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LITERATURE REVIEW ON THE HISTORY OF BUILDING PEAK LOAD AND ANNUAL ENERGY USE CALCULATION METHODS IN THE U.S.

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EXECUTIVE SUMMARY

This report provides a detailed literature review on the history of building peak heating and cooling load and annual energy use calculation methods from the 1800s to the present. Building annual energy use calculations include: forward methods, data-driven methods and simulation methods.

The report is organized as follows:

- Section 1 describes the introduction of this report, including the history of the related sciences, computer developments and a brief history of ASHRAE information about U.S. commercial buildings including the distribution and age are covered in this section as well.
- Section 2 details the history of peak heating and cooling load calculation methods.
- Section 3 presents building annual energy use calculation methods, where the basic concepts are introduced and the most popular calculation methods are reviewed.
- Section 4 includes a summary followed by the related references.

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

This report reviews the methods for calculating building peak heating and cooling loads and annual energy use calculations during the past one hundred years. Building peak load calculations are mainly used for sizing HVAC equipment, so it can provide adequate heating or cooling when extreme weather conditions occur. Building annual energy use calculations are performed to provide building owners, architects and engineers with a prediction about how much energy will be consumed after the buildings are put into operation. A review of the calculation methods is important to understand the methods that were used for designing existing buildings and what aspects of those methods could be improved to better design energy efficient commercial buildings in the future.

1.1 History of Related Science

The development of peak load and annual energy use calculation methods could not be performed without a solid foundation based on the related sciences. This section provides a review of the previous sciences and engineering practices from the 1700s to the 1900s including[1]: gas laws, heat transfer, and thermodynamics.

1.1.1 Gas Laws

The development of the science of the behavior of gasses, such as moist air, was important for sizing heating and cooling system. The studies of gas laws began in the 17th century first with experiments that defined temperature, pressure and volume relationships, followed shortly thereafter with a better understanding of partial pressures, molecules and eventually atoms. One of the earliest studies was performed by the British scientist and philosopher, Robert Boyle (1627-1691), who performed experiments with an air vacuum pump to observe the effects of reducing air pressure, which was reported in his book “New Experiments Physico-Mechanicall, Touching the Spring of the Air, and its Effects” in 1660; Two years later, he published his results, which demonstrated that the product of gas pressure and volume was constant at a given temperature; now referred to as “Boyle's Law”. Robert Boyle is usually credited with being the first to research gas properties through observations based on experiments.

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[1] References for this introduction materials can be found in West (2005), Donaldson *et al.* (1994), Acott (1999), Elena and Manuela (2006), Gas Law History (n.d.), Sandfort (1962), Woo and Yeo (n.d.), Hirang (2008-2009), Bergles (1988), Cheng and Fujii (1988), Narasimhan (1999), Backman and Harman (2001), Mätzler (2012), Carter (2004), Winhoven and Gibbs (n.d.), Powers (2012), Javadi (n.d.).

One hundred years later, in 1787, Jacques Charles (1746-1823), the French chemist and physicist, formulated Charles' Law stated that the gas volume was proportional to the gas temperature at a given gas pressure. However, Charles' Law was not published until 1802 when it was cited by Joseph Louis Gay-Lussac, a French chemist and physicist. Gay-Lussac's Law showed the relationship between gas pressure and temperature at a constant gas volume. A combined gas law that considered gas pressure, temperature and volume was later derived by combining Boyle's Law and Charles' Law.

In 1801, the English chemist, meteorologist and physicist, John Dalton (1766-1844), introduced the concept of “partial pressure”, which proposed that the summation of the partial pressures of each gas component was equal to the total pressure of mixture. This later became known as "Dalton's Law". Eight years later, in 1809, Joseph Louis Gay-Lussac developed another law about the conservation of gas volumes in chemical reactions at the same temperature and pressure. In 1811, based on Gay-Lussac's data, Amedeo Avogadro (1776-1856) proposed Avogadro's Law, which was the first to suggest that "molecules" should be differentiated from “atoms”, which helped to further understand gaseous mixture. Avogadro's Law also stated that gases with equal volumes at the same temperature and pressure had equal numbers of molecules. Eventually, all these discoveries lead to the Ideal Gas Law that formed the basis of today’s thermodynamic principles for moist air.

1.1.2 Heat Transfer

Heat transfer, the discipline that studies the process transferring heat from one object to another, is composed of three important fields: conduction, convection and radiation. The earliest theories of heat transfer began with Isaac Newton (1642-1727) who published “Newton's Law of Cooling” in 1701 that first introduced the term “heat transfer coefficient”. Newton proposed a proportional relationship between the cooling rate and temperature difference of two surfaces based on his early experiments. His Law of Cooling was considered the beginning of convective heat transfer studies. The three modes of heat transfer: conduction, convection and radiation, were not separately distinguished until 1757 by Joseph Black (1728-1799), who also introduced the term "Latent Heat".

In 1807, the theory of heat conduction was first formulated by Joseph Fourier (1768-1830) through the use of partial differential equations that described the transient process. Fifteen years later, in 1822, Fourier's Law of Heat Conduction was formally proposed in his published paper

"The Analytic Theory of Heat". In the beginning of the 19th century, the earliest work on radiation heat transfer started with the recognition of "invisible light" by William Herschel in 1800. It was not until sixty years later, in 1860, that Kirchhoff's law of radiation was formulated by Gustav Kirchhoff (l824-1887), which gave us an equation to calculate the radiative heat transfer process at the surface of a material. Shortly after this, Stefan's Law was proposed in 1879, based on experiments performed by Joseph Stefan (1835-1893), which stated that there was a proportional relation between radiation and the fourth power of surface temperature. Then, five years later, in 1884, Ludwig Boltzmann (1844-1906) provided a derivation of a fourth power radiative heat transfer law. Stefan and Boltzmann's work were later combined and are now referred to as the "Stefan-Boltzmann Law", which includes the Stefan-Boltzmann constant for performing the radiative heat transfer calculation. In summary, these heat transfer discoveries provided the basic theories and equations to calculate dynamic building peak load calculations as well as annual energy use calculations.

1.1.3 Thermodynamics

Thermodynamics is a discipline that combines the concepts of heat, work and energy, including: the First, Second and Third Law of Thermodynamics. The science of thermodynamics developed gradually alongside the development of gas laws and heat transfer in the 19th century. Beginning in 1824, Sadi Carnot (1796-1832), also known as the "Father of Thermodynamics", proposed the Carnot cycle, which was published in his "Reflections on the Motive Power of Fire and on Machines Filled to Develop That Power"; this paper marked the birth of the science of thermodynamics and established the foundation for the First and Second Law of Thermodynamics. The First Law of Thermodynamics - Conservation of Energy was first introduced in 1842 by Robert Mayer (1814-1878) who proposed that heat was a form of energy. One year later, the equivalence of heat and mechanical work was demonstrated by James Prescott Joule (1818-1889)[2].

In 1847, an energy conservation formula was first proposed by Hermann von Helmholtz (1821-1894). This led to the development of the Second Law of Thermodynamics, which was presented by Rudolf J. Clausius (1822-1888) in 1850 when be introduced the term "entropy", which was based on Helmholtz and Carnot's work. The Third Law of Thermodynamics was not

[2]The S.I. energy unit was named after James Prescott Joule.

proposed until 1906 by the physical chemist, Walther Hermann Nernst (1864-1941), which stated that the entropy of a system was zero if the temperature was absolute zero. These three Laws of Thermodynamics helped consolidate the concepts of heat, work and energy into calculations of a single subject or system of equations, which together with the science of gas laws and heat transfer became the foundations of building peak heating and cooling load calculations and annual energy use calculations.

1.2 History of Computer Developments

During the early 19th century, the seeds of computer science were first planted, which are important to building energy calculations. Beginning in 1822, Charles Babbage started his design of a difference engine to automate routine calculation (Bannerman, 2010). This marked the beginning of machine calculations. Before that, engineers and scientists used slide rulers or were forced to calculate an equation manually with the assistance of tables of pre-calculated values (i.e., sine, cosine, logarithm, etc.). In 1832, the first portion of the difference engine was developed by Charles Babbage and Joseph Clement (Carlson *et al.*, n.d.). Two years later, Babbage began his work on the analytical engine for which Ada Lovelace, regarded as the world's first computer programmer, wrote the first programs.

The Electric Numerical Integrator and Computer (ENIAC) was the first large-scale electronic digital computer, developed in the U.S. at the University of Pennsylvania in 1946 (Anonymous, 1997). ENIAC was developed to provide the American military with a tool to calculate artillery-firing tables that predicted the trajectory of a shell that compensated for the rotation of the earth among other things. From 1946 to 1960, computers occupied entire rooms, requiring constant attention. In 1960, the first commercial minicomputers became available. Eventually as the hardware improved, sophisticated computer programs emerged as well. Prior to 1960, every computer had to have its own operating system, which limited the wide-spread use of any single program. In the 1950s, IBM developed a new programming language that allowed a program to be written on one computer and run on another - FORTRAN I developed in 1957 (IBM, n.d.). From 1958 to the present, FORTRAN II, III, IV, FORTRAN 66, 77, 90, 95, 2003, 2008 versions were developed. By the late 1960s, the availability of computers and the new FORTRAN programming language provided the tools for building energy simulations.

1.3 History of ASHRAE

Figure 2[3] shows the history of the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE). Unsatisfied with the papers presented in the annual meeting of the Master Stream and Hot Water Fitters Association just focusing on the business matters rather than the engineering knowledge communications, Hugh Barron, who led an effort to build a new engineering society, began the American Society of Heating and Ventilating Engineers (ASHVE) in September of 1894 (Donaldson *et al.*, 1994). *ASHVE Transactions* and the *Journal* were first published in 1895 and 1915, respectively. *ASHVE Guide*[4] was first published in 1922, which was considered the first consolidated guide for heating and ventilating engineers prior to 1922 information had to be found in the textbooks and manufacturer's information. In 1954, ASHVE changed its name to ASHAE[5] to better represent the society of heating and air-conditioning engineers.

The American Society of Refrigerating Engineers (ASRE) was founded in 1904, which was a society for refrigerating engineers. *ASRE Transactions* was published one year later and the ASRE guide "*The Refrigerating Data Book and Catalog*" was published in 1932. 1958 was a breakthrough year for ASHAE and ASRE due to their merger into ASHRAE to better represent the two professions. *The ASHRAE Guide and Data Book* was first published in 1961, which was considered the earliest predecessor version of the ASHRAE handbook. The 1961 ASHRAE Guide was widely used before the development of *ASHRAE Handbook of Fundamentals*. Six years later, in 1967, the first version of the ASHRAE Handbook of Fundamentals was available. Since then, the ASHRAE Handbook of Fundamentals has been updated every four years[6]. The current version is *2009 ASHRAE Handbook of Fundamentals*.

1.4 Distribution/Age of U.S. Commercial Buildings[7]

In order to better appreciate the impact of historical heating and cooling load calculations, it is helpful to know the distribution and age of commercial buildings in the U.S. This section provides a brief review of the distribution and age of U.S. commercial buildings using the

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[3] ASHRAE history refers to the documents: http://www.ashrae.org/File%20Library/docLib/Public/200511311142_347.pdf

[4] 1922 ASHVE Guide was a composite document, including research reports, data section, advertising material from manufacturers, etc. It took forty five years to become ASHRAE Handbook in 1967.

[5] The American Society of Heating and Air-Conditioning Engineers

[6] ASHRAE handbook has four volumes: ASHRAE Fundamentals, Refrigeration, HVAC Applications, HVAC Systems and Equipment. One of the four volumes is updated each year.

[7] Studied building numbers: Northeast, 662,000; Midwest, 1,306,000; South, 1,856,000; West, 850,000. The withheld data in the CBECS survey were ignored.

CBECS[8] database (CBECS, 2003), which shows the existing commercial building distribution in the U.S. Four of the U.S. census regions and divisions are shown in the survey, which include the West, Midwest, Northeast and South. The distributions of commercial buildings in the four regions are 39.7% in the South, 27.9% in the Midwest, 18.2% in the West and 14.2% in the Northeast. In all four regions 40.5% of the total 4.7 million buildings, or 1.89 million buildings were built prior to 1970, when manual heating and cooling load calculations were used by most consulting engineers.

[8] The Commercial Buildings Energy Consumption Survey

2 PEAK LOAD CALCULATION METHODS

Building peak load calculation methods, which include peak heating and cooling load calculations, are used for sizing HVAC equipment in order to provide adequate heating or cooling when extreme weather conditions occur. This section reviews the history of the major peak heating and cooling load methods in four different periods: Pre 1945, 1946-1969, 1970-1989, and 1990-Present.

2.1 The Origin of Peak Load Calculation Methods – Pre 1945

The birth of most engineering methods is often inspired by the need to solve problems which are relevant and practical for a given period. Prior the development of standardized peak load calculation methods, most engineers tried to design building HVAC systems by relying on manufacturer's literature for a specific system, a few available textbooks or even fewer handbooks or guidebooks.

The earliest heating and ventilating design developments started in the 19th century. Unfortunately, engineers had to design systems with rules-of-thumb or approximate design methods because useful textbooks or guidebooks that were based on first principles were in scarce supply. As early as in 1834, Dr. Boswell Reid redesigned the heating and ventilating system for British House of Commons using a chimney to induce air flow through the building , with a water spray cooling and steam heating system (Donaldson et al., 1994). This was probably one of the first successful applications of purposeful "fresh air" into a public space, with evaporative cooling and/or heating applied to the air under manual controls.

About the same time, Eugéne Péclet, a French physicist and a heat engineer, was probably the first to introduce heat transfer calculations by publishing his textbook "*Traité De La Chaleur*" (Treatise on Heating) in 1844 (Donaldson et al., 1994; Nicholls, 1922). Unfortunately, few engineers and architects were aware of Péclet's work since it was written only in French. In 1904, some of Péclet's work was finally translated into English by Charles Paulding (Paulding, 1904).

In 1855, Robert Briggs designed and installed a heating and ventilation system for the U.S. House of Representatives (Donaldson et al., 1994). His system used indirect steam heaters (i.e., underfloor radiators), a chimney[9] , and subterranean airways for each wing. Engineers at that time could only count on their own practical design experience, which was often limited. Useful textbooks that contained design tables and equations did not start to appear until twenty to thirty years later.

In 1884, Frank E. Kidder introduced the first version of his book "*Architect's and Builder's Handbook*" (Kidder, 1906). This book was oriented towards architects and mostly contained information from manufacturer's literature regarding the sizing the steam radiators by the determination of the room size and boiler size. Although a heat loss calculation method was included, it was described in terms of words instead of equations. In addition, thermal mass was not considered in the system design, since all tabulated heat transfer coefficients were for steady-state calculations.

Shortly after, in 1894, a professor of the Technical University of Berlin, Hermann Rietschel published a German textbook called "*Lüftungs-und Heizungs-Anlagen*"[10] (Ventilation and Heating Systems) that was later translated into English version by C.W. Brabbee in 1927 (Rietschel and Brabbee, 1927). This book is widely recognized as Europe's first scientifically-based text on heating and ventilating. It contained relatively complete information about how to calculate heat transfer, including equations that are still in use today. It also described how to size steam systems, piping, etc., and it even provided a detailed solution to the dynamic heat transfer calculation in a single slab of wall material as well as steady-state heat loss calculations for walls, roofs, windows and ventilation. The book also included tables of useful heat transfer coefficients as well as charts and graphs with plotted properties of moist air (Usemann, 1995). Unfortunately, no formulas for moist air were included.

Shortly after, in 1896, Rolla Carpenter, a professor at Cornell University, published the first version of his textbook named Heating and Ventilating Buildings (Carpenter, 1896). This book included theory and applications of heating and ventilating apparatus by Thomas Tredgold (1836), Charles Hood (1855), and Eugéne Péclet (1850). It also included tables of materials, properties of air and math algorithms. It can be considered as an equivalent engineering handbook.

[9]Originally, which was replaced with a large fan added afterwards.
[10]Private communication with Mr. Bernard Nagengast.

Around the same period, in the 1890s, Alfred R. Wolff, a well-known heating and ventilating design engineer in the U.S., published his “heat transfer coefficient” chart that was derived from the previous work by Eugéne Péclet and Thomas Box. It included a graph that showed the heat loss per unit area for windows, doors and walls and ceilings of varying thickness (Wolff, 1894; cited in Donaldson et al., 1994). Wolff was regarded as one of the first U.S. engineers to use “heat transfer coefficients”, and his chart that showed “varying thickness” was probably the first published dynamic effect of thermal mass[11]. Wolff was the designer of the first air conditioning system[12] for the Board Room of New York Stock Exchange in 1903[13], which was regarded as one of the earliest commercial air-conditioning systems to be designed and operated for comfort (Donaldson et al., 1994).

Stepping into the 20th century, new peak cooling load methods began to be developed during the 1900 to 1945 period, including: the psychrometric chart and the governing equations for moist air, the sol-air temperature method and the thermal network method. In 1902, a young engineer at the Buffalo Forge company, named Willis Carrier designed his first ventilation system with cooling coils for the Sackett and Wilhelms Company, in Brooklyn, N.Y. (Donaldson *et al.*, 1994). Unfortunately, the system was not successful, because, although it could cool the air stream, it could not control the humidity. After studying the failure, Carrier determined that a spray-type air washer using chilled water could be used to control temperature and humidity[14].

In 1906, Carrier developed a working system and applied for a patent for an “apparatus for treating air”, which allowed him to control the absolute humidity of the air stream exiting the chilled water spray (Donaldson *et al.*, 1994). Two years later, in 1908, Carrier published his first psychrometric chart based on his psychrometric formulas[15] (Donaldson *et al.*, 1994). In 1928, Carrier designed the mechanical system for the Milam Building in San Antonio, Texas, which was the first high-rise air-conditioned office building in U.S. (ASME, 1991). In the Milam building, two centrifugal refrigeration units developed by the Carrier Company, were used as the cooling system. Unfortunately, the radiant heat that was supposed to be absorbed by the heavy exterior construction was not well understood. This resulted in the system not working as planned due to

[11] Wolff was also aware of Rietschel’s textbook.
[12] Wolff consulted Henry Torrance of the Carbondale Machine Company for this design.
[13] Two years later, in 1905, Stuart Cramer first used the term “air conditioning” for treating air in textile mills in N.C., which became widely adapted as the terminology that described artificial cooling system (Donaldson *et al.*, 1994).
[14] Information was retrieved from: http://en.wikipedia.org/wiki/Willis_Carrier
[15] Carrier’s psychrometric chart was later formally published in 1911 in ASME (Carrier, 1911).

an unexpected asymmetric cooling load. To remedy this, venetian blinds, cloth window shades and duct dampers were installed to solve morning or afternoon overheating problems (ASME, 1991).

In 1914, the Buffalo Forge Engineer's Handbook was published, which was recognized as the first comprehensive U.S. manufacturer's handbook for heating and ventilating (Carrier, 1914). It contained detailed equations for heat loss calculations for walls, roofs, windows and ventilation, including tables of useful coefficients as well as Carrier's psychrometric chart, which was the first time that a psychrometric chart was introduced in a handbook. Eight years later, in 1922, ASHVE published its first guide book, "*The American Society of Heating and Ventilating Engineers Guide*", which also had basic heat loss formula, unfortunately which were presented as "word formulas" (ASHVE, 1922).

During this period, several other useful textbooks appeared. In 1918, John R. Allen *et al.* published the first edition of their book "*Heating and Ventilation*" that provided detailed heat loss calculation methods that included tables of useful coefficients and equations (Allen *et al.*, 1931).

Shortly after Allen, in 1935, Charles Merrick Gay and Charles De Van Fawcett published their textbook, which contained detailed equation-based calculations for heat loss and a very terse advice about how to calculate summertime heat gain[16] (Gay and Fawcett, 1937). One year later, the TRANE Company published its first design manual, which provided a load estimate sheet for engineers to use (TRANE, 1938). This manual used tabulated "solar temperature differences" and also included instructions for using the TRANE air - conditioning ruler[17].

Several important papers were also published during this period in Europe and in the U.S. In 1925, the Response Factor Method was first introduced for transient flow calculation by André Nessi and Léon Nisolle in French (Nessi and Nisolle, 1925). In 1939, Alford *et al.* published a paper on heat storage/heat transfer through walls driven by temperature and solar intensity in the *ASHVE Transactions*. This paper provided a detailed solution to the differential equation in the form of a decrement factor and a time delay (Alford *et al.*, 1939). Three years later, in 1942, the

[16]In the book, they recommended the use of a rule-of-thumb method: "add 25°F to the dry bulb temperature difference for heat transmission calculation".
[17]This ruler was for use with the TRANE psychrometric chart. The heat transfer tables were listed according to the color of the wall, versus thermal mass characteristics.

thermal R/C network method was first developed by Victor Paschkis to simulate building walls (Paschkis, 1942). Later in 1944, C.O. Mackey and L.T. Wright Jr. used a modified version of Alford *et al.*'s equations and proposed the "sol-air temperature method" (Mackey and Wright, 1944). In the same year, in 1944, John G. Linvill and John J. Hess Jr. published their article "Studying Thermal Behavior of Houses", which was an undergraduate student project at M.I.T. Their article showed how the thermal network method could be used to simulate an entire house (Linvill and Hess, 1944).

In summary, during the period prior to 1945, there were at best inconsistent methods for calculating peak heating and cooling loads. These methods appeared in textbooks, handbooks, guidebooks and manufacturer's literature. However, during this same period, the foundation was laid for today's modern methods, which began with sol-air temperatures, decrement factors and the use of a thermal R/C network to calculate dynamic building heat gain/loss.

2.2 Early Methods for Peak Cooling Load Calculation – from 1946 to 1969

Most of the dynamic peak cooling calculation methods used today in the U.S. were proposed during the 1946-1969 period. In 1948, as a design engineer at Carrier Cooperation, James P. Stewart was the first to outline Equivalent Temperature Differentials (ETD), based on Mackey and Wright's earlier work, which was intended to be used as an easy-to-use tabulated design method that would estimate the time delay and amplitude of the dynamic heat gain due to thermal mass. Stewart's method was shown to be suitable for calculating an extended hourly profile only if radiant components were averaged over the representative period for all the thermal mass of the building (Stewart, 1948). The ETD tables were adopted for use in the *1951 ASHVE Guide* (ASHVE, 1951). Unfortunately, judging the amount of thermal mass in a building was a difficult job for an average engineer, which ultimately made the method only useful in the hands of an experienced engineer. To help resolve this, additional tables of Total Equivalent Temperature Difference/ Time Averaging method (TETD/TA) values were later tabulated in the *1961 ASHRAE Guide and Data Book* (ASHRAE, 1961).

In 1955, a new edition of Gay and Fawcett's textbook was published that included a new author, William McGuinness who was a professor of Architecture at the Pratt Institute of Technology (Gay *et al.*, 1955). This new edition included a revised procedure for air conditioning design, as well as improved data for calculating heat gains (Gay *et al.*, 1955), which referenced the *1951 ASHVE Guide*[18]. So, by the mid-1950s either the direct use of Mackey and Wright's sol-air temperature equations or Stewart's tabulated TETD/TA values provided designers with an improved method to calculate the impact of thermal mass.

In the mid-1950, W.R. Brisken, S.G. Reque and P.R. Hill laid the foundations of today's thermal Response Factor Method (RFM), based on Nessi and Nisolle's 1925 work. In 1956, Brisken and Reque published their heat load calculations using the thermal response method (Brisken and Reque, 1956). In this method, they proposed using "square waves" to represent a time-varying "curve" of temperature response. One year later, Hill developed a more accurate "unit triangle" method for calculating the time-varying 1-D surface temperature (Hill, 1957). Based on these previous works, in 1967, G.P. Mitalas and D.G. Stephenson developed the thermal Response Factor Method (RFM), which allowed for the solution to the dynamic heat transfer problem without having the knowledge of how to solve a separate differential equation for each new wall type (Mitalas and Stephenson, 1967; Stephenson and Mitalas, 1967). Later, this method became part of the Weighting Factor Method, which was used for calculating building annual energy use in the *1981 ASHRAE Handbook* (ASHRAE, 1981).

Several authors investigated the use of thermal R/C network models for analysing dynamic heat transfer (Paschkis, 1942; Buchberg, 1955; Nottage and Parmelee, 1954). As previously mentioned, although the first thermal R/C network method appeared in 1942, Harry Buchberg developed a complete R/C thermal network for a house model using heat balance calculations in an analog computer in 1958. This project was an ASHRAE sponsored project and is regarded as the first time that the heat balance method and thermal network method were used together in an analog building simulation (Buchberg, 1958). The heat balance method was later adopted in the *1981 ASHRAE Handbook* along with the weighting factor method as building annual energy use calculation methods (ASHRAE, 1981).

The guide books during 1946-1969 included: the 1955 *TRANE Air Conditioning Manual* (TRANE, 1955), the 1960 *Carrier Handbook of Air Conditioning System Design* (Carrier, 1960), the 1951 *ASHVE Guide* (ASHVE, 1951), several *ASHRAE Guide and Data Book* (ASHRAE, 1961, 1963, 1965), and the first version of ASHRAE Handbook (ASHRAE, 1967). In these handbooks, thermal mass was considered as either sol-air temperature calculations or TETD/TA tables.

[18] Gay *et al*.'s book cited the 1951 ASHVE Guide as the source of Mackey and Wright's 1944 sol-air equation.

Besides the methods discussed above, there were two other widely used methods that were developed to solve the time-varying heat transfer problems: the Finite Difference/Finite Element Method (FDM/FEM) and the admittance method. The FDM/FEM was introduced in 1960 (Clough, 1960; Forsythe and Wasow, 1960) in the form of formal equations that could be directly used in computer algorithms. The admittance method was originally developed by A.G. Loudon in 1968 (Loudon, 1968). The concept of "*Thermal Admittance*" was first introduced in the U.K. by the *Institution of Heating and Ventilating Engineers Guide* (IHVE) in 1970 (Goulart, 2004) to measure the ability of building components to smooth out the temperature swings within a 24-hour cycle. This method was later adopted by the Charted Institution of Building Services Engineers (CIBSE) and is now widely used in the U.K.

In summary, during 1946-1969, the first edition of ASHRAE Handbook appeared, which adopted the available peak heating and cooling load methods from important papers. Several of the popular textbooks and manufacturer's literature were updated to reflect the new methods as well. Finally, steady-state peak heating calculation methods matured and time-varying cooling load calculation methods that considered ambient temperature and solar radiation became available for designers to use.

2.3 Further Developments – from 1970 to 1989

Peak cooling load methods continued to develop during the period 1970-1989. In 1972, the ASHRAE Task Group on Energy Requirements (TGER) first introduced the Transfer Function Method (TFM) for peak cooling load calculation, which was based on Mitalas and Stephenson's earlier work and is considered the first, wide-spread computer-oriented method for solving dynamic heat transfer problems in buildings (Mitalas, 1972).

However, even as new computer-based methods were being developed, manual, tabulated methods were being updated and used. One such method, based on the principles of TFM, is the Cooling Load Temperature Difference/Cooling Load Factor method (CLTD/CLF), which was developed by William Rudoy and Fernando Duran in 1974 (Rudoy and Duran, 1974). It included tabulated results of controlled variable tests summarized in ASHRAE research project RP-138 for cooling load calculations. The CLTD/CLF method attempted to simplify the two-step TFM and TETD/TA method into a single-step technique, which was later published in the *1977 ASHRAE Handbook* of *Fundamentals* (ASHRAE, 1977). Fourteen years later, in 1988, the CLTD/CLF method was modified by Prof. Edward Sowell who ran 200,640 simulations to provide new tabulated answers (Sowell, 1988). That same year, Steven Merrill Harries and Faye C. McQuiston proposed an additional Conduction Transfer Function (CTF) coefficients to cover more groups of roof and wall construction conditions (Harries and McQuiston, 1988).

In summary, during the 1970 to 1979 period, peak heat load methods remain unchanged while major advances were made in peak cooling load calculation methods developed, which are still taught in textbooks today, but no longer exist in the current 2009 ASHRAE Handbook (ASHRAE, 2009)[19].

2.4 Most Recent Methods – from 1990 to present

In 1993, Jeffery Spitler *et al.* updated the CLTD/CLF method to become the CLTD/SCL/CLF method by introducing the term "Solar Cooling Load (SCL)" for an improved solar heat gain calculation through fenestration (Spitler *et al.*, 1993). This new CLTD/SCL/CLF method was later incorporated into the *1993 ASHRAE Handbook* of *Fundamentals* (ASHRAE, 1993).

The most current cooling load calculation method is the Radiant Time Series (RTS) method that Spitler *et al.* developed in 1997, which is an improvement over all previous methods (Spitler *el al*., 1997). In response to research proposed by ASHRAE Technical Committee TC 4.1, the RTS method was derived directly from, but is simpler than, the heat balance method. In the RTS method, the 1-D time-varying conduction is calculated using a 24-term response factor. The RTS method converts the radiant portion of hourly heat gain to hourly cooling loads using radiant time factors, which are the coefficients of the Radiant Time Series method. The accuracy of the Radiant Time Series method is similar to that of the TFM if custom weighting factors and custom conduction transfer function coefficients were used for all components in a building. Finally, in 2003, the ASHRAE building load calculation toolkit (LOADS toolkits) was developed by Curtis Pedersen (Pedersen, *et al*., 2003), which provided a FORTRAN source code for the heat balance calculations for ASHRAE members to use.

For residential load calculations, the Residential Heat Balance (RHB) and the Residential Load Factor (RLF) methods were developed by Charles Barnaby in 2004 (Barnaby *et al.*, 2004). In a similar fashion as the RTS method and LOADS toolkit, the RHB method was developed to be a computer algorithm, which was coded using FORTRAN, while the RLF method was

[19] For non-residential buildings, the heat balance method and radiant time series methods are included in Chapter 18 in the 2009 ASHRAE Handbook of Fundamentals for peak cooling load calculations methods.

developed to be a simple method that could be used by manually or with a spreadsheet. In 2000, an extensive analysis was developed that compared peak cooling load calculation methods in the U.S. and the U.K. by Simon Rees (Rees *et al*., 2000). The analysis concluded the cooling load calculation methods recommended in the U.S. and U.K. have the possibility to converge in the future.

2.5 Summary

Prior to the 1944 sol-air temperature method by Mackey and Wright and the ETD tables by Stewart in 1948, there were no widely-used design methods for calculating time-varying peak cooling loads in the U.S. To design building HVAC systems during this period, engineers and architects had to refer to manufacturer's literature, textbooks, guidebooks or their own experiences, which varied widely. The earliest textbooks include: Eugéne Péclet, Frank Kidder, Hermann Rietschel, Rolla Carpenter, Charles Paulding, John Allen, Charles Merrick Gay and Charles De Van Fawcett. Manufacturers like TRANE and Carrier developed and used their own methods, which were eventually published. Interestingly, prior to 1944, building peak heating load calculation methods primarily used "word formulas" to describe the calculation procedure. In the U.S., building peak cooling load calculations began with the decrement factor by Alford *et al.* in 1939, which provided the foundation of the sol-air temperature method developed by Mackey and Wright in 1944.

In 1948, Stewart developed the Equivalent Temperature Differentials table from the sol-air temperature equations of Mackey and Wright, which resulted in the ETD tables adopted by 1951 ASHVE Guide and TETD/TA method later tabulated in *1961 ASHRAE Guide and Data Book*.

The thermal response factor method was introduced by Mitalas and Stephenson in 1967, based on the previous work done by Nessi and Nisolle, Hill, Brisken and Reque. In 1958, the heat balance and thermal network methods were demonstrated by Buchberg for simulating a house on an analog computer as part of ASHRAE sponsored research project. In 1972, ASHRAE Task Group published the transfer function method for calculating dynamic heat transfer, which laid the basis for the CLTD/CLF method that was later modified by Sowell, Harries, McQuiston, and Spitler to become the CLTD/SCL/CLF method. In 1993, Jeff Spitler published the Radiant Time Series method that remains as the most accurate method for dynamic peak cooling load calculation method. The RTS method served as a foundation for the residential RHB and RLF methods developed in 2004 by Barnaby. Finally, in 2003 ASHRAE released its LOADS Toolkit, developed by Professor Curtis Pedersen, which included FORTRAN code for the heat balance method.

Today, all three methods (i.e., TETD/TA, CLTD/SCL/CLF, RTS) remain in use in the industry. However, only the RTS method is referenced in the ASHRAE Handbook.

3 BUILDING ANNUAL ENERGY USE CALCULATION METHODS

Since the 1973 oil embargo, ASHRAE has responded with efforts to improve building efficiency. Building annual energy use calculation methods, as well as the established building energy efficiency codes, became important steps toward achieving more efficient buildings. The first commercial building energy standard, *ASHRAE Standard 90-1975*, was published by ASHRAE as a direct response to the energy crisis (Skalko, 2012; Spanos and Comstock, 1995).

In addition to calculating peak heating and cooling loads to size a building's heating and cooling system, annual heating and cooling energy use needed to be calculated to estimate the annual fuel used by a building. Methods for calculating building annual energy use are divided into three categories: Forward Methods; Data-Driven Methods (also called Inverse Methods) and Simulation.

3.1 Forward Methods

Forward Methods, also called classical methods are used for estimating annual energy requirements of the buildings (ASHRAE, 2009). Compared to the peak load calculations, average year weather data are used for these calculations instead of extreme or peak weather conditions. The average energy use of a building during a year (i.e., 8760 hours) typically includes heating and cooling energy use as well as all other building energy end uses.

As early as 1925, the "*Response Factor*", first developed by André Nessi and Léon Nisolle for solving the transient heat flow problems, was demonstrated to be a useful method for solving the transient heat gain (Haberl and Cho, 2004). However, in 1925, there was no concept of a building energy simulation program so the original calculations remained as only a manual calculation. The thermal Response Factor Method (RFM) was first proposed for dynamic room cooling load calculation by Stephenson and Mitalas (Mitalas and Stephenseon, 1967; Stephenseon and Mitalas, 1967) based on the previous work done by Brisken and Reque in 1956 (Brisken and Reque,1956) ,as modified by Hill in 1957 (Hill,1957). The RFM later appeared as part of the Weighting Factor Method in the *1981 ASHRAE Handbook of Fundamentals* (ASHRAE, 1981). The Weighting Factor Method (WFM) was considered an annual building energy estimation method, which included heat gain and zone temperature as two types of "Weighting Factors" to avoid iteration. Since it was an instantaneous calculation, the present and the past cooling loads were related through "heat gain weighting factors" (ASHRAE, 1981). Following the same concept, the actual air temperature for a given hour was derived, from the HVAC heat removal rate and calculated temperature weighting factors (ASHRAE, 1981).

The Heat Balance calculations can be traced back to aerospace engineering and other industries (Sowell and Hittle, 1995). The detailed Heat Balance Method (HBM) for building energy calculation showed up in Harry Buchberg's 1958 ASHRAE study (Buchberg, 1958; Kusuda[20], 1999). This method applied the conservation of energy at each point representing an enclosing surface or a zone. Weighting factors were then determined from the Heat Balance Method. In 1981, the HBM appeared in the *1981 ASHRAE Handbook of Fundamentals* (ASHRAE, 1981).

Three manual calculation methods for estimating annual heating and cooling use were available in mid-1960s including: the degree-day method, the equivalent full load hour method and the bin method (Ayres and Stamper, 1995). The earliest degree-day method can be traced back to 1931, where it was used for snow-melting calculations to calculate water run-off from snow - packed mountains (Clyde, 1931).The original degree-day method was for heating energy calculations, which was later called the heating degree-day method. It was calculated by summing up all degree days for one year by subtracting a base 65F temperature from average daily temperatures. During period 1950s-1960s, many studies were performed for degree-day methods (Thom, 1966; Arens, 1977; Harries, 1955; cited in Fischer *et al*., 1982).This simple method involved calculating an overall building heat loss (i.e., $UA \bullet \Delta T$) and multiplying it times the total heating degree-days, adjusted for the heating plant efficiency and fuel units. Similarly, the cooling degree-day method was used to calculate cooling energy use by using cooling degree-days associated with overall building heat gains, which was also adopted in *1981 ASHRAE Handbook of Fundamentals* (ASHRAE, 1981).

The equivalent full load hour method was available in mid 1960s (Stamper, 1995) in order to estimate the cooling energy requirements that could be calculated from estimated equivalent full-load hours during a year. To accomplish this, the method relied on the brake horsepower of the chiller, maximum air conditioning design load and motor efficiency for an average load (Ayres and Stamper, 1995*)*. A bin method was also developed for both heating and cooling energy calculations that required the whole year to be divided into temperature bins. For each

[20] Kusuda developed National Bureau of Standards Load Determination (NBSLD), based on Buchberg's detailed heat balance calculations

temperature bin, the heat losses/heat gains were calculated using a product of the overall building heating/cooling loss coefficient, temperature difference and number of hours in each bin. By simply summing up those products across all bins, the heating/cooling requirements could be obtained. However, the original Bin Method did not separate solar and internal heat gains from heat losses, which was later corrected in 1979 by R.L.D. Cane in (Cane, 1979).This led to the development of the modified bin method as proposed by D.E. Knebel in 1983 (Knebel, 1983).

3.2 Data-Driven Methods

Data-Driven Methods are defined as methods that estimate building system parameters by deriving a mathematical description or parameters from the actual measured data (ASHRAE, 2009). There are eight primary methods that belong to this category: Simple Linear Regression (SLR) method, Multiple Linear Regression (MLR) method, Change-Point models (Kissock *et al.*, 1998; Ruch and Claridge, 1992), a data-driven or inverse bin method (Thamiseran and Haberl, 1994), Multistep Parameter Identification method (Reddy *et al.*, 1999), the Autogressive Moving-Average (ARMA) Model (Rabl, 1988; Reddy, 1989), Artificial Neural Networks (ANN) and correlation methods (ASHRAE, 2009).

3.3 Methods That Belong to Both Forward and Data-Driven Methods

There is also a special category of methods that belong to both forward methods and data-driven methods including: the Variable-Base Degree-Day (VBDD) method; the thermal network method; the Fourier analysis method; the Primary and Secondary terms Analysis and Renormalization (PSTAR) and the modal analysis method.

According to Fischer *et al.*'s study, T. Kusuda introduced "variable-base" concept in 1981 (Kusuda, 1981; cited in Fischer *et al*., 1982), which led the Variable-Base Degree-Day (VBDD) Method appeared in the *1981 ASHRAE Handbook of Fundamentals* (ASHRAE, 1981). Instead of a fixed base temperature of 65 F which is used in heating degree days, this method relied on separate "balance point temperature" to be calculated for each building. The VBDD were then calculated in the same fashion as degree days. This method is also the basis for the Princeton Scorekeeping Method (PRISM) (Fels, 1986).

Although the thermal network method was added into the ASHRAE Handbook in 1997, it has been in use since 1944, where it appeared in an article by Linvill (M.I.T) and Hess (the Sperry Gyroscope Company) in their paper titled "Studying Thermal Behavior of Houses"

(Linvill and Hess, 1944). In their article, a custom thermal resistance-capacitance network was built up for the house. This R/C network was then subjected to varying heating rate (i.e., varying voltages) to ascertain the resultant. Prior to 1958, thermal network models could only be solved by analog computer (Buchberg, 1958; Paschkis, 1942; Willcov *et al*., 1954; cited in Nelson, 1965).

The Fourier analysis, (PSTAR) and the modal analysis Methods are considered dynamic models, which were referenced in the *1977 ASHRAE Handbook of Fundamentals* (ASHRAE, 1977).

3.4 Simulation Methods

The history of six hourly building energy simulation programs used for whole-building energy simulation in the U.S. are briefly presented here including: DOE-2, eQuest, EnergyPlus, TRNSYS[21], TRACE, and HAP[22]. Many of the methods used in the previous sections were also used as computer algorithms for calculating building peak load and annual energy use.

Simulation methods developed as an increasing need for automated calculations to replace the manual calculation methods, which was documented in the publications of Automated Procedures for Engineering Consultants, Inc. (APEC) in 1965 (Ayres and Stamper, 1995). In 1969, the program HCC[23] was developed for hourly heating and cooling load calculations based on ASHRAE TETD/TA Method (Haberl and Cho, 2004). During this same period, the ASHRAE Task Group on Energy Requirements (TGER) was established. Two years later, the Post Office Program was developed under sponsorship of the U.S. Post office for analyzing energy use in postal facilities in 1971, which was based on the weighting factor method (Haberl and Cho, 2004; Stamper, 1995). This program was later improved by NASA[24] and renamed NECAP[25] in 1975 (Ayres and Stamper, 1995*)*. Half a year later, with the efforts of LBL[26], LASL[27] and ANL[28], NECAP was significantly upgraded by adding a text-based BDL to the program and was renamed CAL-ERDA (Ayres and Stamper, 1995*)*. Shortly after, it was renamed DOE 1.0, and released in 1978, to correspond to the renaming of the federal energy department from ERDA to

[21] Transient System Simulation Tool
[22] Hourly Analysis Program
[23] Heating & Cooling Calculation
[24] The National Aeronautics and Space Administration
[25] NASA Energy Cost Analysis Program
[26] Lawrence Berkeley Laboratory
[27] Los Alamos Scientific Laboratory
[28] Argonne National Laboratory

DOE. Succeeding versions of the DOE program emerged, including DOE-2.0, 2.1a, 2.1b, 2.1c, 2,1d, 2.1e, 2.1e-087, 2.1e-113, 2.1e-119 and 2.1e-121 (Haberl and Cho, 2004*)*. The development of PowerDOE based on the DOE 2.2 engine started in 1992 by LBL and Electric Power Research Institute[29]. It was released in November 1996, and is regarded as the early version of eQuest v1.0. eQuest was released by James J. Hirsch and Associates in June 1999(Tupper *et al*., 2011). Succeeding eQuest versions released since then, include: eQuest v1.2, v2.17c, v3.55, v3.60, v3.64[30].

The NBSLD[31] program was developed by Tamami Kusuda in 1973 based on the detailed heat balance method published by Buchberg in 1958 (Kusuda, 1999). In 1977, the first generation of the BLAST[32] program, created by CERL[33], was released four years later (Hittle, 1977). The succeeding versions of BLAST were BLAST v1.2, BLAST v2.0 and BLAST v3.0 until the funding was cut by the Department of Defense in 1995 (Tupper *et al*., 2011*)*. Later, in 1996, Department of Energy (DOE) chose to stop funding DOE-2 and BLAST. Instead, DOE decided to develop "EnergyPlus" based on the algorithms of DOE-2 and the BLAST programs, which represented a new generation of software (Crawley *et al*., 1999). The succeeding versions of EnergyPlus were EnergyPlus v1.0, v1.0.1, v1.0.2, v1.0.3, v1.1, v1.1.1, v1.2, v1.2.1, v1.2.2, v1.2.3, v1.3, v1.4, v2.0, v2.1, v2.2, v3.0, v3.1, v 4.0, v5.0, v6.0, v7.0, v7.1 and v7.2.

TRNSYS is a differential equation solver used for transient simulations, including solar systems, building energy analysis, etc. It was originally developed by Sanford A. Klein in 1975 for his Ph.D. dissertation using modular concept (Kummert *et al*., 2002). The first public version TRNSYS v6.0 was released in March 1975 (Kummert *et al.*, 2002). Succeeding versions were released including TRNSYS v12.1, v12.2, v13.1, v14.1, v14.2, v15, v16 and v17.

In 1938, TRANE published its "*Load Estimation Sheet*" in the *TRANE Air Conditioning Manual*, which provided a method to estimate cooling loads based on the heat gain calculation method. As the computer technologies developed, TRANE released its first computer program named TRACE Direct in 1972 (Tupper *et al*., 2011.*)*.Succeeding versions of TRACE include: TRACE 77, 600, 700 and 700 v6.2.

[29] Retrieved from http://eetd.lbl.gov/newsletter/cbs_nl/nl09/cbs-nl9-powerdoe.html
[30] Retrieved from http://doe2.com/equest/index.html
[31] National Bureau of Standards Load Determination
[32] Building Loads Analysis and System Thermodynamics
[33] U.S. Army Construction Engineering Research Laboratory

As a competitor, the Carrier Company published their *Handbook of Air Conditioning System Design* in 1960 with the same idea as TRANE to provide a load estimation sheet to both architects and engineers for the preliminary design HVAC systems. In 1981, the first PC-based program by the Carrier Company was introduced; named *Commercial Load Estimating v1.0 (*Farzad, 2012*)*. Shortly after, the Bin Opcost Analysis program v1.0 was developed, which was based on the bin method. Succeeding versions of the HAP program include: HAP v1.0, v2.0, v3.0, v4.0, v4.1, v4.2, v4.3, v4.4 and v4.5.

4 SUMMARY

All the methods discussed are summarized in a comprehensive diagram, shown in Figure 1. The y-axis is divided into two main categories, including: the peak load and building annual energy use calculation methods. Peak load calculations include peak heating and peak cooling load calculation methods, while building annual energy use calculations cover forward, data-driven and simulation methods. The x-axis represents the years from 1900 to 2012. Different color regions show the different calculation methods that are also marked with four different periods: Pre - 1945 (Pre-World War II), 1946-1969 (Pre Computer), 1970-1989(Early Computer) and 1990-present (Present).There are three types of flags on the x-axis, which include guide books (yellow flag), important events (blue flag) and references (maroon flag). The orange-colored circles on the top of the chart give a summary of the computer technology development history.

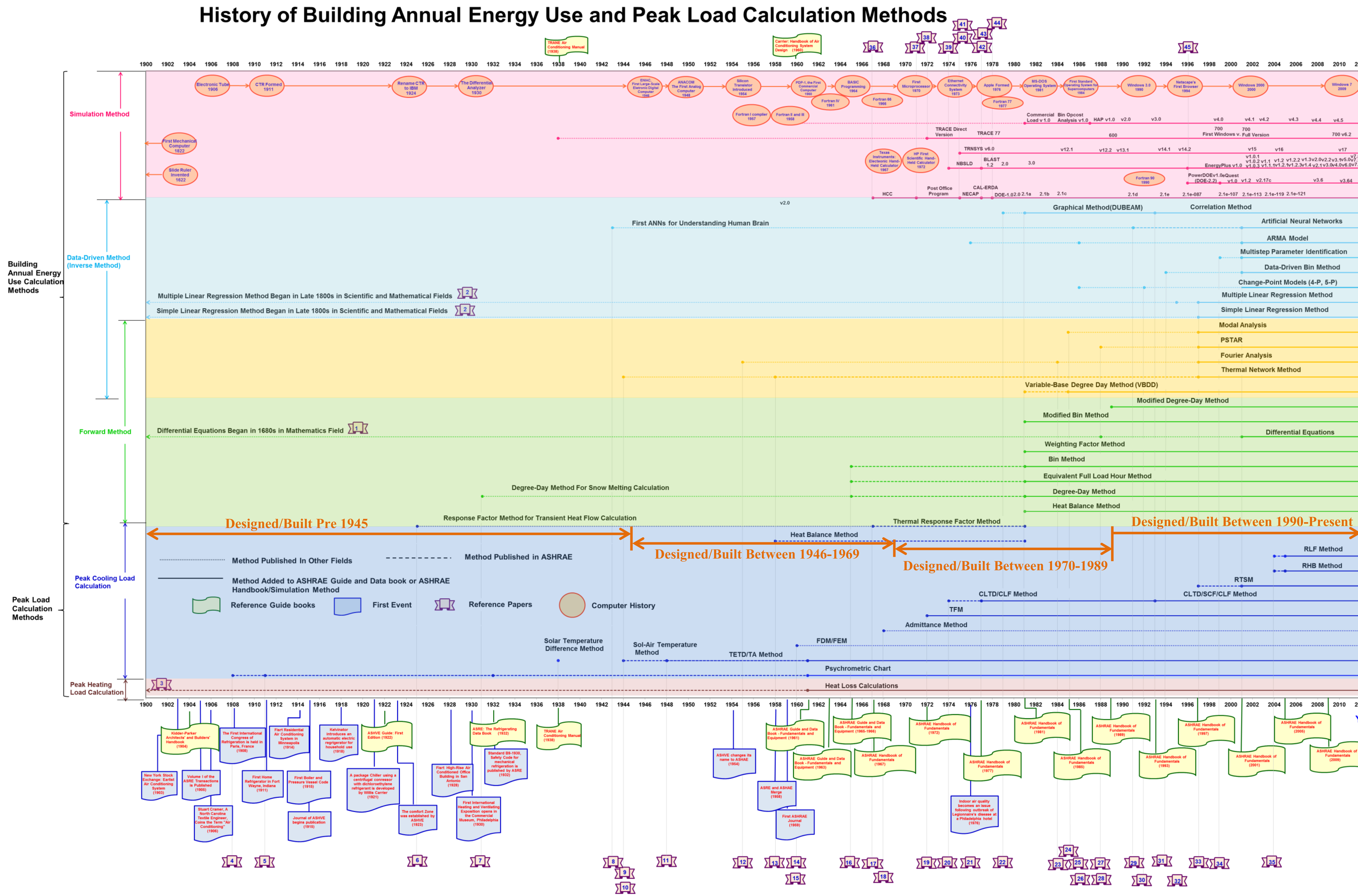

Figure 1 History of Building Annual Energy Use and Peak Load Calculation Methods

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APPENDIX

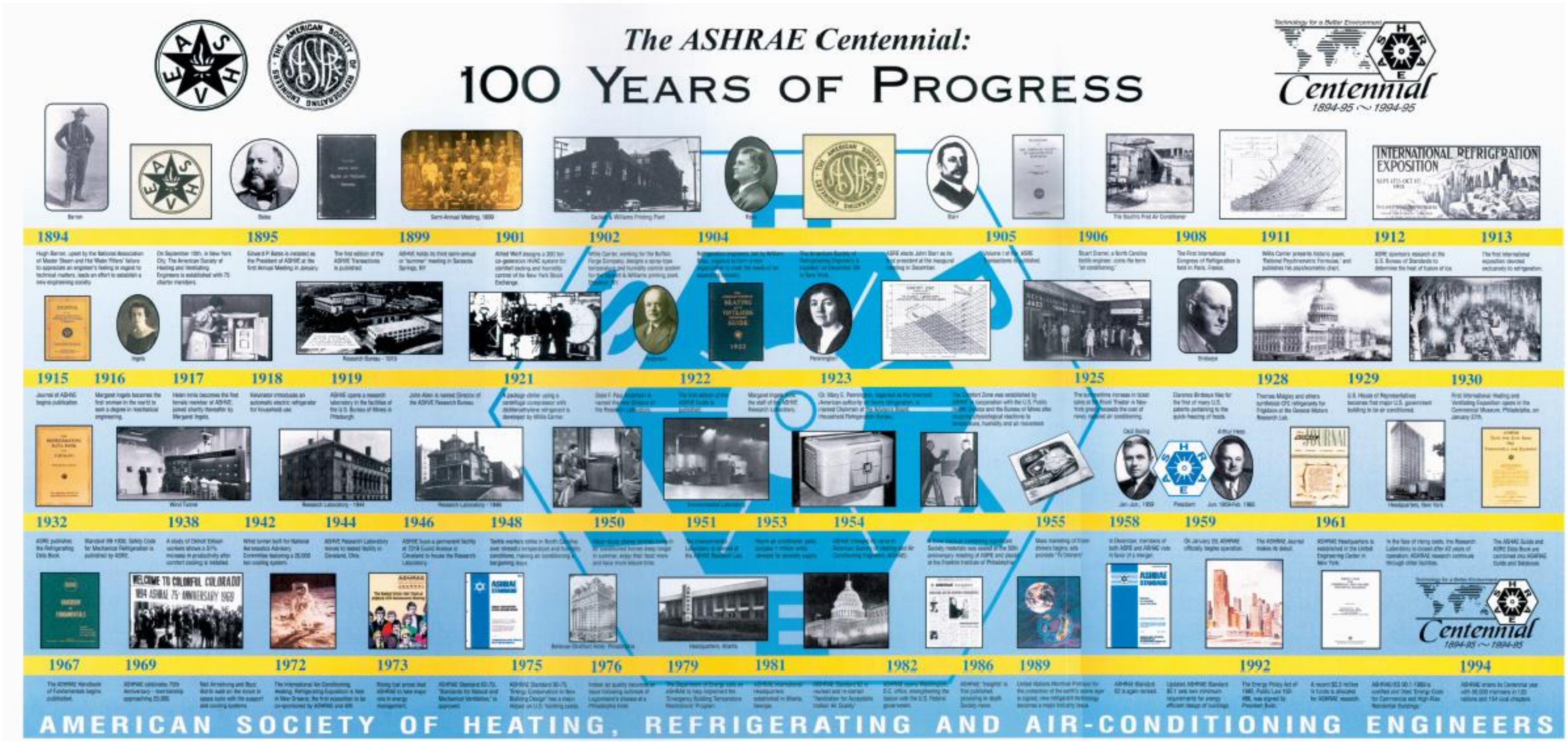

Figure 2 History of ASHRAE

(Source: http://www.ashrae.org/File%20Library/docLib/Public/200511311142_347.pdf)

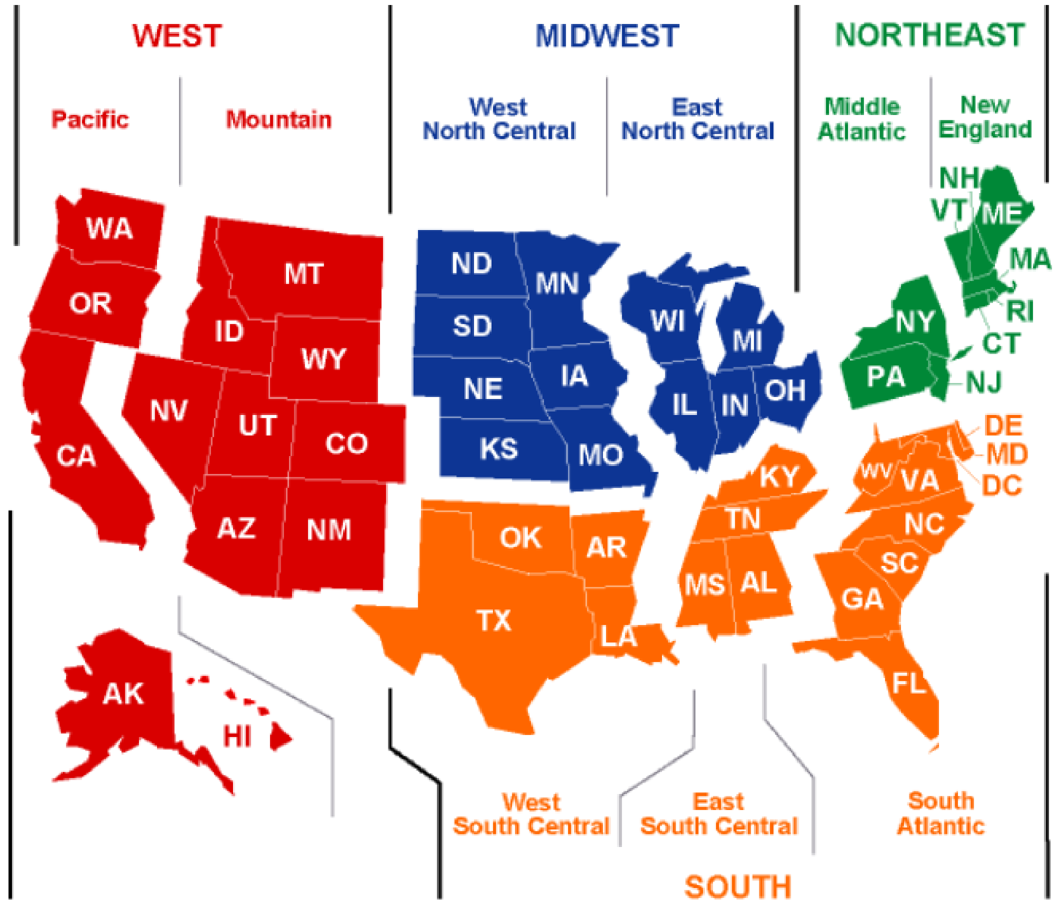

Figure 3 U.S. Census Regions and Divisions for 2003 CBECS

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

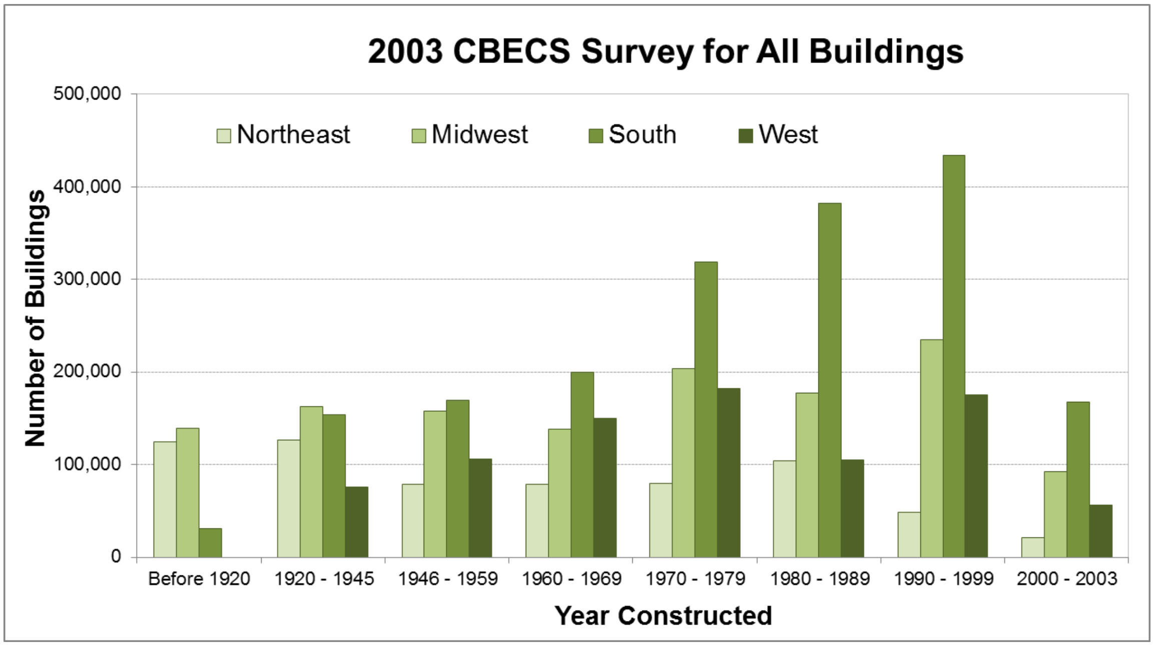

Figure 4 Numbers of Building Versus Constructed Year from 2003 CBECS

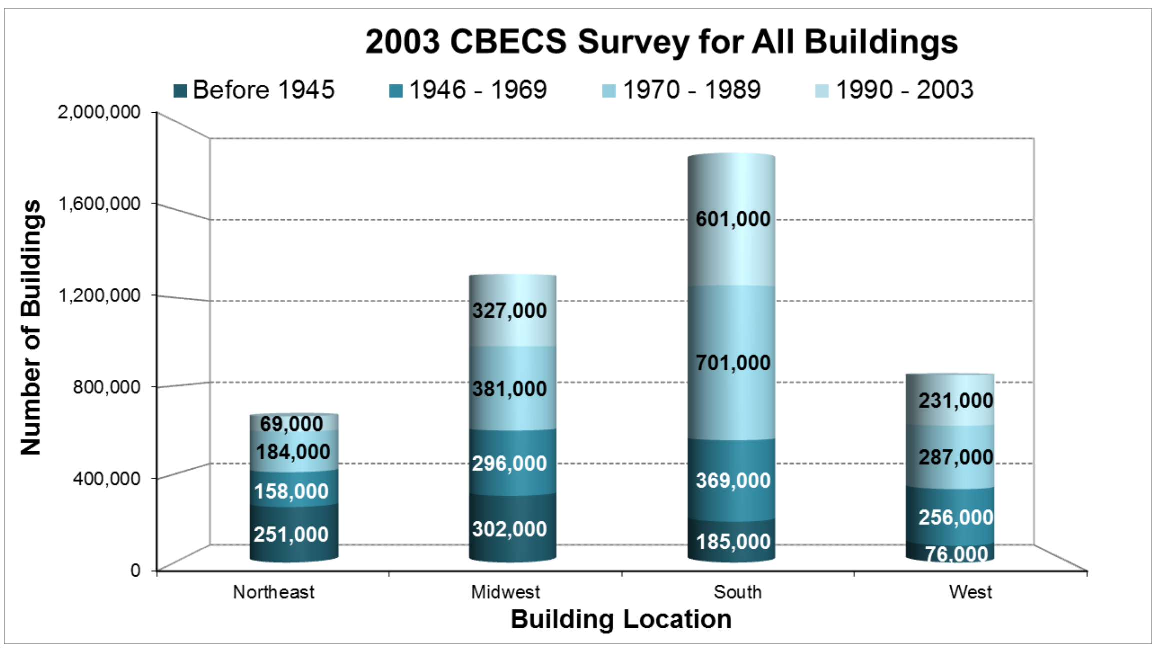

Figure 5 Numbers of Building Versus Building Location from 2003 CBECS

(Data Source:

http://www.eia.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html#enduse03)