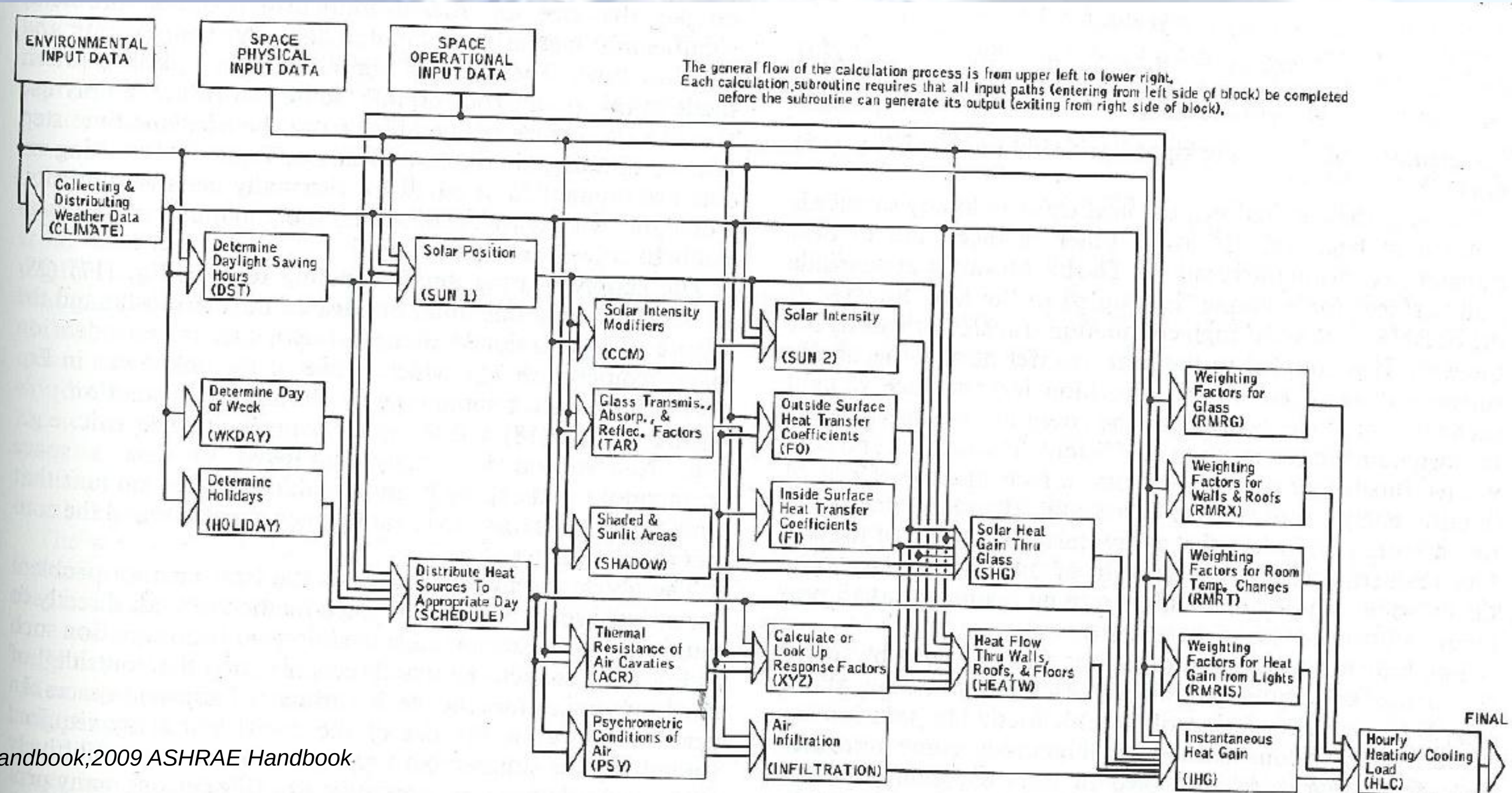
History: 1970 – 1989 Annual Energy Use

Computer Algorithms:

DOE-2 (Weighting Factor Method)



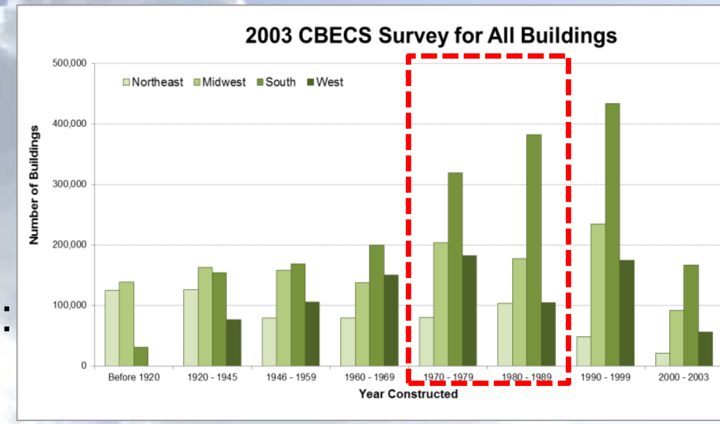
Complete Set of ASHRAE Algorithms



Source:1985 ASHRAE Handbook;2009 ASHRAE Handbook

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

History: 1970 – 1989 Guide Books

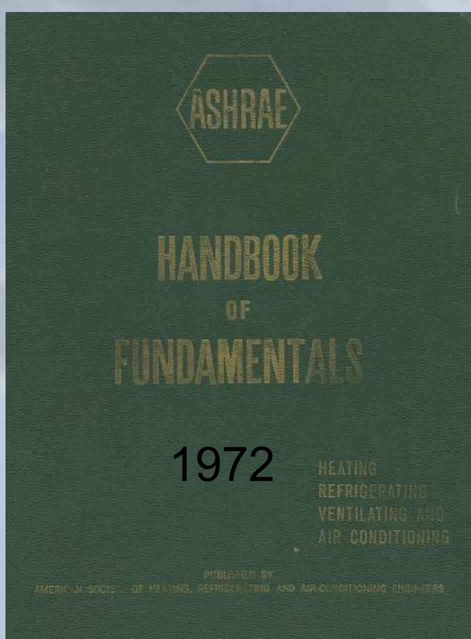


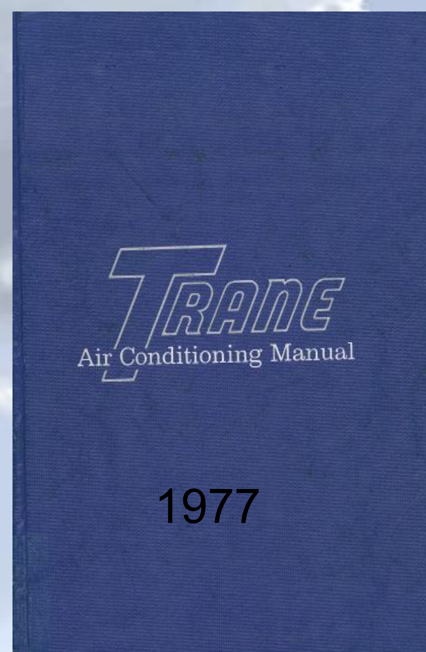
Guide Books:

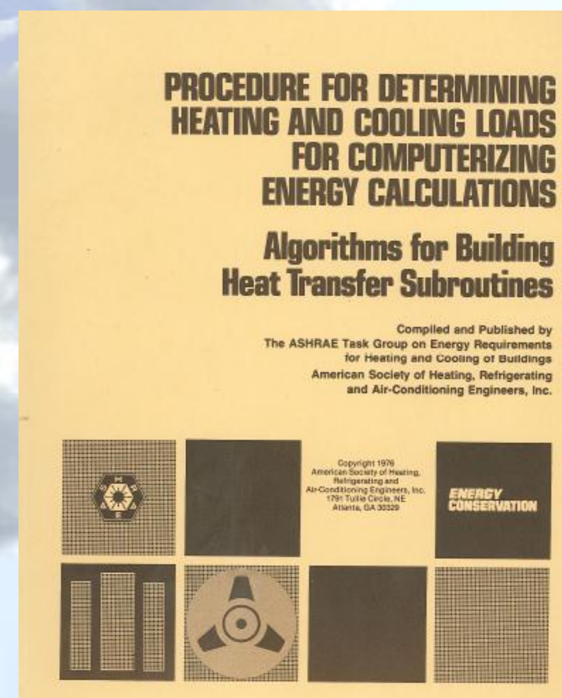
1972 *ASHRAE Handbook of Fundamentals*

1977 *TRANE Air Conditioning Manual*

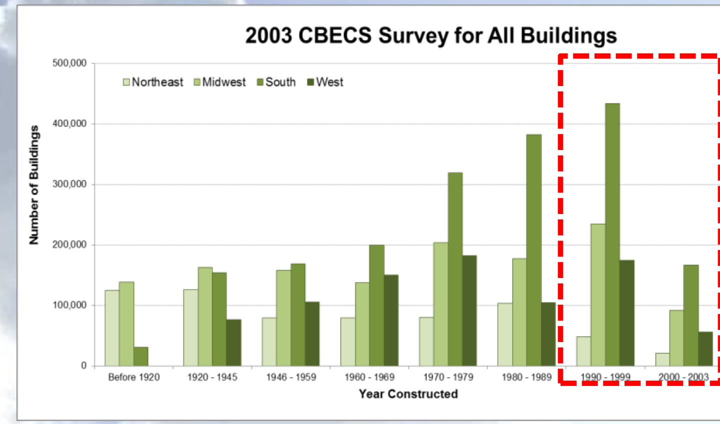
1975 *ASHRAE Task Group on Energy Requirements*: Procedure for Determining Heating and Cooling Loads for Computerizing Energy Calculations







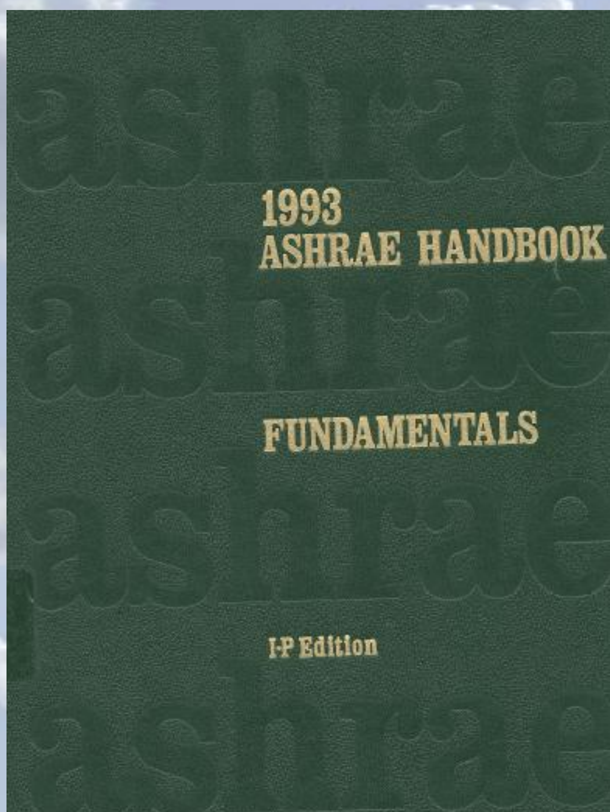
History: 1990 – Present Guide Books

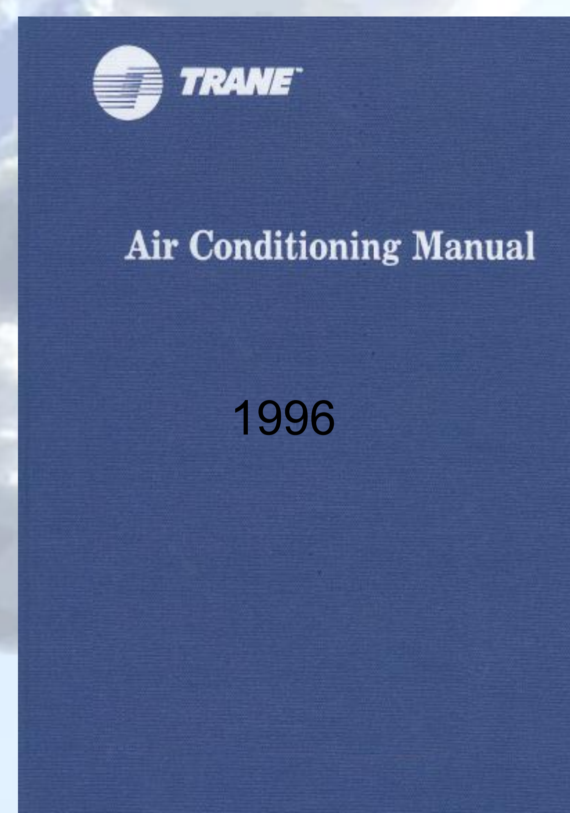


Guide Books:

1993 *ASHRAE Handbook of Fundamentals*

1996 *TRANE Air Conditioning Manual*



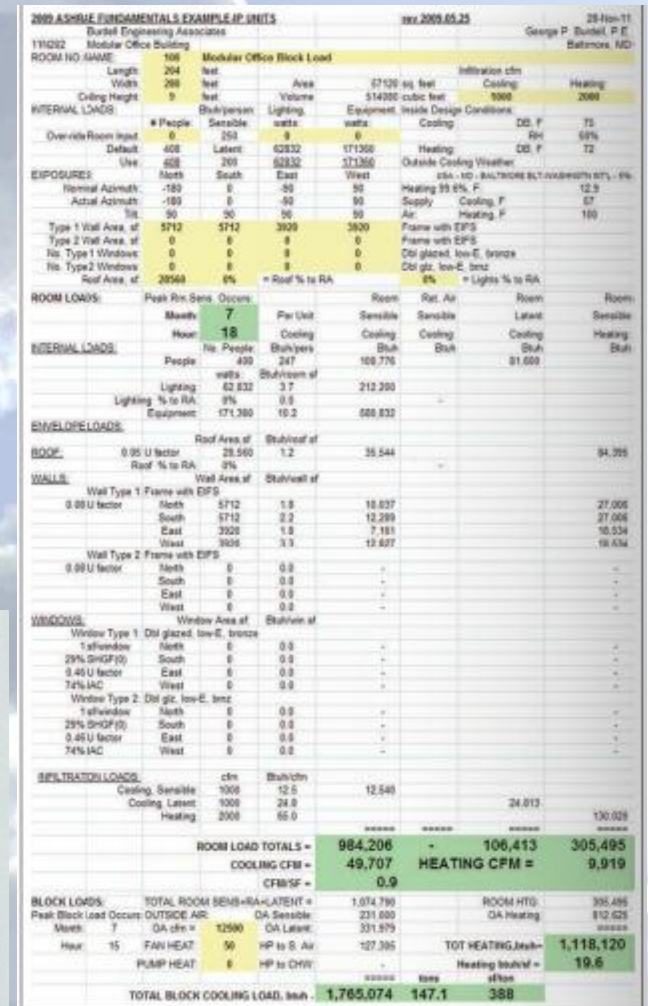


History: 1990 – Present Cooling Load Calculation

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

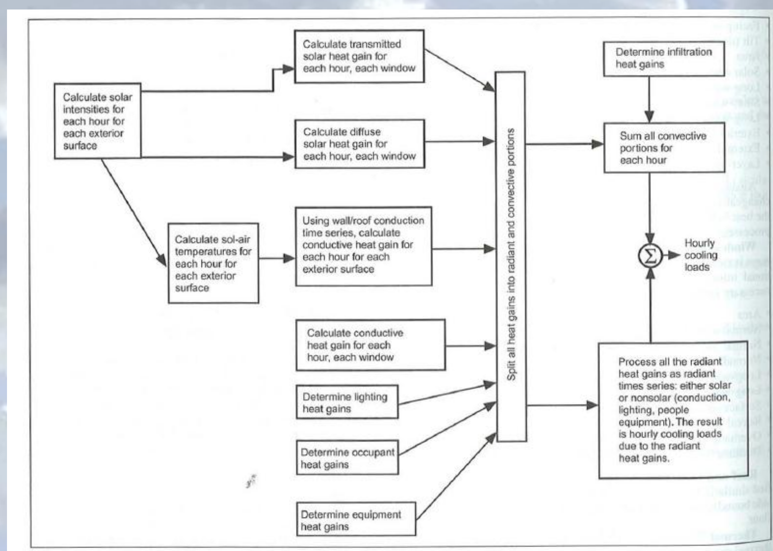


Fig. 8 Overview of Radiant Time Series Method

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 ASHRAE Final Report
- ✓ Both methods used for residential calculations
- ✓ Later appeared in ***2005 ASHRAE Handbook of Fundamentals***

Table 1 RLF Limitations

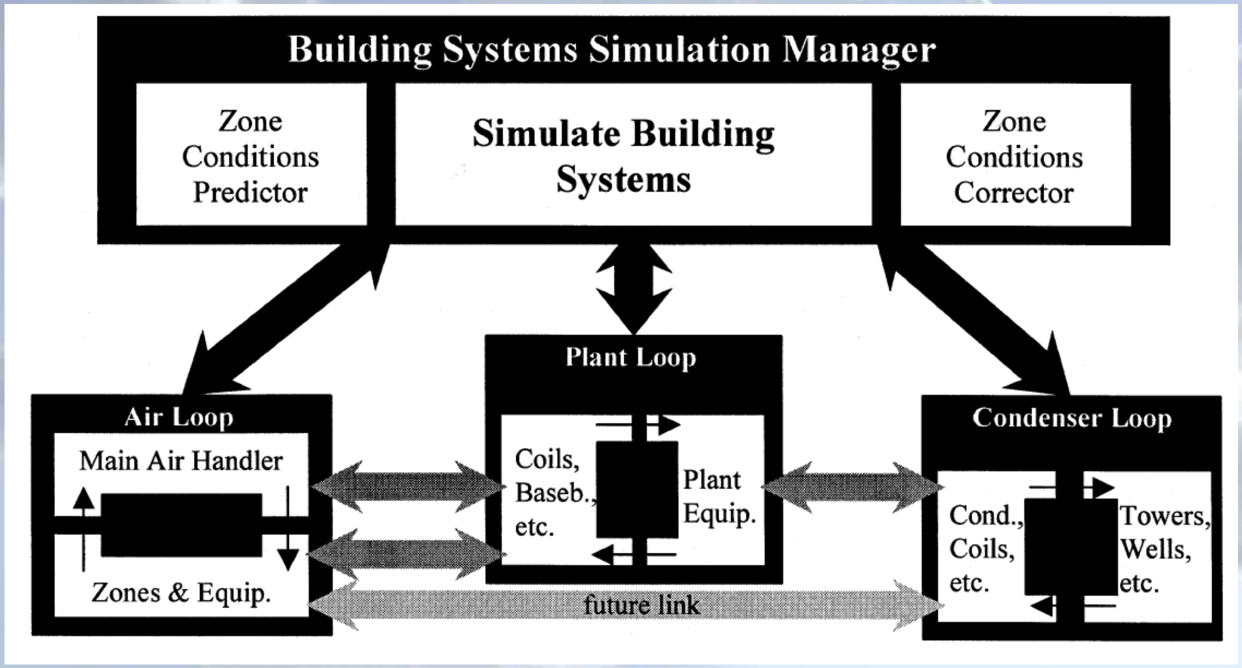
Item	Valid Range	Notes
Latitude	20 to 60°N	Also approximately valid for 20 to 60°S with N and S orientations reversed for southern hemisphere.
Date	July 21	Application must be summer peaking. Buildings in mild climates with significant SE/S/SW glazing may experience maximum cooling load in fall or even 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.
Occupancy	Residential	Applications with high internal gains and/or high occupant density should be analyzed with RHB or nonresidential procedures.
Temperature swing	1.7 K	
Distribution losses	Typical	Applications with extensive duct runs in unconditioned spaces should be analyzed with RHB.

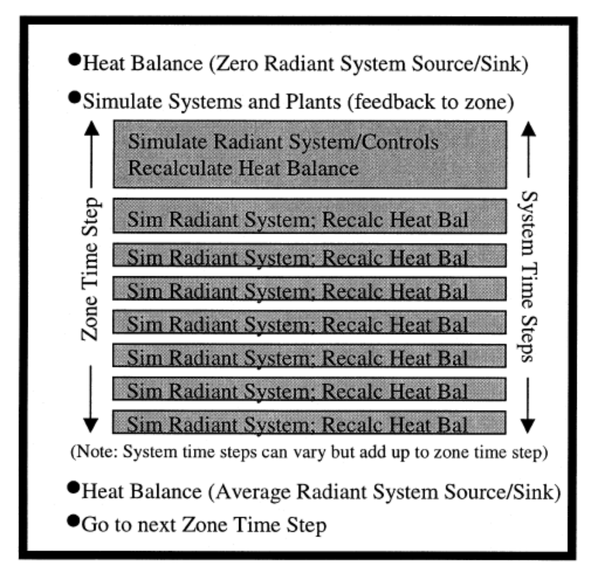
Source: 2005 ASHRAE Handbook of Fundamentals

History: 1990 – Present Cooling Load Calculation

Modeling Radiant 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

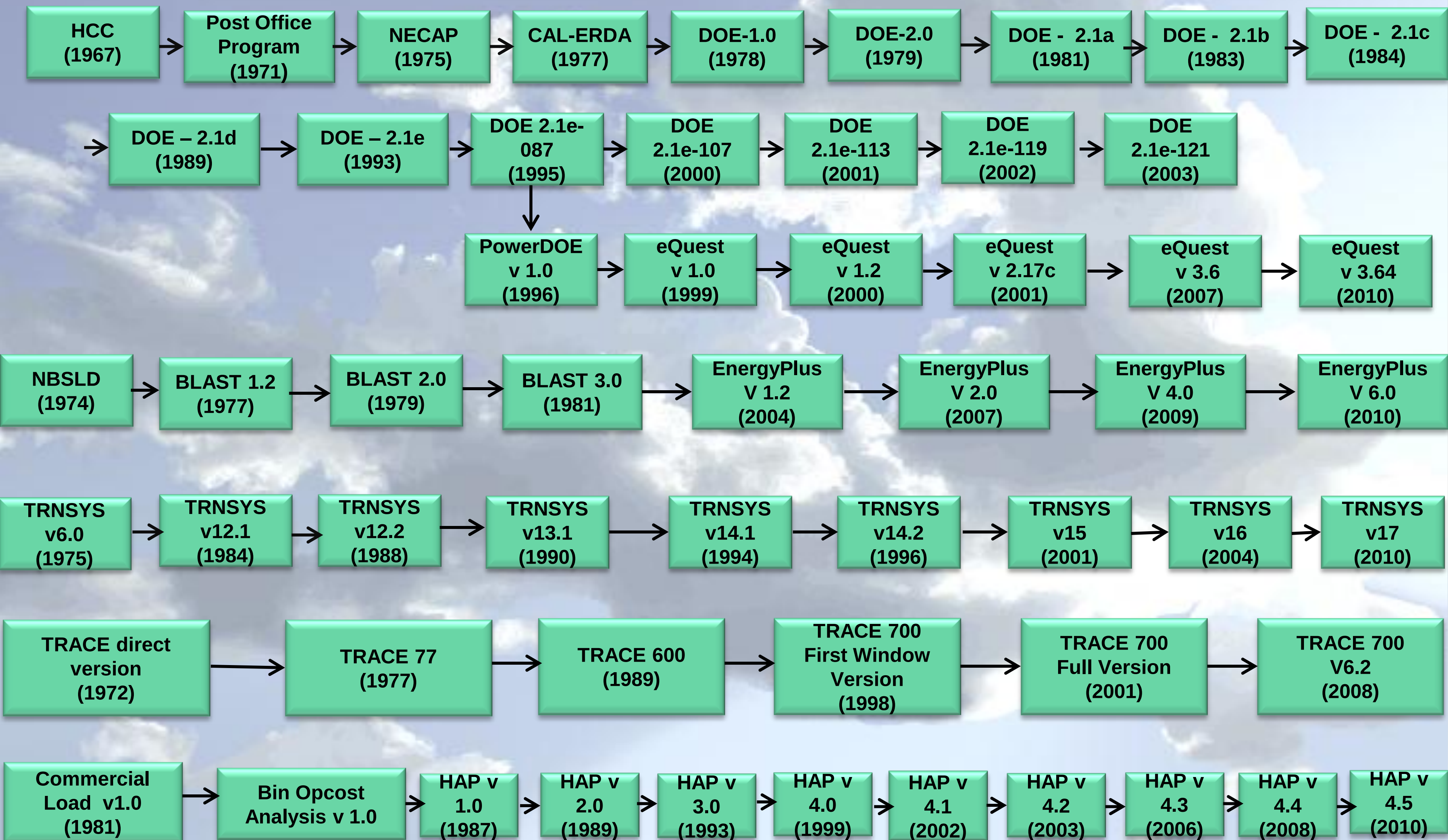




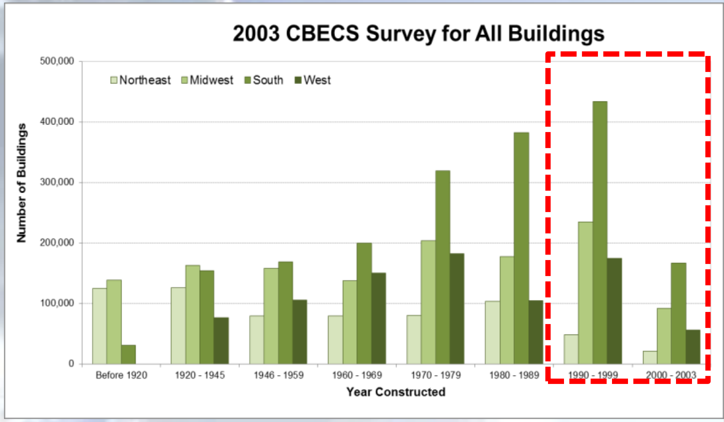
Source: 2005 ASHRAE Handbook of Fundamentals

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)

Structure Factors for Walls with Cores Composed of Heavyweight Concrete and Insulation, Shown in Figure 1

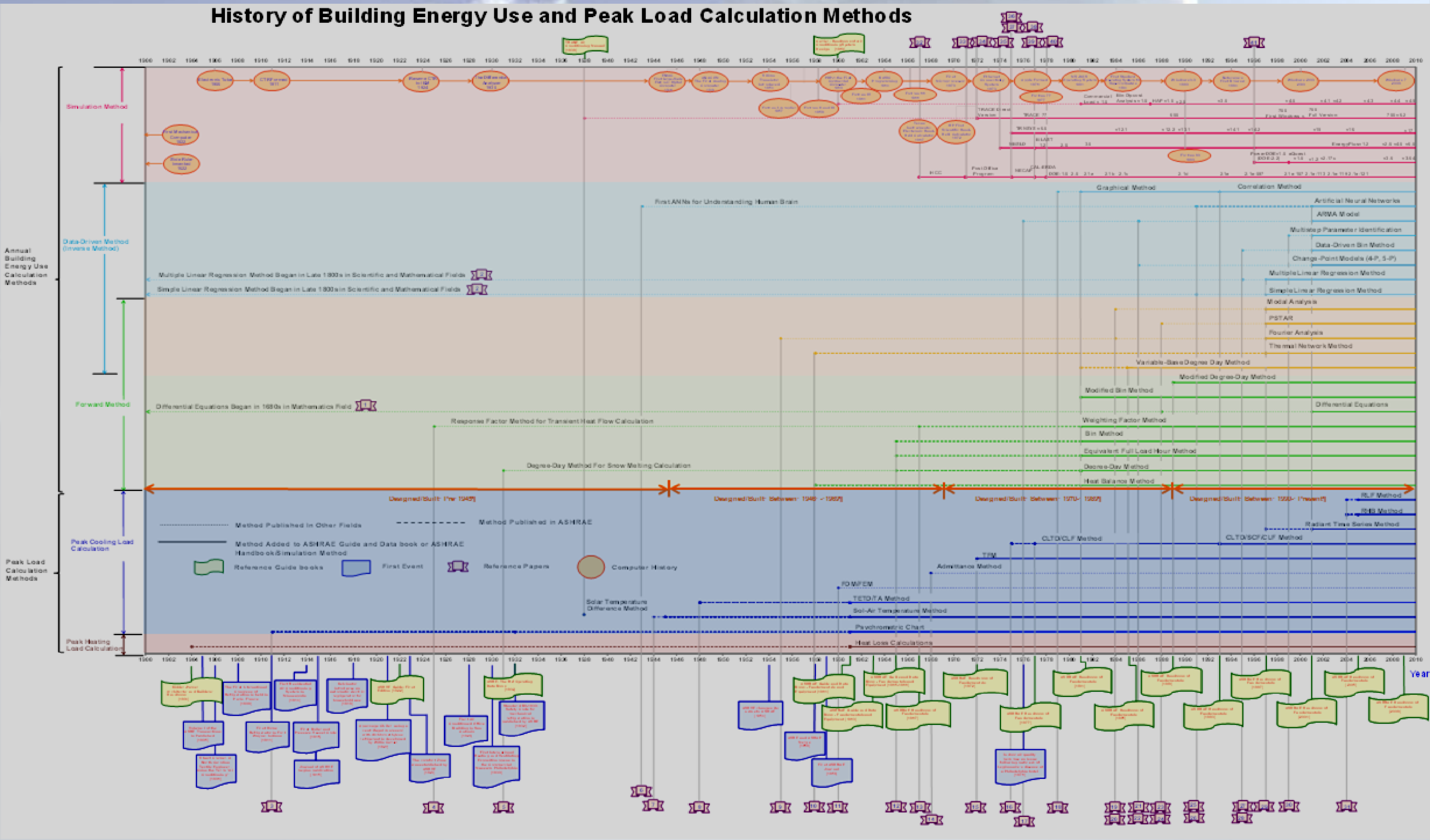
Structure No.	Layer thicknesses (in.)	φ_{ii}	φ_{ie}	φ_{ee}
Gypsum - Heavyweight Concrete - Insulation - Heavyweight Concrete - Stucco				
1	1/2 - 3 - 4 - 3 - 3/4	0.408	0.048	0.496
2	1/2 - 4 - 4 - 2 - 3/4	0.530	0.053	0.363
3	1/2 - 6 - 4 - 0 - 3/4	0.770	0.068	0.094
Gypsum - Insulation - Heavyweight Concrete - Insulation - Stucco				
4	1/2 - 4 - 6 - 0 - 3/4	0.034	0.040	0.885
5	1/2 - 1 - 6 - 3 - 3/4	0.460	0.187	0.167
6	1/2 - 2 - 6 - 2 - 3/4	0.234	0.222	0.322
Homogeneous Core	1/2 - 10 - 3/4	0.294	0.162	0.382

Decrement Factors, Amplitudes, and Time Shifts of the Transmittance and Admittance Response for Walls with Cores Composed of Heavyweight Concrete and Insulation, Shown in Figure 1

Wall No	$\varphi_{ie}/\varphi_{ii}$	1/B Response			D/B Response	
		DF	Amplitude Btu/h·ft^2·°F	τ_{ie} (h)	Amplitude Btu/h·ft^2·°F	τ_{ii} (h)
Gypsum - Heavyweight Concrete - Insulation - Heavyweight Concrete - Stucco						
1	0.048/0.408	0.270	0.0148	-8.831	0.758	1.565
2	0.053/0.530	0.251	0.0138	-8.524	0.764	1.231
3	0.068/0.770	0.205	0.0112	-7.478	0.746	0.908
Gypsum - Insulation - Heavyweight Concrete - Insulation - Stucco						
4	0.040/0.034	0.356	0.0196	-6.761	0.153	4.072
5	0.187/0.460	0.070	0.0038	-8.237	0.226	1.905
6	0.222/0.234	0.059	0.0032	-8.288	0.171	2.998
Homogen. Core	0.162/0.294	0.039	0.0021	-20.548	0.398	2.386

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



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?