ORIGINS OF WHOLE-BUILDING ENERGY SIMULATION PROGRAMS

USED FOR HIGH PERFORMANCE COMMERCIAL BUILDINGS:

CONTRIBUTIONS OF THE MATEUS, SHEP, TACS, CP-26, CP-33 AND

RESPTK PROGRAMS

A Thesis

by

JOUNGHWAN AHN

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Chair of Committee,	Jeff S. Haberl
Committee Members,	Juan-Carlos Baltazar
	Michael Pate
Head of Department,	Robert Warden

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ABSTRACT

Today, there are many building energy simulation programs in use. Some programs are publicly available, while others are restricted to private use. However, currently, there are only a few large, public domain programs that are widely used, such as DOE-2.2/eQUEST, TRNSYS, EnergyPlus and proprietary programs, such as TRACE and HAP. All these programs have their roots in the development of the 1950s and 1960s.

Several previous papers have traced the origins of building energy simulation programs to the Post Office program. However, there were earlier programs that were not widely discussed in these previous papers, including the Mathematical Analysis of Thermal Environment in Underground Shelters (MATEUS) program, the SHelter Environmental Prediction (SHEP) program, the Thermo-dynamic Analysis Computer System (TACS) program and several miscellaneous computer programs that contributed significantly to the development of the Post Office program and the NBSLD program, which included: the FORTRAN IV program to calculate heat flux response factors for a multi-layer slab (i.e., the CP-26 program), the Response Factors Calculation program (RESPTK) and the FORTRAN IV program to calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs (i.e., the CP-33 program). In addition, contributions of the American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE) Task Group on Energy Requirements (TGER) to the development of early computer programs were not widely discussed in detail in these previous

studies. Therefore, this study revisits the importance of the earlier programs that contributed to

the development of the Post Office program and the NBSLD program.

DEDICATION

To my loving father, mother, and wife,

Especially to my late grandfather and grandmother.

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Finally, I would love to express my appreciation to my family for their love and trust. My father, Byungguk Ahn, always supported me and showed continuous trust in me. My mother, Raekyung Song, always trusted and encouraged me. My sister always encouraged me to finish this journey. I would like to thank my wife, Inui Lee, who trusted and support me with incredible patience and love. This journey could not be completed without the support from my loving wife.

CONTRIBUTORS AND FUNDING SOURCES

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CHAPTER I

INTRODUCTION

1.1 Background

Today, there are many building energy simulation programs in use. Some programs are publicly available, while others are restricted to private use. However, currently, there are only a few large, public domain programs that are widely used, such as the DOE-2.2/eQUEST simulation program (Hirsch, 2017), the TRaNsient SYSstem program (TRNSYS; SEL, 2010), the EnergyPlus program (Roth, 2017), and proprietary programs, such as the TRane Air Conditioning Economics program (TRACE; Trane, 2017) and the HAP program (Carrier, 2003). All these programs have their early roots in the analytical developments of the 1950s and 1960s.

Several previous papers, including: Gupta et al. (1971), Lau and Ayres (1979), Feldman and Merriam (1979), Shavit (1995), Haberl and Cho (2004), Tupper et al. (2011) and Oh and Haberl (2016), have traced the origins of building energy simulation programs to the Post Office program. However, there were earlier simulation programs that were not discussed in detail in all but one of the previous historical papers (Gupta et al, 1971). The earlier efforts that made significant contributions to the Post Office program and the National Bureau of Standards Load Determination (NBSLD) program included: the Mathematical Analysis of Thermal Environment in Underground Shelters (MATEUS) program (Achenbach et al., 1962); the SHelter Environmental Prediction (SHEP) program (GARD/GATC, 1968); and the Thermo-dynamic Analysis Computer System (TACS) program (Milnark, 1968). In addition, several miscellaneous

computer programs also contributed to the development of the Post Office program and the

NBSLD program that were not discussed in these previous papers, which included: the

FORTRAN IV program to calculate response factors for a multi-layer slab (i.e., CP-26 program)

(Mitalas and Arseneault, 1967); the Response Factors Calculation program (i.e., RESPTK

program) (Kusuda, 1969); and the FORTRAN IV program to calculate z-transfer functions for

the calculation of transient heat transfer through walls and roofs (i.e., CP-33 program) (Mitalas

and Arseneault, 1972). Finally, the contributions of the American Society of Heating,

Refrigerating and Air conditioning Engineers (ASHRAE) Task Group on Energy Requirements

(TGER) to the development of the early computer programs was not discussed in detail in these

previous studies. Therefore, there is a need to revisit the importance of these early programs that

contributed to the development of the Post Office program and the NBSLD program to

determine their significant contributions to today's building energy simulation programs.

1.2 Purpose and Objectives

The purpose of this study is to further clarify the origins of the whole-building energy simulation programs as well as the contributions of the ASHRAE TGER Committee to the development of the early computer programs. This work is valuable because it fills a gap in the literature regarding the origins of today's whole-building energy simulation programs as well as the contributions of ASHRAE to the early computer programs. This study seeks to identify the earliest origins of the whole-building energy simulation programs and further clarifies the contributions of the ASHRAE TGER Committee using several analysis methods, which includes: a review of the previous literature, an interview with a key expert and an analysis of the published key features of the programs (i.e., input and output variables, sub-routine names, calculation methods, algorithms, etc.).

This research has the following objectives:

1. Review and analyze the previous literature to trace the earliest origins of whole-building energy simulation programs;

2. Review and analyze the work of ASHRAE's TGER Committee to further identify ASHRAE's contributions to the development of early simulation programs;

3. Interview key expert(s) to clarify the relationships between early simulation programs; and

4. Analyze published user and engineering manuals (or equivalent documents) from the early simulation programs to help identify detailed characteristics or shared characteristics between the early simulation programs and the publications from ASHRAE's TGER committee.

1.3 Organization of the Thesis

This thesis has six chapters, which included: 1) Introduction, 2) Literature Review, 3) Significance and Limitations of the Study, 4) Methodology, 5) Results, and 6) Conclusions and Future Work, as well as additional materials provided in appendices.

CHAPTER II

LITERATURE REVIEW

This literature review covers: the previous literature regarding various early computer simulation programs and the history of whole-building energy simulation tools. The sources of the literature include documents from: publications of the American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE); the Electric Power Research Institute (EPRI); the Energy Systems Laboratory (ESL) at Texas A&M University; the Rocky Mountain Institute (RMI); and various other studies that discussed the origins of whole-building energy simulation programs.

2.1 A Review of Previous Literatures that Discussed and Traced the Whole-Building Energy Simulations

Numerous papers have discussed the history of building energy simulation, including: Gupta et al. (1971), Christopher and Crall (1975), Lau and Ayres (1979), Feldman and Merriam (1979), the U.S. Department of Energy (1985), Degelman and Andrade (1986), Ayres and Stamper (1995), Sowell and Hittle (1995), Shavit (1995), Haberl and Cho (2004), Crawley et al. (2005), Tupper et al. (2011), Oh (2013) and Oh and Haberl (2016). However, the following references are the most significant when it comes to explaining the historical lineage of building energy simulations, including: The paper by Gupta et al. (1971); the Bibliography on Early Computer Programs (Christopher and Crall, 1975); the Proceedings of the 11th Winter Simulation Conference (Lau and Ayres, 1979); the report by the Electric Power Research Institute (EPRI) for

Computer Programs with Solar Heating and Cooling Systems (Feldman and Merriam, 1979); the

1995 publications celebrating the 100th anniversary of ASHRAE (Ayres and Stamper, 1995;

Sowell and Hittle, 1995; and Shavit, 1995); and papers that were covered by the Haberl and Cho

(2004), the Rocky Mountain Institute (2011) and Oh and Haberl (2016).

2.1.1 *A Conceptual Survey of Computer-oriented Thermal Calculation Methods* **(Gupta et al.,**
1971)

This paper discussed the analysis methods that were used for calculating heating and

cooling loads or evaluating thermal environments in buildings, which included: the Numerical

method, the Harmonic method and the Response Factor method. To analyze these calculation

methods, this paper included: key equations that were used in these calculation methods, key

documents that represented each calculation method, advantages and limitations for the use of

each analysis method, relevant computer programs that were developed on the basis of these

calculation methods, etc. This paper is important for this study because it was the first

publication that mentioned the MATEUS program, the CP-26 program and the RESPTK

program. However, this paper did not mention the SHEP program and the TACS program

although this paper was published in 1971 (i.e., after the SHEP and TACS programs were

developed). In addition, a genealogy chart that shows the origins of early computer programs

was not provided in this paper. Finally, detailed information about the early computer programs

was not discussed, such as program sub-routines, input and output variables, program source

code, etc.

2.1.2 *Bibliography on Available Computer Programs in the General Area of Heating,*

Refrigerating, Air conditioning and Ventilating **(Christopher and Crall, 1975)**

This document provided information about eighty-seven computer programs that were

used in various areas of the building system simulations before 1975. The different areas of

analysis that were discussed in this study included: load calculations, energy analysis, duct

design, piping design, equipment selection and solar programs. The information collected about

each computer program was described in a one-page statement for each entry. The statement

provided key information about the programs, which included: the purpose of program,

description of program, input requirements, program output, program developer, program

language, etc. This study is important because it discussed the relevant computer programs for

the current research, which included: the Response Factor Calculation program (i.e., RESPTK

program), the Post Office program, the CP-33 program and the NBSLD program. In addition, the

information provided about program inputs and outputs is useful for analyzing the origins of

whole-building computer simulation programs. However, this study did not discuss the

MATEUS program, the CP-26 program, the SHEP program and the TACS program that were

developed before 1975 and contributed to the development of the Post Office program and the

NBSLD program. In addition, detailed information about the programs that were mentioned (i.e.,

input variables, output variables, sub-routines, algorithms, etc.) was not provided.

2.1.3 *Building Energy Analysis Programs* **(Lau and Ayres, 1979)**

The report discussed the historical aspects of building energy analysis programs used

before the 1980s. In this report, Lau and Ayres discussed general structure of the building energy

analysis programs at the time the paper was written, which included: the LOADS program, the

SYSTEMS program, the PLANT program and the ECONOMICS program (i.e., LSPE). In addition, this paper discussed key calculation methods for determining heating and cooling loads in buildings, which included: the Total Equivalent Temperature Differential method (i.e., TETD method), the Response Factor method, the Weighting Factor method and the Heat Balance method. Finally this paper discussed the Quasi-steady-state simulation procedure that was the key procedure to simulate HVAC systems in building energy analysis programs.

This paper is important because it provided the one of first published diagrams that showed the relationships between the public domain building energy analysis programs (see Figure 2.1). The diagram was divided into two groups depending on which ASHRAE calculation algorithms were used (i.e., the Heat Balance method or the Weighting Factor method). Along with the important diagram, this paper also provided information about key institutions that contributed to the development of building energy analysis programs. However, this report did not discuss earlier computer programs that contributed to the development of the Post Office program and the NBSLD program, such as the MATEUS program, the SHEP program, the TACS program and miscellaneous computer programs (i.e., CP-26 program, RESPTK program and CP-33 program).
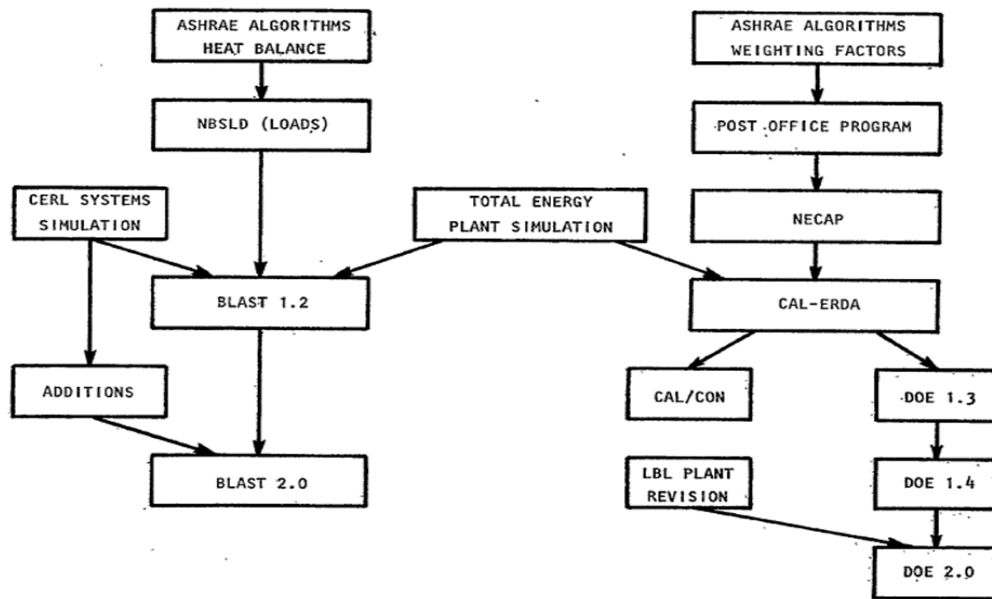
Figure 2.1. Family trees of public domain programs. Reprinted with permission from "Building Energy Analysis Programs," by Lau and Ayres, 1979, *Proceedings of the 11th Conference on Winter Simulation.* Copyright 1979 by IEEE (www.ieee.org).

2.1.4 *Building Energy Analysis Computer Programs with Solar Heating and Cooling System Capabilities* **(Feldman and Merriam, 1979)**

The report for the Electric Power Research Institute (EPRI) provided a comprehensive list of the characteristics of computer simulation programs as well as manual calculation methods for the analysis of the performance of solar heating and cooling systems. This report is significant because it provided one of the first genealogy charts that covered the period 1965 up through 1980 (see Figure 2.2). The genealogy chart provided in the report traced the origins of the most popular energy analysis computer programs in the 1980s. In addition, it provided a comparative table for whole-building energy simulation and solar heating and cooling simulation programs that covered ten specific areas, which included: the history and program uses,

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applications, program characteristics, availability, documentation and computer related

characteristics, building heating and cooling loads, passive systems, active solar systems,

conventional HVAC systems and equipment, output data, and utility related data. The

information that was discussed in this report has significant importance to the study of the

origins of whole-building energy simulation programs because it covered many programs.

Although this study broadly reviewed seventy-computer simulation programs, which were used

to predict the performance of solar heating and cooling systems up through the 1980, the detailed

information about early building energy simulation programs prior to 1970 was not included,

such as inputs and outputs of programs, sub-routines, calculation algorithms, etc. In addition, the

genealogy charts provided in the report did not discuss the MATEUS program, the SHEP

program, the TACS program as well as miscellaneous computer programs (i.e., CP-26 program,

RESPTK program and CP-33 program), which contributed to the development of the Post Office

program and the NBSLD program.
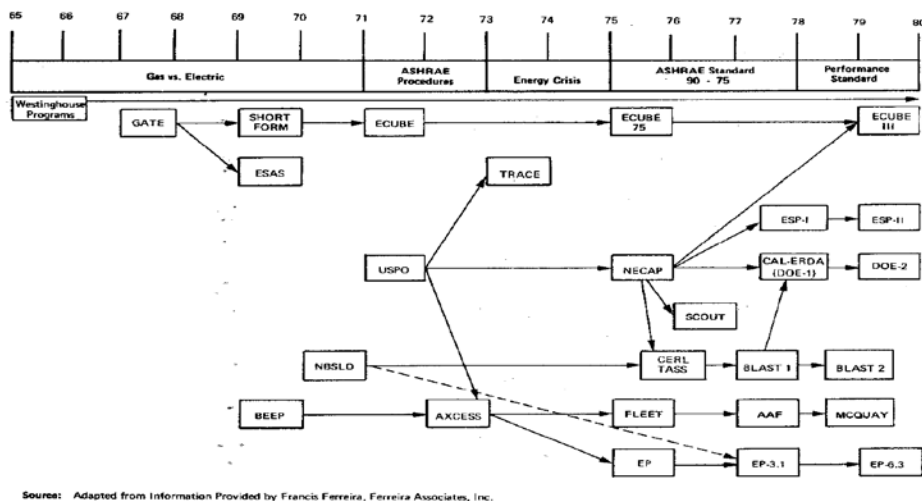
Figure 2.2. History of energy analysis computer programs. Reprinted from Building Energy
Analysis Computer Programs with Solar Heating and Cooling System Capabilities 1979.

2.1.5 *Historical Development of Building Energy Calculations* (**Ayres and Stamper, 1995**)

This article discussed the history of building energy calculation methods. In this article, building energy calculation methods were discussed in two categories: manual calculation methods that were suitable for hand calculations and automated calculation methods that were suitable for computerized calculations (i.e., computer). This paper also discussed how governmental funding from the U.S. Post Office Department (POD), the U.S. Department of Energy (DOE), and the U.S. Department of Defense (DOD) was used for the development of building energy calculation procedures that were applied to the two widely used public domain building energy simulation programs through the 1970s and 1980s: the DOE-2 program and the BLAST program (Hittle, 1977). This article is important because it provided information about the Post Office program, the NBSLD program, the NECAP program and the CAL-ERDA program, which included: the historical development, load calculation methods, procedures and algorithms for HVAC system simulations and key organizations. In addition, the article provided a brief glimpse into the possible origins of the development of hourly weather data files that were required for building energy calculation. However, this article did not discuss the MATEUS program, the SHEP program, the TACS program as well as miscellaneous computer programs (i.e., CP-26 program, RESPTK program and CP-33 program). In addition, detailed information about other early building simulation programs was not included.

2.1.6 *Evolution of Building Energy Simulation Methodology* (**Sowell and Hittle, 1995**)

This paper discussed the development of the building energy modeling strategies, which included: the program structure that was divided into the LOADS sequence, the SYSTEMS sequence, the PLANT sequence and the ECONOMICS sequence (i.e., LSPE) and the structure

that integrated the LOADS, SYSTEMS, PLANT and ECONOMICS (i.e., LSPE) sequences. In addition, this paper also discussed characteristics of a component-based (i.e., modular) simulation, such as the TRNSYS program (TRNSYS; SEL, 2010). This paper is important for the current research because it discussed the two categories of heating and cooling loads calculation methods. One category was the Weighting Factor method, and its subsequent enhancement, the Custom Weighting Factor method. The other category was the Heat Balance method. This paper provided detailed explanations of the historical developments of these two major load calculation methods. In addition, this article provided information about key documents that contributed to the development of whole-building energy simulation programs. However, this paper did not discuss the MATEUS program, the SHEP program and TACS program prior to the Post Office program and the NBSLD program. In addition, the CP-26 program, the RESPTK program and the CP-33 program were not included in this paper.

2.1.7 *Short-time-step Analysis and Simulation of Homes and Buildings During the Last 100 Years* **(Shavit, 1995)**

This paper provided information about the historical development of minute-by-minute analysis methods and performance-based building energy simulations, which was divided into three time periods: the pre-World War II, from the World War II (1940) to the second energy crisis (1973), and the post-second energy crisis (Figure 2.3). In this article, the author discussed the key equations of the minute-by-minute analysis methods that were designed to simulate dynamic control interactions in real time between the building thermal mass, the electrical system, and the HVAC systems. In addition, this article discussed characteristics of several performance-based simulations (i.e., minute-by-minute simulations). This paper is important

because it also discussed how analog computers and digital computers were used for the analysis

of the building performance from the World War II (1940) to the second energy crisis (1973). In

addition, this article provided a genealogy chart that covered two groups of building analysis

programs: performance-based simulation programs and design simulation programs (see Figure

2.3). However, the genealogy chart in this article did not discuss the MATEUS program, the

SHEP program and the TACS program that were developed prior to the Post Office program and

the NBSLD program. In addition, the genealogy chart included information about the

development of building analysis programs that does not agree with other genealogy charts (For

example, the NBSLD program was a derivative of the Post Office program).
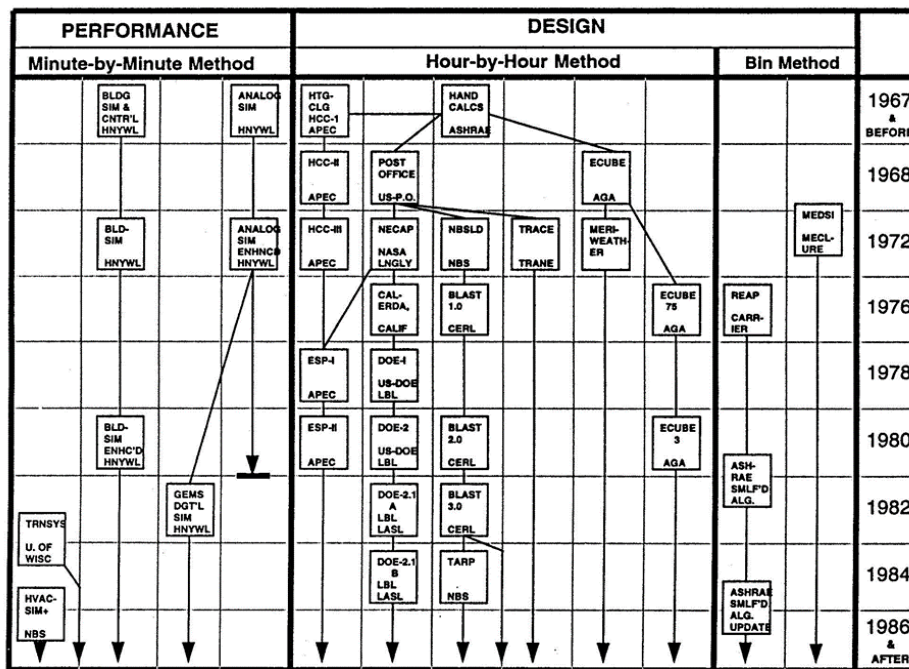
Figure 2.3. Development timeline of simulation programs. Reprinted with permission from "Short-
time-step Analysis and Simulation of Homes and Buildings During the Last 100 Years," by Shavit,
1995, *ASHRAE Transactions, 101,* p. 864. Copyright 1995 by ASHRAE (www.ashrae.org).

2.1.8 *Literature Review of Uncertainty of Analysis Methods (DOE-2 Program)* **(Haberl and Cho, 2004)**

The report discussed the uncertainty of the DOE-2 simulation program by comparing predictions of the DOE-2 program with measured data, other simulation test results, and analytical calculations. In addition, an historical diagram was included in this report that discussed the origin of the DOE-2 program (see Figure 2.4). This report is important because the diagram included in the report provided useful information about several key studies that contributed to the development of the Response Factor method and the Weighting Factor method that were applied to the DOE-2 program, key institutions that contributed to the development of the DOE-2 program and the historical development of the DOE-2 program that evolved from the Post Office program, the NECAP program and the CAL-ERDA program. In addition, this report discussed contributions of the ASHRAE TGER Committee to the early building simulation programs. However, the diagram did not discuss the MATEUS program, the SHEP program and the TACS program that preceded the Post Office program and the NBSLD program. In addition, the diagram that showed the Post Office program provided or shared routines with the NBSLD program, which is inconsistent with other genealogy charts. Finally, details about programs were not analyzed; for example the programs' calculation procedures, algorithms, etc.
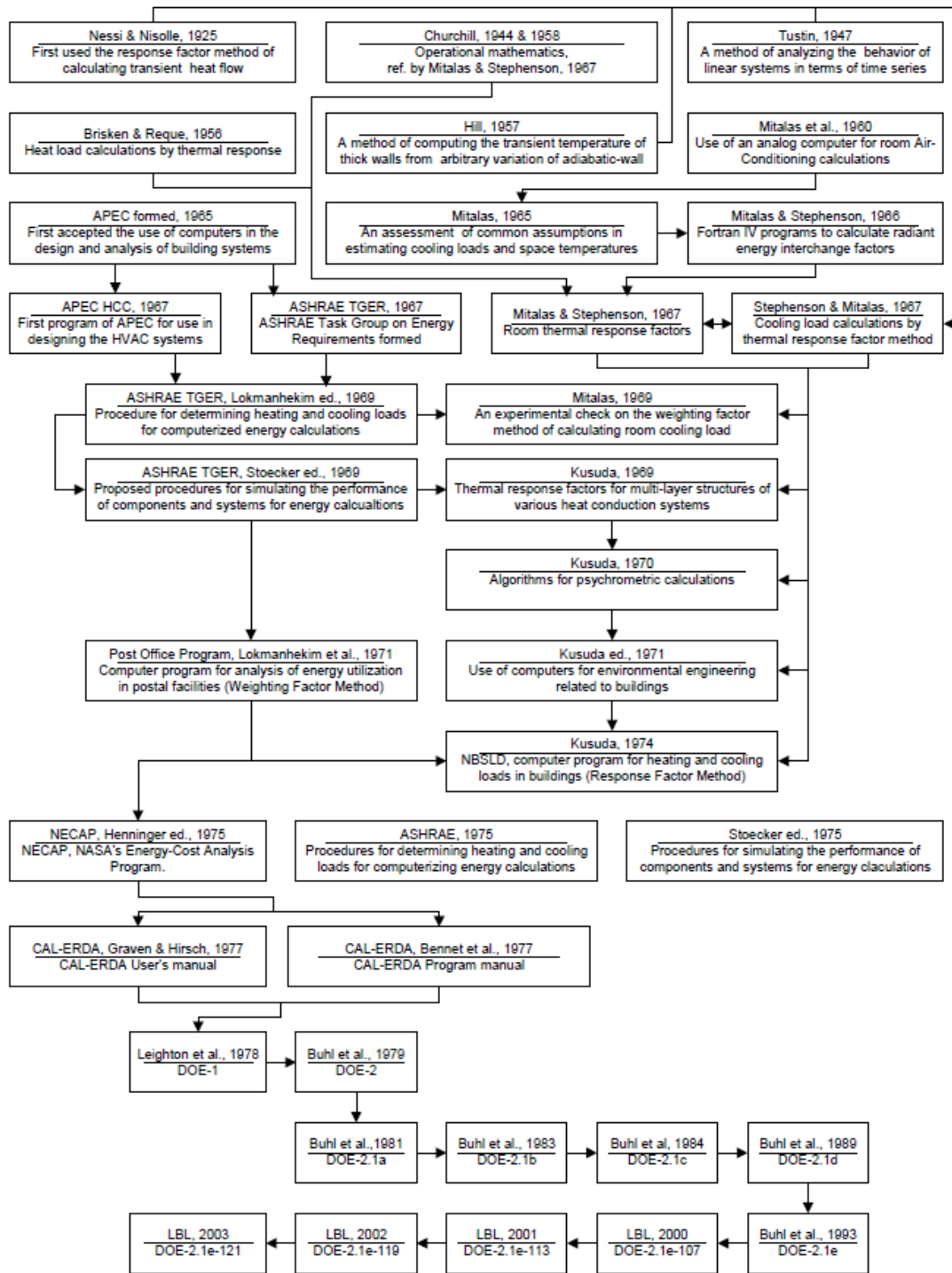
Figure 2.4. History diagram of the DOE-2 simulation program. (Haberl and Cho, 2004;
Reprinted with permission).

2.1.9 *Pre-read for Building Energy Modeling (BEM) Innovation Summit* **(Tupper et al.,**

2011)

The document discussed various aspects of the field of whole-building energy

simulation, which included: the key institutions involved in their development, the whole-

building energy simulation market in the United States, methods and procedures for simulating

the whole-building, key documents, funding sources, representative certifications in the field of

building energy simulation, etc. This document is important because it provided an explanation

of the origins of whole-building energy simulation programs that were widely used in the U.S.

from the 1960s through 2010. In this document, a genealogy chart was developed to discuss the

origins of whole-building energy simulation programs (see Figure 2.5). The chart contained brief

comments that explained important events in the field of whole-building energy simulation. The

genealogy chart also showed the historical development of these programs.

However, in difference to the previous historical papers (Feldman and Merriam 1979,

Lau and Ayres 1979, Shavit 1995, Haberl and Cho 2004, Oh 2013 and Oh and Haberl 2016), the

genealogy chart in this paper discussed key market drivers that led to the development of

building energy simulation programs, which included: the American Society of Heating,

Refrigerating and Air-conditioning Engineers (ASHRAE), the Title 24 program and the U.S.

Green Building Council (USGBC). In addition, the paper discussed the first international

building performance simulation conference that was organized by Dr. Tamami Kusuda at 1970.

However, this paper did not discuss the earliest simulations, such as the MATEUS program, the

SHEP program and the TACS program that contributed to the development of recent whole-

building energy simulation programs (i.e., EnergyPlus program, DOE-2.1e program, eQUEST

program, etc.).

Key: ASHRAE History | Title 24 History | USGBC History

1925 - 1957 Development of Foundational Algorithms

1959: ASHRAE forms
1960
1960 Use of analog computer for AC calcs

1965 1965 APEC formed First use of computers for building systems

1967 First APEC program for use in HVAC system design

1969 ASHRAE TGER forms procedures for computerized heating and cooling load calcs

1970 1970-1971 Kusuda Papers
1970 First international building performance simulation conference

1971 Post Office Program Computer program for analysis of energy utilization in postal facilities (Weighting Factor Method)
1972 TRACE Direct

1975: Standard 90.1 Developed
1975 NECAP (NASA Energy-Cost Analysis Program)
1974 NBSLD computer program for heating and cooling loads in buildings (RFM)
1975 TRNSYS v6.0 (first public release)

1977 CAL-ERDA
1977 BLAST released
1977 TRACE 77 (first personal terminal)

1978: First generation of Title 24
1978 Release of DOE-1
BLAST 1.2

1980: Title 24 Standards adopted by California
1979 Release of DOE-2
1980

1985: Second Generation Title 24 Standard
1981 Release of DOE-2.1a
1985 Comply 24
BLAST 2.0
1985

1987 IBPSA formed
1990 TRNSYS v13 (ASHRAE 140)

1990 1989 Comply 24 (DOE-2 Engine)
1989 TRACE 600

1993: USGBC forms
1993 DOE-2.1e
1995 BLAST Funding Cut
1993 TRNSYS v14.2 (Windows GUI)
1995

Nov 1996 PowerDOE v1.0
1996 EnergyPro (Windows)
1996 E+ Development begins
1996 IMT founded

1998: LEED 1.0 pilot release
June 1999 eQUEST v1.0
Dec 1998 E+ Alpha Version
1998 TRACE 700 (1st Windows v.)
1997 Bentley BIM

2000: LEED 2.0 release to market
Jan 2000 eQUEST v1.2 (widely released)
Dec 1999 E+ Beta Testing
Late 1990s IES VE 3.0
2000
June 2000 gbXML released

2003: 2005 Title 24 Standard
Dec 2001 eQUEST v2.17c (refrigeration version)
April 2001 E+ First Release
2001 TRACE 700 (Full version)

2004: 90.1 Appendix G included as informative language
2002 Autodesk acquires Revit
2005

April 2007 eQUEST v3.6 (certified for Title 24)

2007: 90.1 Appendix G included as normative language
2009: LEED v3
2008 v8i BIM

2010: 2008 Title 24 Standards effective
Revit 2010
2010
August 2010 eQUEST 3.64 (LEED compliance)
October 2010 EnergyPlus 6.0.0 (integrates building management)
2010 TRNSYS v17

Figure 2.5. History diagram of energy simulation programs. (Tupper et al., 2011; Reprinted with permission).

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2.1.10 *Origins of Analysis Methods Used to Design High-performance Commercial Buildings: Whole-building Energy Simulation* **(Oh and Haberl, 2016)**

This study investigated the origins of whole-building energy simulation programs and analysis methods for determining heating and cooling loads that were used in these programs. The study traced key documents that contributed to the development of whole-building energy simulation programs. In this study, the analysis methods for determining heating and cooling loads in buildings were divided into two-groups: the simplified calculation methods and detailed calculation methods. The simplified calculation methods included the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) method and the Radiant Time Series (RTS) method. The detailed calculation methods included the Transfer Function method or Weighting Factor method and the Heat Balance method. In addition, this study developed a new comprehensive genealogy chart that covered both of the origins of whole-building energy simulations as well as analysis methods for heating and cooling loads in buildings (see Figure 2.6).

This study is important to the current research because it provided a thorough understanding of where whole-building energy simulations came from. In addition, the detailed explanation about the calculation methods for determining the heating cooling loads in buildings hinted at the possible origins of the whole-building energy simulation programs, such as the MATEUS program and the SHEP program. However, this article did not cover other important parameters that affected heating and cooling loads in buildings which included: the solar heat gain through windows, infiltration heat gain, heat gains from occupants, lighting fixtures, equipment, etc. In

addition, the MATEUS program, the SHEP program, the TACS program and miscellaneous computer programs (i.e., the CP-26 program, the RESPTK program and the CP-33 program) that contributed to the development of the Post Office program and the NBSLD program were not covered.
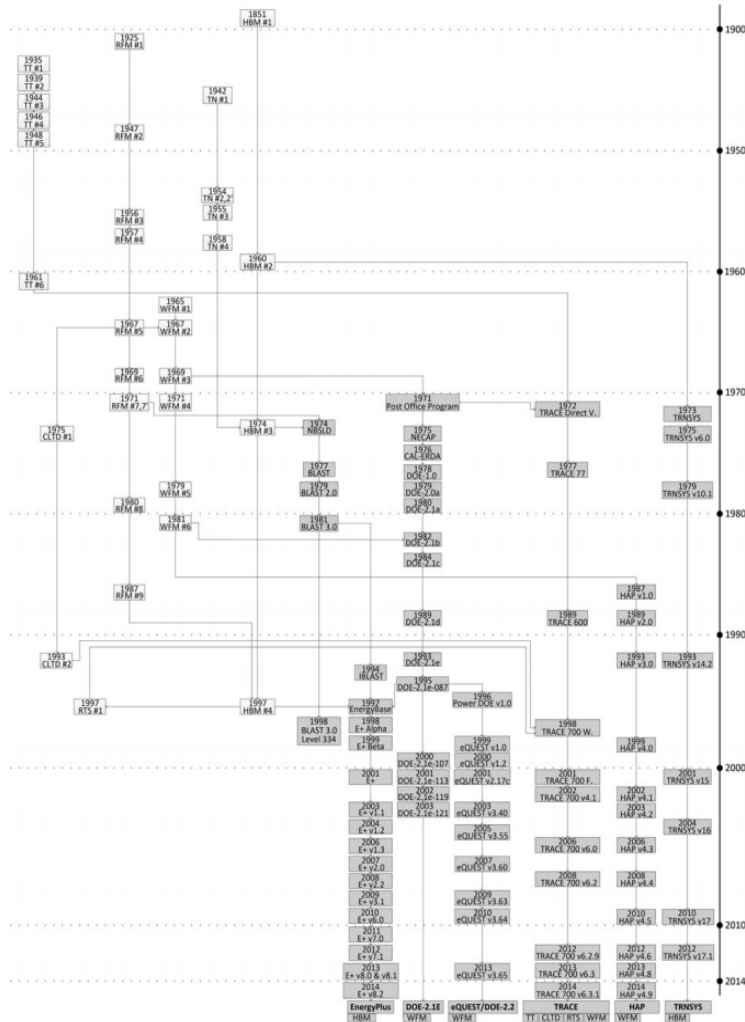
Figure 2.6. Comprehensive genealogy chart for whole-building energy simulation programs. Reprinted with permission from "Origins of Analysis Methods Used to Design High-performance Commercial Buildings: Whole-building Energy Simulation," by Oh and Haberl, 2016, *Science and Technology for the Built Environment, 22,* p. 127. Copyright 2016 by ASHRAE (www.ashrae.org).

2.2 Summary of Literature Review

To summarize, numerous papers have been reviewed many details about the history of whole-building energy simulation programs. However, none of the previous studies have explicitly discussed the MATEUS program, the SHEP program, the TACS program and the miscellaneous computer programs (i.e., CP-26 program, RESPTK program and CP-33 program), which contributed to the development of the Post Office program and the NBSLD program. In addition, none of the previous studies discussed detailed and comprehensive information about early computer programs (i.e., calculation methods, algorithms, sub-routines, input and output variables, etc.). Finally, none of the previous studies provided a detailed discussion about the contributions of the ASHRAE TGER Committee to the development of early computer programs.

CHAPTER III

SIGNIFICANCE AND LIMITATIONS OF THE STUDY

3.1 Significance of the Study

This study will investigate the origins of whole-building energy simulation programs and the contributions of ASHRAE TGER Committee to early simulation programs. Currently, the DOE-2.1E program, the eQUEST/DOE-2.2 program, the TRACE program, the HAP program, the TRNSYS program and the EnergyPlus program have been the most widely used in the United States for evaluating building energy (Oh and Haberl, 2016). To calculate the heating and cooling loads in buildings, all of these programs use either the Weighting Factor method or the Heat Balance method. For instance, the DOE-2.1E program, the eQUEST/DOE-2.2 program, the TRACE program and the HAP program used the Weighting Factor method. On the other hand, the TRNSYS program and the EnergyPlus program used the Heat Balance Method. Thus, it is important to identify and clarify the origins of whole-building energy simulation programs that were based these two important heating and cooling loads calculation methods (i.e., Weighting Factor method and Heat Balance method) in order to understand the present status and existing limitations in the field of whole-building energy simulations.

Most of previous historical papers have studied selected details about the origins of whole-building energy simulation programs on the basis of available papers or the program author's memories at that time. As a result, many of the previous historical papers failed to include all relevant simulation programs that significantly contributed to the early whole-building energy simulation programs. None of the previous papers discussed the origins of

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whole-building energy simulation programs on the basis of a published document review (i.e., user and engineering manuals or equivalent documents). In addition, none of the previous papers thoroughly discussed contributions of important miscellaneous publications (i.e., the ASHRAE TGER publications) as well as several early computer programs (i.e., MATEUS program, SHEP program, TACS program, CP-26 program, RESPTK program and CP-33 program) that made a major contribution to today's building energy simulation program. Therefore, this research is significant because it fills a gap in the literature regarding the early origins of whole-building energy simulation programs, and it provides users with a better understanding about today's most widely used simulation programs.

3.2 Limitations of the Study

This study will be conducted within the following limitations:

1. This study is focused on the analysis of the LOADS calculation portion in selected simulation programs. The SYSTEMS, PLANT and ECONOMICS sub-programs will only be covered in general as they related to selected program.

2. This study is focused on the contributions of the early public domain building energy simulation programs that contributed to the Post Office program and the NBSLD program, and therefore only includes a general discussion of the Post Office program and the NBSLD program.

3. This study does not review proprietary building energy simulation programs, such as the TRACE program or the HAP program.

CHAPTER IV

METHODOLOGY

4.1 Overview of Methodology

The methodology of this research is described in this chapter. The objectives of this research are as follows: (a) to review the previous historical studies in order to clarify the origins of the whole-building energy simulation programs and to identify whether these previous historical studies included accurate information; (b) to identify early computer programs that none of previous studies discussed in detail; (c) to identify contributions of the ASHRAE TGER Committee to the development of early building energy simulation programs; and (d) to identify details of early computer programs, such as calculation methods, input and output variables, sub-routines, algorithms, etc. With these objectives, the following tasks were conducted:

1. Identify the early computer programs that were not discussed in detail in the previous historical studies. Analyze the details of these early computer programs by reviewing published user and engineering manuals or equivalent documents. Identify contributions of these very early computer programs to the early building energy simulation programs (i.e., Post Office program and NBSLD program).

2. Analyze previous ASHRAE publications that provided the recommended algorithms for the calculation of heating and cooling loads in buildings. Identify contributions of the ASHRAE TGER Committee to the development of early building energy simulation programs (i.e., Post Office program and NBSLD program).

3. Interview with key expert(s) who were involved in the development of early building energy simulation programs.

4. Develop a revised genealogy chart based on the analysis of published documents as well as interview with key expert(s). The revised genealogy chart should include the early computer programs that none of previous genealogy charts have discussed in.

In order to clarify the origins of the early computer programs, a new comprehensive analysis of the publications by the ASHRAE TGER Committee, the National Bureau of Standards (NBS), the U.S. Postal Service (USPS) as well as interview(s) with key expert(s) who were involved in the development of early building energy simulation programs is provided in Section 4.2. In Section 4.3, based on the published documents (i.e., user and engineering manuals or equivalent documents), details of the computer programs are provided, such as purpose of the program, key documents, calculation methods, sub-routines, input and output variables, etc.

4.2 Level 0 Analysis: Identification of the Origins of Whole-building Energy Simulation Programs by Reviewing the Previous Studies and by Interviewing Expert(s)

A comprehensive analysis was conducted to identify contributions of the ASHRAE TGER Committee as well as the early computer programs that were not discussed by the previous historical studies. To clarify contributions of the ASHRAE TGER Committee and the origins of whole-building energy simulation programs, various documents that were published by the American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE), the National Bureau of Standards (NBS), the U.S. Postal Service (USPS) and Dr. Kusuda are analyzed in the Section 4.2. In addition, interview(s) with key expert(s) who were involved in the development of early building energy simulation programs are included in the Section 4.2.

4.2.1 American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE) Publications

In the Section 4.2.1, three ASHRAE TGER publications are discussed, which includes: "*Proposed procedure for determining heating and cooling loads for energy calculations - Algorithms for building heat transfer subroutines*" (ASHRAE, 1968), "*Procedure for determining heating and cooling loads for computerized energy calculations - Algorithms for building heat transfer subroutines*" (ASHRAE, 1971) and "*Procedure for determining heating and cooling loads for computerizing energy calculations - Algorithms for building heat transfer subroutines*" (ASHRAE, 1975).

The purpose of the ASHRAE TGER Committee publications was to provide HVAC engineers with standardized procedures for building energy calculations as well as data sets for

the evaluation of HVAC equipment. Based on these ASHRAE publications, HVAC engineers were able to evaluate heating and cooling systems in buildings with uniform and validated methods (USPS, 1971). Before ASHRAE developed the new procedures for determining heating and cooling loads for energy calculations, practicing HVAC engineers approximated monthly, daily, or hourly heating and cooling loads and determined building energy requirements using the Degree Day method or Bin method. These simplified methods approximated building energy requirements by proportioning the design load that was based on design weather conditions (ASHRAE, 1971; ASHRAE, 1975).

However, design load calculations using design weather conditions were not suitable for calculating accurate annual energy requirements in buildings for several reasons. First, the design load calculation method only evaluated the hourly peak heating and cooling loads based on the extreme weather conditions, which may not accurately represent the dynamic conditions during the heating and cooling seasons. Second, the peak design load calculation method resulted in a single value of the peak heating and cooling loads. Therefore, ASHRAE recognized the need for the development of new heating and cooling loads calculation procedures to determine the annual energy requirements for buildings (USPS, 1971). Compared to the peak design load calculation method, the new ASHRAE calculation procedures calculated more accurate annual energy requirements for several reasons. First, the new ASHRAE procedure calculated the hourly heating and cooling loads that varied with actual weather conditions for a given site. Second, the new ASHRAE procedure analyzed the dynamic heat transfer conditions in buildings using the local weather conditions (i.e., ambient air temperature, humidity, wind, and solar radiation).

Finally, the new ASHRAE procedure resulted in time series values of heating and cooling loads through the entire heating and cooling seasons.

To document these new methods, ASHRAE published three documents that included the new ASHRAE procedures for evaluating heating and cooling loads for energy calculations, which included: "*Proposed procedure for determining heating and cooling loads for energy calculations - Algorithms for building heat transfer subroutines*" (ASHRAE, 1968), "*Procedure for determining heating and cooling loads for computerized energy calculations - Algorithms for building heat transfer subroutines*" (ASHRAE, 1971) and "*Procedure for determining heating and cooling loads for computerizing energy calculations - Algorithms for building heat transfer subroutines*" (ASHRAE, 1975). These ASHRAE publications were developed by the ASHRAE Task Group on Energy Requirements (TGER) Committee for Heating and Cooling.

The new ASHRAE calculation procedures, that were suitable for calculating hourly heating and cooling loads for building energy requirements, consisted of many new heat transfer procedures that were presented in separate sub-routines. The new approach of using multiple sub-routines had advantages for HVAC engineers who wanted to use the new calculation procedures in their own computer programs versus trying to develop and use one long and continuous procedure for an entire program. In addition, the use of short, single-purpose sub-routines also provided HVAC engineers with new tools for analyzing the building energy use that provided several benefits. First, sub-routines that used only a few algorithms were easier to modify. Second, programs that consisted of the new sub-routines were also capable of performing multiple tasks, such as calculating heating and cooling loads for solid objects and the temperature rise within the wall during fire conditions (GARD/GATC, 1971a). With these new

heat transfer sub-routines, HVAC engineers quickly developed their own computer programs for varying engineering requirements on different types of computer facilities (ASHRAE, 1968).

4.2.1.1 *Proposed Procedure for Determining Heating and Cooling Loads for Energy Calculations - Algorithms for Building Heat Transfer Subroutines* **(ASHRAE, 1968)**

In 1968, the ASHRAE TGER sub-committee on heating and cooling load requirements released the first publication that was edited by Dr. Metin Lokmanhekim (ASHRAE, 1968). This first publication included detailed descriptions of the new procedures for determining heating and cooling loads for energy calculations, which were developed by the ASHRAE TGER Committee (Ayres and Stamper, 1995). Although the development of the new procedures for hourly load calculation was not complete at the time of the first publication, the preliminary work was distributed to a limited number of HVAC engineers and scientists (i.e., 150 members of ASHRAE) in 1968 in order to obtain reviews and constructive comments back to the ASHRAE TGER Committee (USPS, 1971; ASHRAE, 1971).

In the late 1960s, the hourly heating and cooling calculations for annual building energy requirements that used the exact thermal load calculation technique (i.e., Heat Balance method) was not practical because it required multiple iterations in order for the solution to converge. Therefore, in this first publication, the ASHRAE TGER recommended the use of the transfer function concept and the Weighting Factor method for the calculation of hourly heating and cooling loads for annual building energy requirements. The Weighting Factor method that was developed by Mitalas and Stephenson (1967) was an approximation method that simplified the exact heating and cooling loads calculation procedures (i.e., Heat Balance method). With the

computers that were available in the 1960s, this reduced the computing time significantly

without compromising the accuracy. (Kusuda, 1974). In Section 5.2, detailed analysis of this

publication is provided.

4.2.1.2 *Procedure for Determining Heating and Cooling Loads for Computerized Energy*

Calculations - Algorithms for Building Heat Transfer Subroutines **(ASHRAE, 1971)**

In 1971, the ASHRAE TGER sub-committee on heating and cooling load requirements

released the second publication that was the final form of the first 1968 publication. This second

publication included revised algorithms from the first 1968 publication to calculate heating and

cooling energy requirements in buildings using the Response Factor method and Weighting

Factor method. This second publication was released three years after the first publication and

included comments and additional work from the ASHRAE TGER load calculation sub-

committee. In difference to the first publication, ASHRAE published this second edition for

general distribution to its members (USPS, 1971; ASHRAE, 1971). The sub-routines for the

calculation of the response factors and weighting factors in the second publication were

implemented in the Post Office program and the NECAP program for the load calculation

portion since a number of the ASHRAE TGER sub-committee members on heating and cooling

load calculations and engineers at the General American Research Division/General American

Transportation Corporation (i.e., GARD/GATC) cooperated on the development of Post Office

program. In addition, specific computer programs that were developed by the National Bureau of

Standards (NBS), National Research Council of Canada (NRC), and GARD/GATC contributed

to the development of the new ASHRAE TGER Committee load calculation procedure

(ASHRAE, 1971). In the Section 5.2, a detailed analysis of this publication is provided.

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4.2.1.3 *Procedure for Determining Heating and Cooling Loads for Computerizing Energy Calculations - Algorithms for Building Heat Transfer Subroutines* **(ASHRAE, 1975)**

In 1975, the ASHRAE TGER sub-committee on heating and cooling load calculations released the third publication that included revised ASHRAE load calculation procedures for energy calculations. In the second publication in 1971, the Response Factor method was used to calculate the transient heat conduction through multi-layered walls, roof or floor, and the Weighting Factor method was used to calculate hourly heating and cooling loads for the annual building energy requirements. In the third publication in 1975, the Conduction Transfer Functions method that calculated the transient heat conduction through multi-layered walls, roof or floor and the Heat Balance method that calculated the hourly heating and cooling loads for the annual building energy requirements were presented. Algorithms for the heat balance equations in the third publication were implemented in the National Bureau of Standards Load Determination (NBSLD) program with minor modification by Dr. T. Kusuda. In the Section 5.2, a detailed analysis of this publication is provided.

4.2.2 Other Publications

In the Section 4.2.2, the three-publications are discussed, which include: "*Use of Computers for Environmental Engineering Related to Buildings*" (Kusuda ed., 1971), "*U.S. Postal Service Symposium Computer Program for Analysis of Energy Utilization*" (USPS, 1971) and "*Building Environment Simulation before Desktop Computers in the USA through a Personal Memory*" (Kusuda, 2001). All three of these publications provided valuable information for this research, which included: a detailed description of the specific contributions

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of the ASHRAE TGER Committee toward the development of early building energy simulation programs; a discussion of specific historical events that motivated to the development of whole-building energy simulation programs; a description of the various studies in the field of building environmental engineering and simulation around the 1970's; and a brief discussion of the existence for very early computer programs that were not discussed in the previous historical papers.

4.2.2.1 *Use of Computers for Environmental Engineering Related to Buildings* **(Kusuda ed., 1971)**

This document is the proceedings of the first international symposium on the application of computers to building environmental system simulations that was organized by Dr. T. Kusuda and held in Maryland in the United States in 1970 (see Table F.1 in the Appendix). This first international symposium was sponsored by the National Bureau of Standards (NBS), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the Automated Procedures for Engineering Consultants (APEC). This conference attracted over four-hundred HVAC engineers and scientists from all over the world (Kusuda, 2001).

The document included fifty-nine technical papers that discussed the use of computers for various areas of the building environmental engineering. Among the various areas of building environmental issues that were discussed in this document, the largest portion covered the heating and cooling loads calculation for buildings. The areas that were discussed in fifty-nine technical papers included: computer graphics, heat transfer calculations for determining the building thermal loads, building heating and cooling load calculations, HVAC system

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simulations, analysis of the building energy usage, application of weather data to the building energy analysis, linear programming and time sharing techniques, etc. This document is important because it provided important information about the various uses of computers in the field of whole-building energy simulation programs in the early 1970s, which is a very important time period for this research. For example, this document discussed the application of the Response Factor method to building energy calculations, the application of the ASHRAE's recommended algorithms to the development of the Post Office program and the FORTRAN IV program to calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs (i.e., the CP-33 program). A detailed analysis of the fifty-nine technical papers in this document is provided in the Appendix F**.**

4.2.2.2 *U.S. Postal Service Symposium Computer Program for Analysis of Energy Utilization* **(USPS, 1971)**

This document is the proceedings of the U.S. Postal Service (USPS) symposium that was held at Washington, USA in 1971. This document discussed the features of the Post Office program, which included: the historical events that motivated the development of the Post Office program; funding sources for the development of the Post Office program; key institutions that contributed to the development of the Post Office program; the Post Office program's sub-routines and application of the Post Office program to buildings other than postal facilities. The content of this proceeding was divided into thirteen sections that followed the order of this USPS symposium. This document is important because it provided a description of the key algorithms that were used in the LOADS sub-routine, the SYSTEMS sub-routine and the overall sub-routines sequence of the Post Office program. In addition, the section that covered the

contribution of the ASHRAE TGER to the field of building simulation hinted that the calculation procedures that were developed by ASHRAE TGER, such as the "*Procedure for determining heating and cooling loads for computerized energy calculations-algorithms for building heat transfer subroutines*" (ASHRAE, 1971), were used in the development of the Post Office program. Finally, this document discussed important historical events in the early 1970s, which were related to the development of other early computer programs, such as the CP-33 program and the NBSLD program. A detailed analysis of this document is provided in the Appendix G.

4.2.2.3 *Building Environment Simulation before Desktop Computers in the USA through a Personal Memory* **(Kusuda, 2001)**

This paper discussed important historical events that Dr. Kusuda was involved in regarding the application of computers to the building environmental engineering during the 1950's through the 1980's. The important events that were discussed in this paper included the development of various computer simulations, psychrometric calculations, room air flow motion analysis, thermal load calculation methods, HVAC system simulations, ground contact heat transfer analysis and air-leakage analysis. This paper is important because it provided valuable information about the early computer programs that none of the previous historical studies have discussed. The early computer programs that were discussed in this paper included: the Mathematical Analysis of Thermal Environment in Underground Shelters (MATEUS) program (Achenbach et al., 1962); the SHelter Environmental Prediction (SHEP) program (GARD/GATC, 1968); the FORTRAN IV program to calculate heat flux response factors for a multi-layer slab (i.e., CP-26 program) (Mitalas and Arseneault, 1967); the Response Factor Calculation program (i.e., RESPTK program) (Kusuda, 1969); and the FORTRAN IV program to

calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs (i.e., CP-33 program) (Mitalas and Arseneault, 1972).

The MATEUS program was based on the Finite Difference method and the Heat Balance method to analyze thermal environment in the underground shelter. Like the MATEUS program, the SHEP program was also based on the Finite Difference method and the Heat Balance method to evaluate the thermal environment in the underground shelter. The miscellaneous programs (i.e., the CP-26 program, RESPTK program and CP-33 program) used the Response Factor method and the Conduction Transfer Functions (CTFs) method to calculate values of response factor and conduction transfer function. All of these early computer programs were involved in the development of the Post Office program and the NBSLD program, which were the early building energy simulation programs. A detailed analysis of this paper is provided in the Appendix H**.**

4.2.3 Interview with Expert(s)

To clarify the origins of whole-building energy simulation programs as well as review early computer programs (i.e., MATEUS program, SHEP program, TACS program, CP-26 program, RESPTK program and CP-33 program), this study included an interview with Mr. Robert Henninger who was a key expert on the early whole-building energy simulation programs. When Mr. Henninger worked at the General American Research Division/General American Transportation Corporation (GARD/GATC) as the principal engineer, he was involved in many important projects for the development of early whole-building energy simulation

programs, which included: the Post Office program and the NASA's Energy-Cost Analysis

Program (NECAP).

Appendix A includes a letter from the Texas A&M Institutional Review Board (IRB)

regarding the approval of the interview with Mr. Henninger (see Figure A.1). Appendix B

includes the interview with Mr. Henninger.

4.3 Level I Analysis: Analysis of Simulation Programs by Reviewing Published Documents

In this part of the analysis, a comprehensive analysis was performed to identify detailed

characteristics of the early computer programs by reviewing the published program manuals or

equivalent documents. While the major emphasis was on the program user and engineering

manuals, the analysis also reviewed other key documents. Unfortunately, some of the early

computer programs only provided limited information about the programs (i.e., no source code

listing). Therefore, the level of information that was used in the Section 5.3 depended on the type

of documents (i.e., programs' user and engineering manuals or equivalent documents).

4.3.1 Simulation Programs by the National Bureau of Standards (NBS)

In Section 4.3.1, the three-computer programs that were developed by Dr. Kusuda at the

National Bureau of Standards (NBS) are analyzed, which included: the Mathematical Analysis of

Thermal Environment in Underground Shelters (MATEUS) program; the Response Factor

Calculation program (i.e., RESPTK program); and the National Bureau of Standards Load

Determination (NBSLD) program.

4.3.1.1 Mathematical Analysis of Thermal Environment in Underground Shelters (MATEUS) Program

In 1962, an underground shelter simulation program was developed by Dr. Kusuda who worked at the National Bureau of Standards (NBS). Although the underground shelter simulation program was released to researchers and engineers in several published articles, Dr. Kusuda officially didn't name the shelter simulation program. Therefore, in this study, Dr. Kusuda's shelter simulation program was named as the MATEUS program. The name of MATEUS derived from the key document: "*Mathematical Analysis of Thermal Environment in Underground Shelters*" (Achenbach et al., 1962), which discussed the underground shelter simulation program for the first time and included many important information about the shelter program.

In the early 1960s, the United States was threatened by a nuclear attack from the Union of Soviet Socialist Republics (USSR). USSR missile sites that were built in Cuba were a serious threat to the United States. As a result, a large numbers of community underground fallout shelters were quickly built in the U. S. to cope with the nuclear threat. Although much of the previous research discussed the protection of the occupants in underground shelters from the harmful nuclear radiation and blast, the adequacy of the shelter environment for the occupants under limited conditions (i.e., high-level of occupant density, limited ventilation air circulation and occupancy at least two weeks because of harmful nuclear radiation) hadn't been fully studied (Kusuda, 2001). To analyze the thermal environment of underground fallout shelters using a digital computer, Dr. Kusuda developed the MATEUS program with funding from the Office of Civil Defense (OCD).

News about the MATEUS program was released to researchers and engineers in two published ASHRAE articles: *"Mathematical analysis of thermal environment in underground shelters"* (Achenbach et al., 1962) and *"Numerical analyses of the thermal environment of occupied underground spaces with finite cover using a digital computer"* (Kusuda and Achenbach, 1963). The first article (Achenbach et al., 1962) discussed the detailed information about the MATEUS program and the reliability and capability of the MATEUS program. The article also included a comparison of the calculated results from Analytical methods and simulations of the MATEUS program. The second article (Kusuda and Achenbach, 1963) was an improved version of the MATEUS program from the first version at 1962. The reliability and capability of the MATEUS program were demonstrated by conducting several validation tests. The existence of the MATEUS program stimulated the work of HVAC engineers who were interested in the application of digital computers, including Dr. M. Lokmanhekim who was at GARD/GATC (Kusuda, 2001). Dr. Lokmanhekim is one of GARD/GATC engineers who is credited with the creation of the SHEP program (1968).

Dr. Kusuda's MATEUS program calculated the indoor temperature and relative humidity inside a shelter and the temperature in the earth that surrounded the shelter during an occupied period. The occupancy period for the simulation of a fallout shelter was up to two weeks, which was a long enough period for the surrounding ambient conditions to have reduced nuclear radiation level. To simulate the thermal environment in underground fallout shelter, the Finite Difference method was used for the analysis of the dynamic heat conduction through the surrounding earth and shelter envelopes (i.e., the shelter's concrete walls, ceiling and floor). The dynamic analysis of the transient heat conduction through shelter envelope allowed the

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MATEUS program to evaluate the thermal environment in a underground shelter using the Heat Balance method.

Before the MATEUS program, the NBS scientists had used analytical methods to evaluate the thermal environments in underground shelters (Kusuda, 2001). However, the application of analytical methods was a complicated set of differential equations that had to be solved for each time period to calculate the temperature and relative humidity inside the shelter space because the rates of heat and moisture transfer varied over day. In addition, the inclusion of other important parameters, such as the thermal and physical characteristics of the shelter, the site characteristics, climate characteristics and operational characteristics, in a three dimensional finite difference matrix for the analysis of the heat conduction increased the complexity of the analysis beyond the point of solution by an analytical method. To solve the energy balances of each time period, the Finite Difference method provided a reasonably accurate dynamic solution to the overall heat balance without resorting to the use of over-simplified parameters.

In order to analyze the thermal environment in the underground shelter, the MATEUS program performed three major tasks, which included: the analysis of the dynamic heat and moisture transfer (i.e., dynamic heat transfer through the surrounding earth or through the shelter's envelope), the analysis of heat generation from sources inside the shelter (i.e., heat generation by occupants or by other sources), and the use of a heat balance among the various elements (i.e., heat exchange with the indoor air, interior surfaces, occupants, ventilation air, etc.). Based on the dynamic heat balance analysis of the various elements, the MATEUS program determined the temperature and humidity inside the shelter at a given time step (i.e., every four hours). This new dynamic analysis of thermal environment in the underground shelter helped

HVAC engineers to be more accurate with the sizing of the mechanical system in the underground shelter, and it provided several weeks snap-shot of the calculated conditions.

Although the MATEUS program manual could not be found, details of the MATEUS program were provided in two published ASHRAE articles: *"Mathematical analysis of thermal environment in underground shelters"* (Achenbach et al., 1962) and *"Numerical analyses of the thermal environment of occupied underground spaces with finite cover using a digital computer"* (Kusuda and Achenbach, 1963). A closer look at the first article (Achenbach et al., 1962) that provides a detailed analysis of the MATEUS program is provided in Section 5.3.

4.3.1.2 Response Factor Calculation Program (RESPTK program)

In 1969, the Response Factor Calculation program (i.e., RESPTK program) was developed by Dr. Kusuda at the National Bureau of Standards (NBS). The development of the RESPTK program was based on the CP-26 program that also used the Response Factor method (Kusuda, 1969). In the late 1960's, Mitalas and Stephenson at the National Research Council (NRC) of Canada developed the Response Factor method for the analysis of dynamic the heat conduction through multi-layered walls, roofs and floors (Mitalas and Stephenson, 1967; Stephenson and Mitalas, 1967). Before the development of the Response Factor method, the Finite Difference method was used for the analysis of the transient heat conduction through multi-layered walls, roofs and floors. However, the Response Factor method was more suitable for simulating the transient heat conduction than the Finite Difference method because the Response Factor method reduced the computation time for the analysis of the transient heat conduction through multiple surfaces. In addition, the Response Factor method was based on

more stable calculation procedure than the Finite Difference method which contained numerical instabilities that were inherent in the finite difference calculation procedure. Therefore, Dr. Kusuda adopted the Response Factor method for the transient analysis of multi-layer walls and developed the RESPTK program that was based on the Response Factor method.

Although a RESPTK program manual could not be found, the details of the RESPTK program, including the calculation methods, equations, algorithms and sample calculations, were included in the ASHRAE journal paper "*Thermal response factors for multi-layer structures of various heat conduction systems*" (Kusuda, 1969). In addition, the ASHRAE publication entitled "*Bibliography on Available Computer Programs in the General Area of Heating, Refrigerating, Air Conditioning and Ventilating*" (Christopher and Crall, 1975) provided additional information about the RESPTK program. Therefore, based on these publications, a detailed analysis of the RESPTK program is provided in the Section 5.3.

4.3.1.3 National Bureau of Standards Load Determination (NBSLD) Program

In 1974, with funding from the Department of Housing and Urban Development, the National Bureau of Standards Load Determination (NBSLD) program was developed by Dr. Kusuda who worked at the National Bureau of Standards (NBS). The NBSLD program was created to analyze unconventional building designs, heating and cooling systems and the impact of varying control settings. Some of the special features of the NBSLD program included: the "inside-out" construction of outside walls where exterior walls have the thermal insulation layer and interior walls have the thermal mass; indoor partitions or floor-ceiling sandwich structures that effected the heat storage of the room; the ability to analyze undersized HVAC systems; the

analysis of simultaneous heating and cooling loads in different zones during the spring and autumn; the use of delayed heat gain from solar radiation for reducing heating and cooling loads in buildings; the analysis of attic ventilation, etc. These new features were important because many of the computer programs used approximate methods for calculating heating and cooling loads (i.e., the Weighting Factor method). In addition, these same computer programs were not capable of the analysis of unconventional building constructions, heating and cooling systems and HVAC controls. Therefore, the NBSLD program was developed using the Heat Balance method instead of the Weighting Factor method. Although use of the more rigorous calculation method (i.e., the Heat Balance method) required more computation time and computer memory than the use of the approximate calculation method (i.e., the Weighting Factor method), the use of the Heat Balance method reduced the uncertainty of the Weighting Factor method and conducted a more accurate heating and cooling load calculation (Kusuda, 1974).

The NBSLD program was a rigorous load calculation that used the Conduction Transfer Functions (CTFs) method and the Heat Balance method. To calculate the dynamic hourly heating and cooling loads in buildings, the NBSLD program analyzed a detailed heat balance network of the room. The thermal components that were involved included: heat exchange within the room system, the transient conduction through multi-layered walls, roofs and floors, the radiative heat transfer between interior surfaces, the infiltration heat gain or loss, the solar radiation heat gain, heat gains from internal heat sources (i.e., lights, equipment and occupants), etc.

Dr. Kusuda published the final report entitled "*NBSLD, Computer Program for Heating and Cooling Loads in Buildings*" (Kusuda, 1974), which included detailed information about the NBSLD program as the engineering manual for the NBSLD program. In addition, the ASHRAE

TGER Committee publication entitled "*Procedure for Determining Heating and Cooling Loads for Computerizing Energy Calculations - Algorithms for Building Heat Transfer Subroutines*" (ASHRAE, 1975) included additional information about the NBSLD program. Therefore, based on these publications, a detailed analysis of the NBSLD program is provided in the Section 5.3.

4.3.2 Simulation Programs by the General American Research Division/General American Transportation Corporation (GARD/GATC)

In the Section 4.3.2, the three-computer programs developed by the General American Research Division/General American Transportation Corporation (GARD/GATC) are analyzed, which include: the SHelter Environmental Prediction (SHEP) program, the Thermo-dynamic Analysis Computer System (TACS) program and the Post Office program.

4.3.2.1 SHelter Environmental Prediction (SHEP) Program

The SHelter Environmental Prediction (SHEP) program was developed by the General American Research Division/General American Transportation Corporation (GARD/GATC) in 1968 with funding from the Office of Civil Defense (OCD). The SHEP program was written in FORTRAN IV, which included approximately 780 lines of computer code.

In the 1960s, the United States was in a conflict with the Union of Soviet Socialist Republics (USSR) over the USSR's nuclear missile sites in Cuba. To cope with the nuclear threat, many community fallout shelters were constructed in the United States (Kusuda, 2001). At that time, the OCD funded several research projects to evaluate the adequacy of the fallout shelter thermal environment for occupants using a digital computer. For example, the development of the MATEUS program by Dr. Kusuda who worked at the National Bureau of

Standards (NBS) was one of the first research projects funded from the OCD. Similarly, the GARD/GATC was another of the OCD contractors that researched shelter thermal environments and developed the SHEP computer program to simulate the adequacy of the shelter thermal environment by using a digital computer (Kusuda, 2001).

The SHEP program simulated the thermal environments of an underground shelter or large structure. To evaluate the thermal environment of the shelter, the SHEP program analyzed the effects of the different thermal loads and ventilation, which included: the effects of the thermal loads, the ventilation air in the shelter, the effects of the dynamic heat transfer through shelter's envelopes (i.e., the shelter's walls, ceiling, and floor), the solar radiation incident on the exterior of the shelter, moisture condensation and evaporation on the interior surfaces of the shelter, the heat generation from occupants, lighting, equipment and the air-conditioning system.

To evaluate the transient heat conduction through shelter's envelope, the SHEP program used the Finite Difference method. This method for the analysis of the transient heat conduction (i.e., Finite Difference method) in the SHEP program was similar to the method for the analysis of the transient heat conduction (i.e., Finite Difference method) in MATEUS program. To determine the total heating and cooling loads of the shelter, the SHEP program used the Heat Balance method in a similar fashion as the MATEUS program. To calculate heating and cooling loads, the sensible and latent heat energy exchanges (i.e., heat transfer through the shelter's envelope, internal heat generations in the shelter space and the heat exchange with the ventilation air) were evaluated in the SHEP program. The governing heat balance equations for the calculation of heating and cooling loads were derived from the overall mass and energy conservation balance. The GARD/GATC published the user's manual for the SHEP program in

1968. Therefore, based on the user's manual of the SHEP program, an analysis of the SHEP program is provided in the Section 5.3.

4.3.2.2 Thermo-dynamic Analysis Computer System (TACS) Program

Information about the TACS program was released to the industry in a series of published articles in the Air-conditioning & Refrigeration Business magazine: *"TACS – A New Approach to System Design"* (Milnark, 1968) and *"TACS – Computer Workhorse for Sale"* (Milnark, 1969). In these articles, Sam Milnark who was a journal editor of the Air-conditioning & Refrigeration Business interviewed key developers of the TACS program as well as key HVAC industry engineers who were interested in computer applications for building energy analysis. Based on interviews with key experts and engineers, Milnark provided important information (i.e., program structure, sub-programs, algorithms, program inputs and outputs, etc.) about the TACS program by publishing these articles.

With the funding from the U.S. Post Office Department, the Thermodynamic Analysis Computer System (TACS) program was developed at 1968 by Jim Anders who was a mechanical engineer in the Post Office Bureau of Research and Engineering. At that time, the Post Office was one of the biggest customers in the field of HVAC equipment in the United States. Therefore, Anders developed the TACS program specification to help the U.S. Postal Service (USPS) better determine the exact size of the HVAC systems for postal buildings. The General American Research Division of General American Transportation Corporation (GARD/GATC), who was the contractor chosen to write the TACS program, also contributed to the development of the TACS program. While Jim Anders developed the outline of the TACS program, Dr.

Lokmanhekim and Herman Beals, who were engineers at the GARD/GATC, developed the details of the sub-systems for the TACS program. At that time, Dr. Lokmanhekim and Beals worked very closely with the ASHRAE TGER Committee who was developing the heating and cooling loads calculation procedures. (Milnark, 1968). Jim Anders also worked on debugging the dynamic heat transfer calculations and the HVAC system simulation for the TACS computer program. After the modification, the new TACS program was used in the evaluation of a new postal building for the first time at December 1968 (Milnark, 1969). In the Section 5.3, a detailed analysis of the TACS program is provided.

4.3.2.3 Post Office Program

In 1970, eighty-six billion pieces of mail in the United States were managed by the U.S. Postal Service (USPS), and these huge volume of mails increased three percent each year. To handle these huge and increasing volume of mails, the U.S. Post Office Department was determined to build five-thousand new postal facilities, remodel existing postal facilities and upgrade mechanical systems in postal facilities. However, analysis using manual calculations for the determination of the postal facilities' design and mechanical equipment sizing required a large amount of engineering time and increased fudge factors. In addition, the inaccuracy of the manual calculations considerably increased the final costs of the mechanical equipment and the operation and maintenance for postal facilities. Therefore, the U.S. Post Office Department was determined to develop and use the Post Office program for the accurate analysis of energy requirements and mechanical system selection in postal facilities as well as for reducing the engineering time using a digital computer. In addition, using the Post Office program allowed for analysis of the most economical combination of mechanical systems and energy sources (i.e.,

gas, oil, coal, steam, or electricity) for a postal facility. Although the purpose of the Post Office program was for the analysis of postal facilities, the Post Office program also had capability to analyze any type of buildings, such as commercial buildings with small modifications to the computer code (USPS, 1971).

The final version of the TACS program was renamed the Post Office program and was released at the 1971. During the development of the Post Office program, Dr. M. Lokmanhekim who was the manager of thermal systems and computer applications programs at GARD/GATC headed the project, and Robert H. Henninger at GARD/GATC also participated in the development of the Post Office program as the one of project members.

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) also contributed to the development of the Post Office program because ASHRAE's new heating and cooling loads calculation procedures were used in the LOADS portion of the Post Office program. While developing the Post Office program, members of the ASHRAE TGER Committee also provided technical assistance for the development of the Post Office program. The ASHRAE TGER members included: Dr. Kusuda who worked at the National Bureau of Standards (NBS) of USA, as well as D.G. Stephenson and G.P. Mitalas who worked at the National Research Council (NRC) of Canada (GARD/GATC, 1971a). The GARD/GATC published the user's and engineering manuals for the Post Office program in 1971. Therefore, based on these manuals of the Post Office program, an analysis of the Post Office program is provided in the Section 5.3.

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4.3.3 Simulation Programs by the National Research Council (NRC) of Canada

In the Section 4.3.3, two computer programs that were developed by the National Research Council (NRC) of Canada were analyzed, which included: the FORTRAN IV program to calculate heat flux response factors for a multi-layer slab (i.e., the CP-26 program) and the FORTRAN IV program to calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs (i.e., the CP-33 program).

4.3.3.1 FORTRAN IV Program to Calculate Heat Flux Response Factors for a Multi-layer Slab (CP-26 Program)

In 1967, a FORTRAN IV program for the calculation of response factors for a multi-layered slab (i.e., CP-26 program) was developed by Mitalas and Arseneault at the National Research Council (NRC) of Canada. The FORTRAN IV program for the calculation of response factors was called the CP-26 program, which stood for *"Computer Program No. 26"* (i.e., CP-26 program), which was developed by the Division of Building Research (DBR) that belonged to the National Research Council (NRC) of Canada. The CP-26 program was released to researchers and HVAC engineers through the NRC publication: *"FORTRAN IV Program to Calculate Heat Flux Response Factors for a Multi-layer Slab"* (Mitalas and Arseneault, 1967). This NRC publication included: the general information about the CP-26 program; a description of the calculation method (i.e., Response Factor method) that applied to the CP-26 program; input requirements and output formats of the CP-26 program; key studies that contributed to the development of the CP-26 program; the FORTRAN source code of the CP-26 program; and

sample inputs and outputs for the CP-26 program. In the Section 5.3, a detailed analysis of the CP-26 program is provided.

4.3.3.2 FORTRAN IV Program to Calculate Z-transfer Functions for the Calculation of Transient Heat Transfer through Walls and Roofs (CP-33 Program)

In 1972, a FORTRAN IV program for the calculation of z-transfer functions for a multi-layered walls and roofs (i.e., the CP-33 program) was developed by Mitalas and Arseneault at the NRC of Canada. The FORTRAN IV program for the calculation of z-transfer functions was called the CP-33 program, which stood for *"Computer Program No. 33"* (i.e., the CP-33 program). The CP-33 program was released to researchers and HVAC engineers through the NRC publication: "*FORTRAN IV Program to Calculate Z-transfer Functions for the Calculation of Transient Heat Transfer through Walls and Roofs"* (Mitalas and Arseneault, 1972). This NRC publication included: the general description of the CP-33 program; the calculation method (i.e., Conduction Transfer Functions) that applied to the CP-33 program; input requirements and output formats of the CP-33 program; key studies that contributed to the development of the CP-33 program; flow diagrams that showed calculation sequences; the FORTRAN source code of the CP-33 program; and sample inputs and outputs for the CP-33 program. In the Section 5.3, a detailed analysis of the CP-33 program is provided.

4.4 Summary of the Methodology

Chapter IV has presented the methodology used to discuss the contributions of the ASHRAE TGER Committee to the development of early whole-building energy simulation programs and analyze detailed characteristics of early computer programs (i.e., the MATEUS program, the SHEP program, the TACS program, the CP-26 program, the RESPTK program, the CP-33 program, the Post Office program and the NBSLD program) that were not discussed in previous historical papers. To accomplish this, four tasks were performed as follows: 1) Analyze previous ASHRAE TGER publications that provided recommend algorithms for the calculation of heating and cooling loads in buildings, 2) Analyze details of early computer programs by reviewing user and engineering manuals or equivalent documents, 3) Identify contributions of ASHRAE TGER as well as very early computer programs to early building energy simulation programs, and 4) Interview with key expert(s) who were involved in the development of early building energy simulation programs. The results of these procedures will be discussed in Chapter V.

CHAPTER V

RESULTS

5.1 Results of the Level 0 Analysis

In the Section 5.1, detailed information about previous ASHRAE TGER Committee

publications is provided, which includes: the names of sub-routines; description of sub-routines;

input variables that were required for the calculation of the sub-routine; output variables that

resulted from the sub-routines; the calculation sequence that was used in the sub-routines; and

notes for additional information about the sub-routine.

5.1.1 Results of the Analysis of ASHRAE Publications

In Section 5.1.1, three ASHRAE TGER Committee publications are discussed, which

include: "*Proposed procedure for determining heating and cooling loads for energy calculations*

- Algorithms for building heat transfer subroutines" (ASHRAE, 1968), "*Procedure for*

determining heating and cooling loads for computerized energy calculations - Algorithms for

building heat transfer subroutines" (ASHRAE, 1971) and "*Procedure for determining heating*

and cooling loads for computerizing energy calculations - Algorithms for building heat transfer

subroutines" (ASHRAE, 1975).

5.1.1.1 *Proposed Procedure for Determining Heating and Cooling Loads for Energy*

Calculations - Algorithms for Building Heat Transfer Subroutines **(ASHRAE, 1968)**

In 1968, the first publication of the ASHRAE TGER Committee was published. In this

publication, the Response Factor method that calculated transient heat conduction through multi-

layered walls, roof or floor and the Weighting Factor method that calculated hourly heating and cooling loads for building energy requirements were presented. The new 1968 ASHRAE calculation procedure consisted of many sub-routines for hourly heating and cooling loads calculation for building energy requirements, which included: the analysis of actual weather conditions, the transient heat conduction through multi-layered walls (i.e., Response Factor method), instantaneous heat gains of a space, heating and cooling loads of a space (i.e., Weighting Factor method), etc. ASHRAE's new heating and cooling load calculation procedures for energy requirements in buildings were mostly derived from the works of Stephenson and Mitalas at the National Research Council (NRC) as well as by Dr. Kusuda at the National Bureau of Standards (NBS) (USPS, 1971).

In the hourly heating and cooling loads calculation procedure, the main sub-routines were the IHG (i.e., Instantaneous Heat Gain calculation) and HLC (i.e., Hourly Load Calculation) sub-routines (see Figure 5.1). The remaining sub-routines were used to determine input values to the main sub-routines (i.e., IHG and HLC subroutines). The IHG sub-routine calculated the instantaneous heat gains of a space. As input variables of the IHG sub-routine, the characteristics of the windows, exterior walls and roofs, lights, internal heat source other than lights, inside doors, outside doors, partitions, underground walls, underground floors, internal infiltration, external infiltration, temperatures, and humidity ratios were required for the calculation of total hourly sensible and latent heat gains of a space. The HLC sub-routine then calculated heating and cooling loads of a space. In the HLC sub-routine, the outputs of IHG sub-routine (i.e., total hourly sensible and latent heat gains) were converted into the total hourly heating and cooling loads by applying subroutines that calculated various weighting factors (i.e.,

RMRG, RMRX, RMRIS, and RMRT). The total hourly heating and cooling loads were then

calculated by the HLC sub-routine that were directly turned into the inputs to the HVAC system

simulation sub-routines. Detailed information about sub-routines, input variables and output
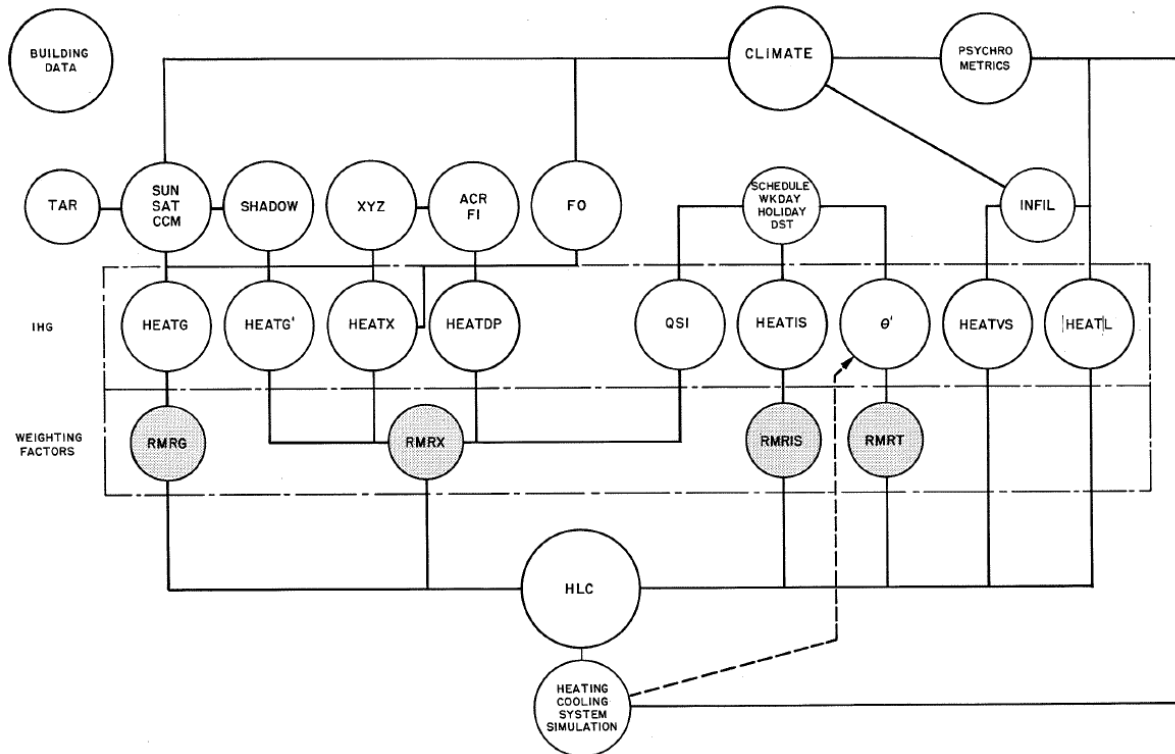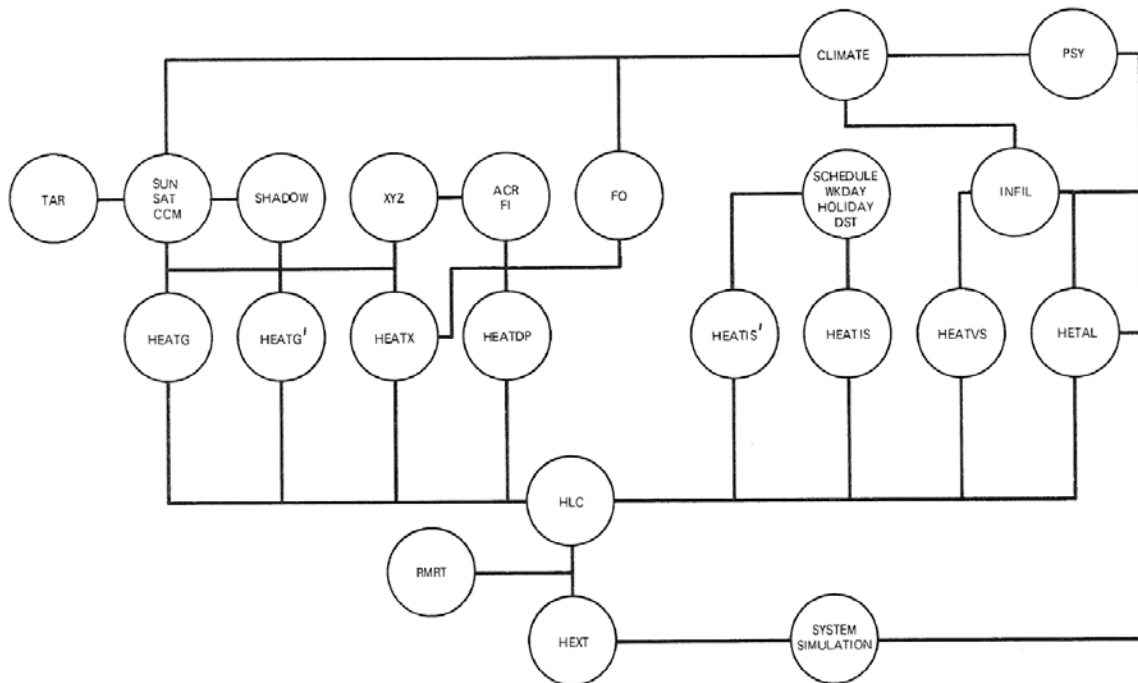
variables is provided in the Appendix C.

Figure 5.1. Interrelationship of various sub-routines in ASHRAE 1968. Reprinted with permission from "Proposed Procedure for Determining Heating and Cooling Loads for Energy Calculations - Algorithms for Building Heat Transfer Subroutines," by ASHRAE, 1968. Copyright 1968 by ASHRAE (www.ashrae.org).

5.1.1.2 *Procedure for Determining Heating and Cooling Loads for Computerized Energy*

***Calculations - Algorithms for Building Heat Transfer Subroutines* (ASHRAE, 1971)**

In the second ASHRAE TGER Committee publication in 1971, the Response Factor

method that calculated transient heat conduction through multi-layered walls, roof or floor and

the Weighting Factor method that calculated hourly heating and cooling loads for building

energy requirements were included. To calculate the hourly heating and cooling loads for

building energy requirements using the Response Factor method and the Weighting Factor

method, the XYZ, HEATW, HLC and RMRT sub-routines were included in the second

publication at 1971 (see Figure 5.2).

Figure 5.2. Interrelationship of various sub-routines in ASHRAE 1971. Reprinted with
permission from "Procedure for Determining Heating and Cooling Loads for Computerized
Energy Calculations – Algorithms for Building Heat Transfer Subroutines," by ASHRAE, 1971.
Copyright 1971 by ASHRAE (www.ashrae.org).

The main sub-routines in the new ASHRAE load calculation procedure in 1971 were the

HLC (i.e., Hourly Load Calculation) and HEXT (i.e., Heat Extraction) sub-routines. The

remaining sub-routines were used to generate input values that were required by the main sub-

routines (i.e., the HLC and HEXT subroutines). The XYZ sub-routine didn't include the

calculation sequence of the response factors, but rather discussed general equations of response factors, sample values of response factor for various building construction components and two computer programs that calculated values of response factor: the CP-26 program and Response Factor Calculation program (i.e., RESPTK program). As the output of XYZ sub-routine, values of response factors (i.e., A_i, B_i, C_i, and D_i) were calculated in the XYZ sub-routine. Based on values of response factors that were calculated by the XYZ sub-routine, the HEATW sub-routine calculated the transient heat conduction through multi-layered walls or roof. To calculate the transient heat conduction through multi-layered walls or roof, the exterior surface temperature was first calculated by solving the heat balance equations. The heat transfer sources that were involved in the calculation of exterior surface temperature included the incident solar radiation, heat gain/loss from the ambient outdoor air, heat gain/loss by conduction and heat gain/loss to the sky. Then, depending on the exterior surface temperature, heat gain at indoor surfaces of walls or roof was calculated in the HEATW sub-routine.

The HLC sub-routine calculated heating and cooling loads of a space when the space temperature was constant. To calculate heating and cooling loads for a constant space temperature, the HLC sub-routine applied values of pre-calculated weighting factors (i.e., weighting factors for typical office spaces with a heavy, medium, or light thermal mass structure) to the calculation of various heat gains. Heat transfer components that were involved in the calculation of heat gains included the solar heat gain, the conduction heat gain through multi-layered walls or roof, internal heat sources, etc. Based on values of the various heat gains, the HLC sub-routine calculated the hourly sensible and latent loads. However, when the space

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temperature was not constant, the RMRT sub-routine calculated the weighting factors that deviated from the design value.

The HEXT sub-routine calculated the rate of sensible heat that was extracted from the space. In the HEXT sub-routine, the sensible cooling load was calculated using a constant space temperature in the HLC sub-routine after adjusting the characteristics of space cooling equipment (i.e., design capacity and throttling curve). The space temperature deviation from the design set-point was determined regarding space temperature weighting factors (i.e., RMRT sub-routine). A detailed information about sub-routines, input variables and output variables is provided in the Appendix D.

5.1.1.3 *Procedure for Determining Heating and Cooling Loads for Computerizing Energy Calculations - Algorithms for Building Heat Transfer Subroutines* (ASHRAE, 1975)

In the third ASHRAE TGER publication in 1975, the Conduction Transfer Functions (CTFs) method that calculated the transient heat conduction through multi-layered walls, roof or floor and the Heat Balance method that calculated hourly heating and cooling loads for building energy requirements were presented. To calculate the hourly heating and cooling loads using the Conduction Transfer Functions and Heat Balance method, the FIJ, XYZ, HEATW and RMTMP sub-routines were included in the third publication in 1975. The FIJ sub-routine analyzed the radiation heat exchange between the inside surfaces of a room (i.e., ceiling, floor, walls, windows and doors) using long wavelength radiation between solid surfaces (i.e., ceiling, floor, wall, windows and doors) of a room, which affected the thermal condition at the interior surfaces. As the output of FIJ sub-routine, radiation shape factors between the interior surfaces

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(i.e., the ceiling, floor and interior walls) of a room were calculated. The FIJ sub-routine was developed by D.M. Burch and B.A. Peavy who worked at the National Bureau of Standards (NBS). The XYZ sub-routine provided information about the calculation of the Conduction Transfer Functions (CTFs). Since the calculation of Conduction Transfer Functions (CTFs) required lengthy and complex mathematical equations, the XYZ sub-routine didn't include the whole-algorithm to calculate Conduction Transfer Functions, but discussed general equations and provided two computer programs that calculated the Conduction Transfer Functions: the Response Factor Calculation program (i.e., RESPTK program) and the CP-33 program. Based on values of the Conduction Transfer Functions (CTFs) that were calculated by the XYZ sub-routine, the HEATW sub-routine then calculated the transient heat conduction through multi-layered walls, roof or floor.

To calculate the transient heat conduction under randomly fluctuating outdoor weather conditions, the hourly history of outdoor and indoor air temperatures as well as Conduction Transfer Functions (CTFs) were used in the HEATW sub-routine. Using these values, the HEATW sub-routine analyzed the transient heat conduction through the various building construction components, which included: the exterior walls and roof; interior walls (i.e., partition walls); and floor/ceiling sandwich; slab on grade floor; and floor over the vented crawl space.

The RMTMP sub-routine then calculated the heating and cooling loads of a room or room temperature by using the Heat Balance method. To calculate heating and cooling loads of a room or room air temperature, the RMTMP sub-routine first analyzed the thermal condition of each room surface by solving the heat balance equations that were involved in each room

surface. The heat balance equations that were involved in each room surface included dynamic

conduction heat transfers through multi-layered walls, roof or floor, radiation heat transfers from

interior surfaces (i.e., ceiling, floor, walls, windows and doors) and internal heat sources (i.e.,

lighting, occupants, and equipment). Second, the room air temperature was then calculated by

solving the heat balance equations. The heat balance equations that were involved in the room air

temperature included the heat exchanges due to the interior surfaces, infiltration, ventilation and

internal heat sources (i.e., lighting, occupants, and equipment). Based on the calculations of the

thermal condition of each room surface and room air temperature, the RMTMP sub-routine

finally calculated the sensible and latent thermal loads that were imposed on the air-conditioning

system. A detailed information about sub-routines, input variables and output variables is

provided in the Appendix E.

5.2 Results of the Level 1 Analysis

In Section 5.2, detailed information about early computer programs is provided by

reviewing published documents (i.e., user and engineering manuals or equivalent documents),

which includes: the calculation methods, input variables, output variables, subroutines, shared

characteristics among early computer programs, shared characteristics between the ASHRAE

TGER publications and early whole-building simulation programs, etc.

5.2.1 Simulation Programs by the National Bureau of Standards (NBS)

In Section 5.2.1, a detailed analysis of the three-computer programs that were developed

by Dr. Kusuda at the National Bureau of Standards (NBS) were analyzed by reviewing published

documents (i.e., user and engineering manuals or equivalent documents). The early computer

programs from the NBS included: the Mathematical Analysis of Thermal Environment in

Underground Shelters (MATEUS) program, the Response Factor Calculation program (i.e.,

RESPTK program) and the National Bureau of Standards Load Determination (NBSLD)

program.

5.2.1.1 Mathematical Analysis of Thermal Environment in Underground Shelters (MATEUS) Program
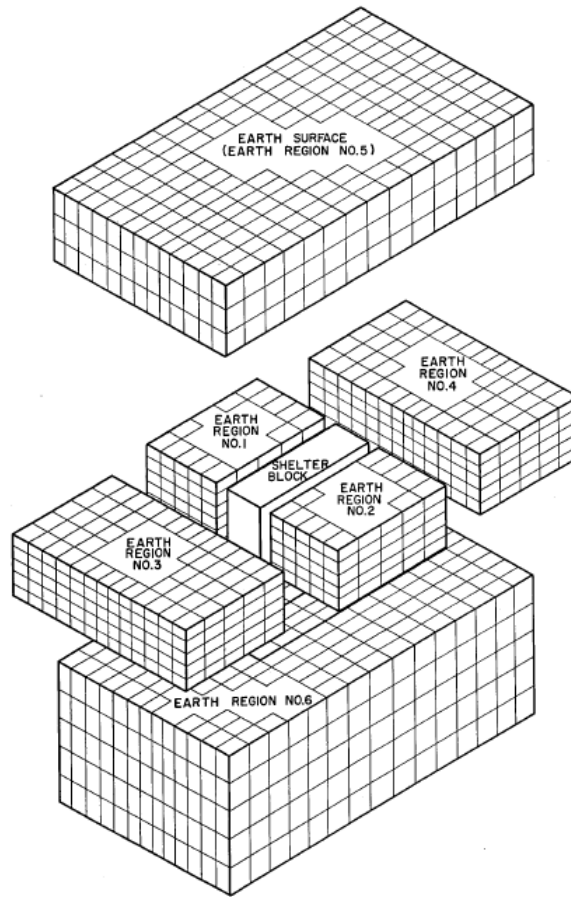
In this Section 5.2.1.1, the MATEUS program is analyzed by reviewing two ASHRAE

articles: "*Mathematical analysis of thermal environment in underground shelters*" (Achenbach et

al., 1962) and "*Numerical analyses of the thermal environment of occupied underground spaces*

with finite cover using a digital computer" (Kusuda and Achenbach, 1963). The MATEUS

program calculated the indoor temperature and humidity to evaluate the adequacy of

underground shelter environment. To calculate the temperature and humidity of the inside shelter

space, the MATEUS program solved dynamic balance equations of heat and moisture transfers

for each time increment (i.e., four-hour time interval). The components that were involved in

these dynamic balances of heat and moisture transfers included: the sensible and latent heat from

internal sources (i.e., occupants, equipment, etc.), heat and moisture exchanges by the ventilation

air and heat and moisture transfers by enclosing surfaces of the underground shelter. The

parameters that were used in the MATEUS program to determine the indoor temperature and

humidity are summarized in Table 5.1.

Table 5.1. *Parameters for determining indoor temperature and humidity of the underground shelter in the MATEUS program*

Shelter Parameters	• Size and shape of shelter • Physical and thermal characteristics of construction materials
Site Parameters	• Earth characteristics (i.e., density, specific heat, thermal conductivity, moisture content and moisture percolation) • Depth of shelter below earth surface • Earth cover thickness
Climate Parameters	• Earth temperature • Climate above ground (i.e., air temperature, humidity, velocity, solar radiation and rainfall)
Operation Parameters	• Ventilation air condition (i.e., ventilation rate, temperature, humidity) • Density and activity of occupants • Heat and moisture from equipment

To simulate the underground shelter, the MATEUS program used the matrix model that consisted of seven-parallelepiped blocks: with one-block located in the center of the matrix model and six-blocks enclosing the center block (see Figure 5.3). The center block represented the underground shelter itself. The center block was divided in concrete elements (i.e., the shelter's walls, ceiling and floor) and the shelter interior space. The six-blocks represented the earth regions around the shelter. The size of matrix model depended on the capacity of digital computer memory on which the program was being run and the number of mathematical operations. As the matrix grid was finer, the MATEUS program conducted a more accurate heat conduction analysis because the finite difference model was more stable when the matrix grid was smaller.

Figure 5.3. Schematic diagram of heat transfer matrix used for the numerical analysis in the shelter. Reprinted with permission from "Mathematical Analysis of Thermal Environment in Underground Shelters," by Achenbach et al., 1962, *Symposium on Survival Shelters*, p. 25. Copyright 1962 by ASHRAE (www.ashrae.org).

Using a digital computer, the MATEUS program analyzed the heat conduction through the earth that surrounded the shelter and the heat conduction through the shelter's envelope using the finite difference network matrix (see Figure 5.4). To analyze the heat conduction through the earth, a three-dimensional network matrix for heat and moisture transfer was simulated in the MATEUS program. On the other hand, to analyze heat conduction through the shelter's envelope (i.e., walls, ceiling and floor), a one-dimensional network matrix was used for analyzing the heat

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transfer through the shelter's envelope. The MATEUS program did not assume the moisture

transfer through inner shelter surfaces. The direction of heat transfer through the shelter's walls,

ceiling and floor was assumed to be perpendicular to each surface.

When the MATEUS program analyzed the heat conduction through earth regions, the

MATEUS program assumed that the thermal and physical characteristics were constant in each

earth region. However, the thermal and physical characteristics could differ among each earth

region. In addition, the MATEUS program assumed that the thermal and physical characteristics

are constant within each wall. However, the thermal and physical characteristics could differ
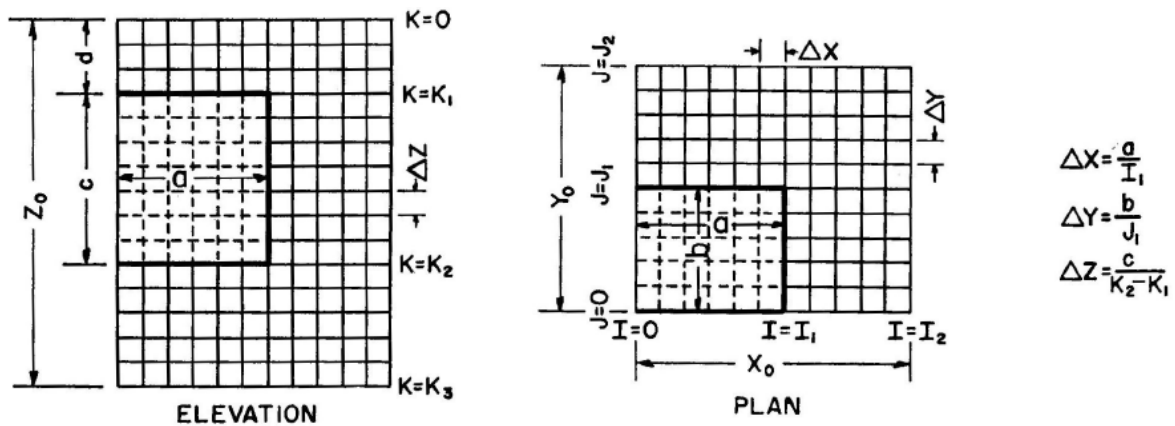
among each wall.

Figure 5.4. Schematic finite difference, three dimensional network matrix for heat conduction in earth. Reprinted with permission from "Numerical Analyses of the Thermal Environment of Occupied Underground Spaces with Finite Cover Using a Digital Computer," by Kusuda and Achenbach, 1963, *ASHRAE Transactions, 69*, p. 442. Copyright 1963 by ASHRAE (www.ashrae.org).

The conditions that were involved in the analysis of the transient heat conduction

through the earth regions and shelter's envelopes included: the heat transfer at the interior

surfaces; the heat conduction through concrete walls, roof and floor; the heat conduction at the exterior shelter's surfaces and earth interface; the heat conduction through earth regions; and the heat exchange at the ground surface and ambient air interface.

To determine the interior thermal environments of the underground fallout shelter, the MATEUS program analyzed the sensible and latent heat exchanges in the underground shelter's thermal system by using the Heat Balance method. Dr. Kusuda developed heat balance equations for the various heat sources in the underground shelter (Kusuda, 2001). The various heat sources that were involved in these heat balance equations included: the internal heat sources (i.e., occupants, lighting, equipment and cooking); the ventilation air; the heat transfer through shelter's envelopes; and the solar radiation through the earth. The Figure 5.5 showed various heat sources that affected thermal environment of the underground shelter.
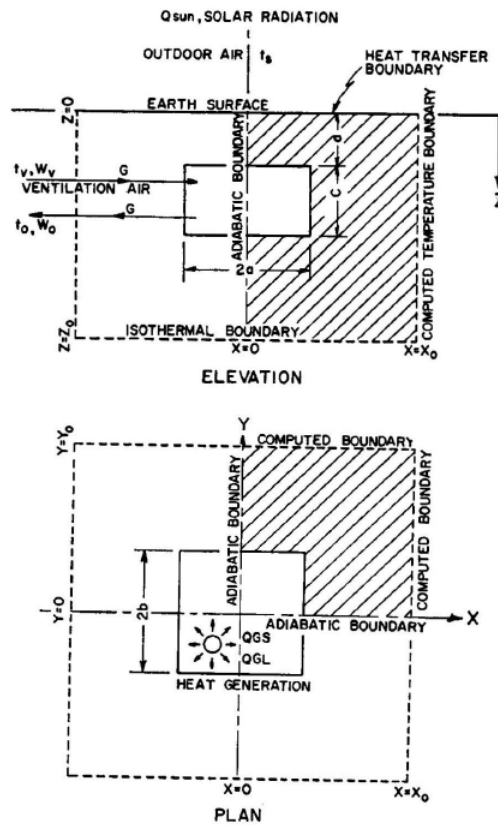
Figure 5.5. Schematic diagram of heat transfer model for underground fallout shelter simulation. Reprinted with permission from "Numerical Analyses of the Thermal Environment of Occupied Underground Spaces with Finite Cover Using a Digital Computer," by Kusuda and Achenbach, 1963, *ASHRAE Transactions, 69*, p. 440. Copyright 1963 by ASHRAE (www.ashrae.org).

To evaluate the heat balance of the shelter indoor air, three thermal components were involved in calculations of these heat balance equations, which included: the sensible and latent heat that were generated by the occupants, the heat exchange between the shelter indoor air and the ventilation air and the heat exchange between the shelter indoor air and the shelter interior surfaces (i.e., walls, ceiling and floor). Based on calculations of sensible and latent heat balance equations, the MATEUS program resulted in the shelter air temperature and the humidity ratio.

The MATEUS program assumed that total sensible and latent heats generation by an occupant was the 400 $\frac{Btu}{hr}$. Therefore, the sensible and latent heat generations by occupants were represented by:

$$Q_{gs} = 350 \text{ when } t_a < 65°F \tag{5.1}$$

$$Q_{gs} = -10 \, t_a + 1000 \text{ when } t_a \geq 65°F \tag{5.2}$$

$$Q_{gl} = 400 - Q_{gs} \tag{5.3}$$

Where,

Q_{gs} = sensible heat that was generated by occupants,

Q_{gl} = latent heat that was generated by occupants, and

t_a = shelter air temperature.

The MATEUS program calculated the sensible and latent heat exchanges between indoor air in the shelter and ventilation air. Inputs that were involved in ventilation air in this calculation were values that varied with the time. The sensible and latent heat exchanges was represented by:

$$Q_{vs} = 0.018V \, (t_a - t_v) \tag{5.4}$$

$$Q_{vl} = 0.075V \, (W_a - W_v) \, \lambda \tag{5.5}$$

Where,

Q_{vs} = sensible heat exchange between indoor air and ventilating air,

Q_{vl} = latent heat exchange between indoor air and ventilating air,

V = ventilation rate,

t_a = shelter air temperature,

t_v = temperature of ventilating air supply,

W_a = humidity ratio of the shelter air,

W_v = humidity ratio of ventilating air supply, and

λ = latent heat of condensation of the water vapor.

The MATEUS program calculated the sensible and latent heat exchanges between the shelter indoor air and interior surfaces (i.e., walls, ceiling and floor) of the underground shelter. The MATEUS program assumed that the value of surface heat transfer coefficient was constant along each shelter's interior surface. However, the value of surface heat transfer coefficient differed among the shelter's interior surfaces. The sensible and latent heat exchanges was represented by:

$$Q_{ws} = \sum_{m=1}^{6} h_m \, s_m \, (t_a - t_{sm}) \tag{5.6}$$

$$Q_{wl} = \sum_{m=1}^{6} h_{Dm} \, s_m \, (W_a - W_{Am}) \, \lambda \tag{5.7}$$

Where,

Q_{ws} = sensible heat exchange between indoor air and interior surfaces,

Q_{wl} = latent heat exchange between indoor air and interior surfaces,

m = index of summation for six interior surfaces,

h_m = surface heat transfer coefficient,

s_m = area of the shelter interior surface,

t_a = shelter air temperature,

t_{sm} = temperature of the shelter surface,

h_{Dm} = mass transfer coefficient,

W_a = humidity ratio of the shelter air,

W_{Am} = humidity ratio of saturated air at the surface temperature t_{sm}, and

λ = latent heat of condensation of the water vapor.

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Based on calculations of the sensible and latent heats that were generated by occupants and the sensible and latent heat exchanges between the shelter indoor air, ventilation air and interior surfaces of the underground shelter (i.e., walls, ceiling and floor), the MATEUS program evaluated the shelter air heat balances inside shelter thermal environment, which was represented by:

$$Q_{gs} = Q_{vs} + Q_{ws} \qquad\qquad (5.8)$$

$$Q_{gl} = Q_{vl} + Q_{wl} \qquad\qquad (5.9)$$

Where,

Q_{gs} = sensible heat that was generated by occupants,

Q_{vs} = sensible heat exchange between indoor air and ventilating air,

Q_{ws} = sensible heat exchange between indoor air and interior surfaces,

Q_{gl} = latent heat that was generated by occupants,

Q_{vl} = latent heat exchange between indoor air and ventilating air, and

Q_{wl} = latent heat exchange between indoor air and interior surfaces.

5.2.1.2 Response Factor Calculation Program (RESPTK program)

For the detailed analysis of the RESPTK program, the ASHRAE Journal paper (Kusuda, 1969) that provided information about the RESPTK program, including the fundamentals of the RESPTK program, calculation methods that were based on the RESPTK program, equations that were used in the RESPTK program, sample calculations using the RESPTK program, etc., is analyzed. Although no manuals could be found for the RESPTK program, the ASHRAE Journal paper entitled "*Thermal response factors for multi-layer structures of various heat conduction*

systems" (Kusuda, 1969) provided a detailed description of the mathematical procedures of the RESPTK program. In addition, the ASHRAE publication *"Bibliography on Available Computer Programs in the General Area of Heating, Refrigerating, Air Conditioning and Ventilating"* (Christopher and Crall, 1975) provided additional information about the RESPTK program, which included: the purpose of the RESPTK program, input variables and output variables of the RESPTK program, programming language, etc.

The RESPTK program extended the simulation capability of the CP-26 program that was developed by Mitalas and Arseneault in 1967. Although both of the RESPTK program and the CP-26 program were based on the Response Factor method, the RESPTK program was an expanded version for calculating response factors than the CP-26 program. Compared to the CP-26 program that calculated values of the response factor for plane walls above ground, the RESPTK program calculated values of the response factor for plane walls as well as curved walls (i.e., cylindrical wall and spherical wall) that were located above ground as well as underground. In the RESPTK program, the extension of the analysis of heat conduction through multi-layered walls that were located above ground to multi-layered walls that were located underground (i.e., semi-infinite systems) was derived from the MATEUS program that simulated the underground shelter.

The RESPTK program required input variables, which included: the thermal characteristics of each layer (i.e., thermal conductivity and thermal diffusivity); the physical characteristics of each layer (i.e., thickness of each layer and number of layers); the time increment for the calculation of the heat flux; the number of response factors that were calculated; curvature index for a surface; and heat conduction system index. Based on these input

variables, the RESPTK program calculated the values of the response factors for the specified heat conduction system.

The calculated values of the response factor for curved multi-layered walls were used in the analysis of transient heat conduction through curved multi-layered walls (i.e., cylindrical wall and spherical wall). In addition, the transient heat conduction for various underground installations (i.e., tunnels, pipes and storage tanks) could be analyzed using the RESPTK program.

5.2.1.3 National Bureau of Standards Load Determination (NBSLD) Program

For the detailed analysis of the NBSLD program, the final report entitled: "*NBSLD, Computer Program for Heating and Cooling Loads in Buildings*" (Kusuda, 1974) is analyzed in this section. This final report included details of the NBSLD program, such as the characteristics of the NBSLD program, calculation methods, simulation algorithms, fundamental equations, input and output variables, sub-routines, FORTRAN source code of the NBSLD program, etc., which served as the engineering manual for the NBSLD program.

In 1974, the NBSLD program was developed by Dr. Kusuda at the National Bureau of Standards (NBS), which followed the MATEUS program that was also developed by Dr. Kusuda in 1962 and the Response Factor Calculation program (i.e., RESPTK program) that was developed by Dr. Kusuda in 1969 (Kusuda, 2001). The MATEUS program used the Heat Balance method to determine the exact heating and cooling loads in the underground shelter. The RESPTK program used Conduction Transfer Functions (CTFs) to analyze the transient heat conduction through multi-layered building envelopes. Both the Heat Balance method and the

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Conduction Transfer Functions (CTFs) were used for the development of the NBSLD program. To calculate the exact heating and cooling loads by using the Heat Balance method, the NBSLD program first determined the energy exchange that was involved in the each interior surface at a given time. The energy exchange equation at the each interior surface was represented by:

$$q_{i,t} = h_{ci} (t_{a,t} - t_{i,t}) + \sum_{\substack{j=1 \\ j \neq i}}^{m} g_{ij} (t_{j,t} - t_{i,t}) + RS_{i,t} + RL_{i,t} + RE_{i,t} \qquad (5.10)$$

for i = 1,2,3,4,5,6

Where,

m = number of surfaces in the space,

$q_{i,t}$ = rate of heat conducted into surface i at the inside surface at time t,

h_{ci} = convective heat transfer coefficient at interior surface i,

g_{ij} = radiation heat transfer factor between interior surface i and interior surface j,

$RS_{i,t}$ = rate of solar energy coming through the windows and absorbed by surface i at time t,

$RL_{i,t}$ = rate of heat radiated from the lights and absorbed by surface i at time t,

$RE_{i,t}$ = rate of heat radiated from equipment and occupants and absorbed by surface i at time t,

$t_{a,t}$ = inside air temperature at time t,

$t_{i,t}$ = average temperature of interior surface i at time t, and

$t_{j,t}$ = average temperature of interior surface j at time t.

The six equations that were involved in this energy exchange at the each interior surface included: the heat conduction into the interior surface; the convective heat transfer between inside air and interior surface; the radiative heat transfer between room surfaces; the solar heat gain through windows; and the heat gains from internal energy sources (i.e., lights, equipment and occupants). After determining the thermal condition at the each interior surface, the energy

balance equations within the room system were simultaneously solved in order to calculate exact

heating and cooling loads in the room. The thermal components that were involved in these

energy balance equations within the room system included: the room air; interior walls; ceiling

and floor; the infiltration air; the ventilation air; and internal energy sources (i.e., lights,

equipment and occupants). The energy balance equation within the room system was represented

by:

$$Q_{L,t} = \sum_{i=1}^{6} h_{ci}\,(t_{i,t} - t_{a,t}) + \rho CG_{L,t}\,(t_{O,t} - t_{a,t}) +$$

$$\rho CG_{V,t}\,(t_{V,t} - t_{a,t}) + RS_{a,t} + RL_{a,t} + RE_{a,t} \tag{5.11}$$

Where,

$Q_{L,t}$ = cooling load at time t,

h_{ci} = convective heat transfer coefficient at interior surface i,

ρ = air density,

C = air specific heat,

$G_{L,t}$ = mass flow rate of outdoor air infiltrating into the space at time t,

$G_{V,t}$ = mass rate of flow of ventilation air at time t,

$RS_{a,t}$ = rate of solar heat coming through windows and convected into the room air at time t,

$RL_{a,t}$ = rate of heat from the lights convected into the room air at time t,

$RE_{a,t}$ = rate of heat from equipment and occupants and convected into the room air at time t,

$t_{i,t}$ = average temperature of interior surface i at time t,

$t_{a,t}$ = inside air temperature at time t,

$t_{O,t}$ = outdoor air temperature at time t, and

$t_{V,t}$ = ventilation air temperature at time t.

The relatively similar analytical base (i.e., the Heat Balance method), shared characteristics and common beginning between the MATEUS program, the RESPTK program and the NBSLD program indicates that the MATEUS program and the RESPTK program contributed to the development of the NBSLD program. In addition, many of the unique simulation capabilities of the NBSLD program were first shown in the MATEUS program and the RESPTK program.

In addition, the unique simulation capability of the MATEUS program that was created for simulating underground survival shelters as well as the RESPTK program that was created for calculating the values of the CTFs for underground conditions can be found in the NBSLD program although the main purpose of the NBSLD program was to calculate heating and cooling loads in buildings above ground. In a similar fashion, the NBSLD program had capabilities to calculate heating and cooling loads in basement rooms using various sub-routines that were derived from the MATEUS program and the RESPTK program. More specifically in the NBSLD program, the package sub-routine that consisted of the ABCD, ABCDP, ABCD-2, ABCDP-2, DERVT, GPF, MULT, RESF, RESFX and RESPTK sub-routines analyzed the transient heat conduction through multi-layered walls, roof or floor when the multi-layered building envelopes were located in underground or above ground. The package sub-routine that was based on the Conduction Transfer Functions (CTFs) method included the RESPTK sub-routine that was derived from the RESPTK program. Finally, the RMTMP sub-routine of the NBSLD program calculated heating and cooling loads in basement rooms using the Heat Balance method that was derived from the MATEUS program.

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The NBSLD program also had a simulation capability for evaluating accurate indoor thermal comfort, which was derived from the MATEUS program. For example, in the NBSLD program, the AIRCON sub-routine calculated the physiological indices for evaluating indoor thermal environment. The outputs of the AIRCON sub-routine included: ASHRAE's New Effective Temperature, Predicted Mean Vote (PMV), Heat Stress Index, KSU Index, Resultant Temperature, Operative Temperature and Index of Thermal Stress.

Finally, many of the algorithms and sub-routines of the NBSLD program were provided in the ASHRAE's third publication that discussed hourly heating and cooling loads calculation for building energy requirements (ASHRAE, 1975). Table 5.2 describes the sub-routines that were used in the NBSLD program and the shared characteristics between sub-routines of the NBSLD program and the ASHRAE TGER Committee's recommended heating and cooling loads calculation procedure that was published at 1975.

Table 5.2. *The sub-routines of the NBSLD program and shared characteristics with ASHRAE 1975*

Symbol of Sub-routine	Description of Sub-routine / Note	Shared Characteristics with ASHRAE 1975
WD, WDX, DECODE, ERROR, WEATHE	• Sub-routine to process the weather data tape 1440. • The weather data tape 1440 was provided by the National Climatic Center.	• Algorithms of these sub-routines in the NBSLD program were included in the ASHRAE 1975 as the CLIMAT sub-routine.
SUN	• Sub-routine to calculate basic sun data. • The basic sun data that was calculated by the SUN sub-routine included: the solar angles, cloud cover, direct and diffuse solar radiation and solar heating of the building exterior surfaces.	• The Algorithm of SUN sub-routine in the NBSLD program was included in the ASHRAE 1975 as the SUN sub-routine and the SOLAD sub-routine.
CCM	• Sub-routine to modify solar radiation for a cloudless sky by instantaneous cloud cover data.	• The Algorithm of CCM sub-routine in the NBSLD program was included in the ASHRAE 1975 as the CCF sub-routine.
TAR	• Sub-routine to calculate the transmission and absorption of glass.	• The Algorithm of TAR sub-routine in the NBSLD program was included in the ASHRAE 1975 as the TAR sub-routine.
SHG	• Sub-routine to calculate solar heat gain through glass.	• The Algorithm of SHG sub-routine in the NBSLD program was included in the ASHRAE 1975 as the SHG sub-routine.
GLASS	• Sub-routine to calculate solar heat gain through glass with given data: the shading coefficient, orientation and type of glass.	• The Algorithm of GLASS sub-routine in the NBSLD program was included in the ASHRAE 1975 as the SHG sub-routine.
FCTR	• Sub-routine to calculate radiation exchange factors between any interior surface.	• The Algorithm of FCTR sub-routine in the NBSLD program was included in the ASHRAE 1975 as the FIJ sub-routine.
F	• Sub-routine to calculate radiation heat exchange factors (i.e., form factors) between two adjacent interior surfaces.	• The Algorithm of F sub-routine in the NBSLD program was included in the ASHRAE 1975 as the FIJ sub-routine.
FO	• Sub-routine to calculate exterior surface heat transfer coefficients.	• The Algorithm of FO sub-routine in the NBSLD program was included in the ASHRAE 1975 as the FO sub-routine.

Table 5.2. *Continued*

Symbol of Sub-routine	Description of Sub-routine / Note	Shared Characteristics with ASHRAE 1975
ABCD, ABCDP, ABCD-2 ABCDP-2, DERVT, GPF, MULT, RESF, RESFX, RESPTK	• Sub-routines to calculate Conduction Transfer Functions (CTFs).	• Algorithms of these sub-routines in the NBSLD program were included in the ASHRAE 1975 as the XYZ sub-routine.
ATTIC	• Sub-routine to calculate temperature of attic space and heat conduction through the ceiling. • The ATTIC sub-routine analyzed the attic of two conditions, which included: vented attic and non-vented attic.	• The Algorithm of ATTIC sub-routine in the NBSLD program was included in the ASHRAE 1975 as the ATTIC sub-routine.
ROOM	• Sub-routine to identify all the data for heat transfer calculation within the room. • The types of data for room heat transfer calculation included: dimensions, surface area, surface orientations, shading coefficients, surface solar absorptivity, etc.	• The ROOM sub-routine in the NBSLD program was not included in the ASHRAE 1975.
RMTMP	• Sub-routine to calculate room temperature. • The components that were involved in the RMTMP sub-routine included: the heat balance of various heat gains, heat storage at surfaces in the room and cooling capacity of the air-conditioning unit.	• The Algorithm of RMTMP sub-routine in the NBSLD program was included in the ASHRAE 1975 as the RMTMP sub-routine.
SOLVP	• Sub-routine to solve simultaneous linear algebraic equations that derived from the RMTMP sub-routine.	• The Algorithm of SOLVP sub-routine in the NBSLD program was included in the ASHRAE 1975 as the RMTMP sub-routine.

Table 5.2. *Continued*

Symbol of Sub-routine	Description of Sub-routine / Note	Shared Characteristics with ASHRAE 1975
OUTSID	• Sub-routine to calculate exterior surface temperature and heat gain through walls or roof. • The components that were involved in the OUTSID sub-routine included: the heating from solar radiation, back radiation to the sky, convective heat loss to the outside air and transient heat conduction through walls or roof.	• The Algorithm of OUTSID sub-routine in the NBSLD program was included in the ASHRAE 1975 as the HEATW sub-routine.
AIRCON	• Sub-routine to calculate instantaneous values of the physiological indices for the space. • Physiological indices included ASHRAE's new effective temperature, Predicted Mean Vote (PMV), Heat stress index, KSU index, Resultant temperature, Operative temperature and Index of thermal stress.	• The AIRCON sub-routine in the NBSLD program was not included in the ASHRAE 1975.
DST	• Sub-routine to identify data of daylight saving time zone.	• The Algorithm of DST sub-routine in the NBSLD program was included in the ASHRAE 1975 as the DST sub-routine.
WKDAY	• Sub-routine to identify the day of week.	• The Algorithm of WKDAY sub-routine in the NBSLD program was included in the ASHRAE 1975 as the WKDAY sub-routine.
PSY-1	• Sub-routine to calculate the thermodynamic properties of moist air with given data: dry-bulb temperature, wet-bulb temperature and barometric pressures.	• The Algorithm of PSY-1 sub-routine in the NBSLD program was included in the ASHRAE 1975 as the PSY sub-routine.
PSY-2	• Sub-routine to calculate the thermodynamic properties of moist air with given data: dry-bulb temperature, dew point temperature and barometric pressures.	• The Algorithm of PSY-2 sub-routine in the NBSLD program was included in the ASHRAE 1975 as the PSY sub-routine.

Table 5.2. *Continued*

Symbol of Sub-routine	Description of Sub-routine / Note	Shared Characteristics with ASHRAE 1975
PVSF	• Sub-routine to calculate the saturated vapor pressure of atmospheric air. • The saturated vapor pressure of atmospheric air that was calculated by the PVSF sub-routine was a function of temperature.	• The Algorithm of PVSF sub-routine in the NBSLD program was included in the ASHRAE 1975 as the PSY sub-routine.
WBF	• Sub-routine to calculate wet-bulb temperature with given data: the enthalpy of moist air and barometric pressure.	• The Algorithm of WBF sub-routine in the NBSLD program was included in the ASHRAE 1975 as the PSY sub-routine.
HOLDAY	• Sub-routine to identify national holidays in the United States.	• The Algorithm of HOLDAY sub-routine in the NBSLD program was included in the ASHRAE 1975 as the HOLDAY sub-routine.
DPF	• Sub-routine to calculate dew point temperature of atmospheric air. • The DPF sub-routine calculated dew point temperature when the information about partial vapor pressure was given.	• The Algorithm of DPF sub-routine in the NBSLD program was included in the ASHRAE 1975 as the PSY sub-routine.

5.2.2 Simulation Programs by the General American Research Division/General American Transportation Corporation (GARD/GATC)

In this section, a detailed analysis of three-computer programs that were developed by the General American Research Division/General American Transportation Corporation (GARD/GATC) is analyzed by reviewing the published documents (i.e., user and engineering manuals or equivalent documents). The early computer programs from the GARD/GATC included: the SHelter Environmental Prediction (SHEP) program, the Thermo-dynamic Analysis Computer System (TACS) program and the Post Office program.

5.2.2.1 SHelter Environmental Prediction (SHEP) Program

In this section, the SHelter Environmental Prediction (SHEP) program is analyzed by studying the user's manual of the SHEP program (GARD/GATC, 1968). The SHEP program evaluated the adequacy of the shelter thermal environments for occupants. In the SHEP program, the fallout shelter's indoor air conditions were represented by two variables: the dry-bulb air temperature and the relative humidity. Because the SHEP program assumed that the shelter indoor air was instantaneously and completely mixed, each value of the shelter's indoor air conditions (i.e., dry-bulb temperature and relative humidity) was represented by one psychrometric air condition. Important factors that affected the shelter's indoor air conditions included: the characteristics of outside air (i.e., ambient temperature and relative humidity); occupancy; ventilation rates; and auxiliary loads (i.e., internal heat generations by lighting and equipment). In the SHEP program, all values of these factors were evaluated at each hourly time increment. Based on the determination of dry-bulb temperature, the SHEP program calculated the wet-bulb temperature by using the Carrier equation, and then the effective temperature was calculated by using of the dry-bulb temperature and wet-bulb temperature.

The SHEP program allowed up to twenty-different characteristics of the shelter's boundary conditions for the simulation of a shelter. The characteristics of shelter's boundary represented two-parameters: the media that was adjacent to the shelter structure (i.e., ambient air, soil, etc.) and the materials of shelter's envelope (i.e., cement, glass, metal, etc.). In addition, the SHEP program provided the analysis of the plane and curved-plane (i.e., curvilinear) envelopes of the shelter. Each shelter envelope represented up to five-layers, and each layer had specific thermal characteristics, respectively.

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For the analysis of the heat transfer within the exterior media, the MATEUS program and the SHEP program used similar methods. The MATEUS program used a three-dimensional finite difference network matrix for the analysis of heat transfer within the exterior media (i.e., the earth). On the other hand, the SHEP program used a one-dimensional finite difference network matrix for the analysis of heat transfer within the exterior media (i.e., ambient air, soil). To analyze the transient heat transfer within the exterior media, the SHEP program assumed that each exterior media was represented by a specific layer, such as the layer within the shelter's envelope. For example, in the SHEP program, the soil that surrounded the shelter's envelopes was represented by a ten feet thick layer because the actual shelter test proved that the soil temperatures ten feet from the shelter were constant (GARD/GATC, 1968). For the analysis of the heat transfer through the shelter's envelope, the MATEUS program and the SHEP program both used the same methods. The MATEUS program used the one-dimensional finite difference network matrix for the analysis of the heat transfer through the shelter's envelopes (i.e., shelter's walls, ceiling and floor). The SHEP program also used the one-dimensional network matrix for the analysis of heat transfer through the shelter's envelopes, which was based on the Finite Difference method.

In the SHEP program, two conditions of the shelter's boundary (i.e., the shelter's envelope) were assumed: an adiabatic boundary condition and a non-adiabatic boundary condition. The adiabatic boundary condition was assumed if the outside weather condition was severe hot weather. For the adiabatic boundary condition, the SHEP program assumed that the heat transfer through the shelter's envelopes didn't occur. On the other hand, for the non-adiabatic boundary condition, the SHEP program analyzed the heat conduction through the

shelter's envelope by using the temperature of each inner surface. To determine the temperature

of each inner boundary surface, the temperature profile within the shelter's envelope was

calculated by using the Finite Difference method.

For the application of the Finite Difference method to the analysis of the transient heat

conduction through the multi-layered walls, roof or floor, each layer was divided into a nodal

point span (i.e., slab thickness, Δx_i) (see Figure 5.6). The nodal point span was determined by the

conductivity of construction material. The nodal point span varied inversely with the material's

conductivity. The nodal points within the shelter's envelopes represented the temperature

distribution within the shelter's envelopes and resulted in the temperature profile within the

shelter's envelopes. Each shelter envelope (i.e., shelter's walls, ceiling, and floor) represented by
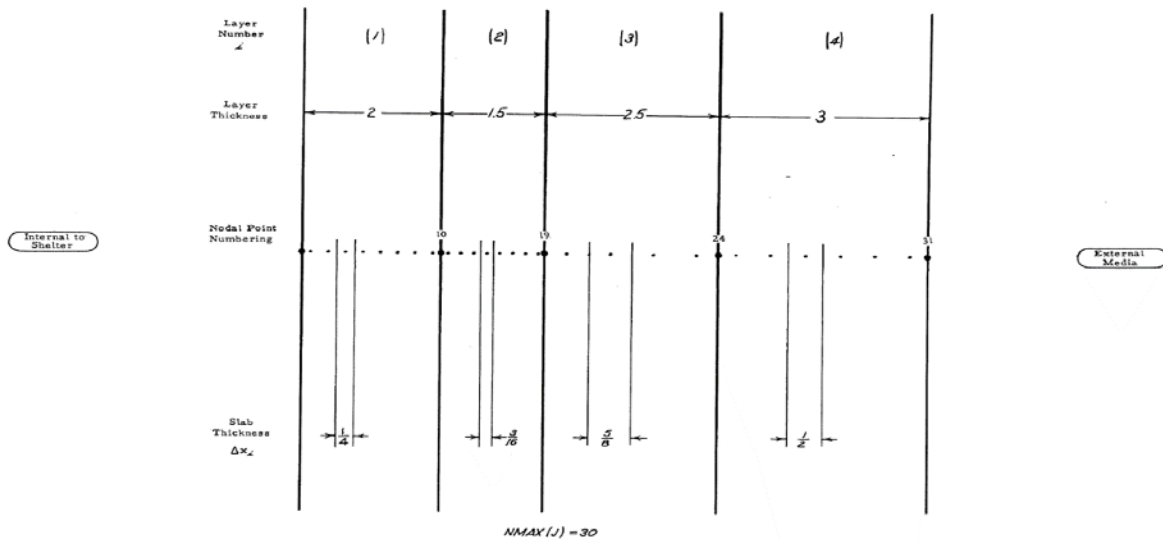
up to forty-nodal points.

Figure 5.6. Typical nodal point arrangement in a four-layered boundary (GARD/GATC, 1968; Reprinted with permission)

In the SHEP program, the temperature at each nodal point was calculated by solving the heat balance equation for the conditions at that node. The various types of the heat transfer that were involved in the calculation of heat balances were depended on node positions. The node positions included: the node at the interior surface, the node within the layer, the node at the interface between different layers and the node at the exterior surface (see Figure 5.7).
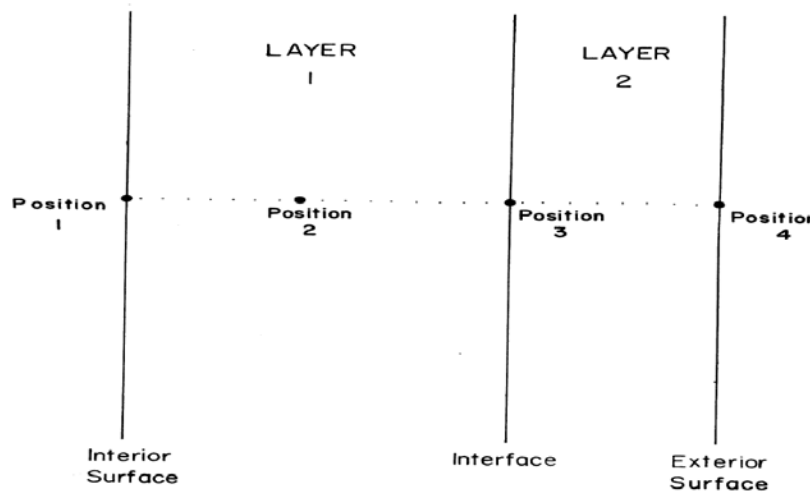
Figure 5.7. Various position of nodal points within shelter's envelope (GARD/GATC, 1968; Reprinted with permission)

For the analysis of the node at the interior surface of the shelter, the convective heat transfer of the inside shelter air and conductive heat transfer by the adjacent slab within the layer were involved in the calculation. For the analysis of the node within the layer, the conductive heat transfer that moved heat into or out of the slab was involved in the calculation. For the analysis of the node at the interface between different layers, the heat transfer by the conduction that moved into or out the layers was assumed. For the analysis of the node at the exterior surface, the types of the heat transfer that were involved in depended on the exterior media (i.e.,

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ambient air, soil, etc.), which was adjacent to the exterior surfaces of the shelter. If the exterior

media was the ambient air, the convective heat transfer with the ambient air and the heat flux by

the solar radiation were involved in the calculation. On the other hand, if the exterior media was

only the soil, conductive heat transfer was involved in the calculation.

The Nodal Point method allows the implicit representation of the temperature within the

shelter's envelopes because the calculation of the temperature is based on the energy balance at

each nodal point. Using this method, the temperature profile within the shelter's envelopes was

determined by solving the simultaneous linear equations. Because each part of the shelter's

envelope (i.e., the shelter's walls, ceiling, and floor) consisted of multi-layers, coefficients of

nodal points were evaluated respectively for multi-layers. The coefficients of nodal points

included the coefficients of the temperatures at each node (i.e., A) and the terms that reflected the

effect of heat storage (i.e., B). In the matrix form, the simultaneous linear equations represented

by:

$$[A] [T] = [B] \tag{5.12}$$

Where,

A = coefficients of the temperatures at each node,

T = temperature at each node, and

B = terms that reflected the effect of heat storage.

After all coefficients were evaluated, the simultaneous linear equations were solved by

using the Gauss-Jordan method of matrix inversion. Therefore, the matrix form converts to:

$$[T] = [A]^{-1} [B] \qquad\qquad (5.13)$$

Where,

A = coefficients of the temperatures at each node,

T = temperature at each node, and

B = terms that reflected the effect of heat storage.

If the shelter's envelope was exposed to the ambient air, the solar radiation that was incident on the exterior surfaces of the shelter included: the direct solar radiation, the diffuse solar radiation and the reflected solar radiation. However, the SHEP program assumed that the effects of all reflected solar radiation were neglected. In addition, two more assumptions were employed for the analysis of effects of the solar radiation if the shelter was exposed to the ambient air. First, the solar radiation that was incident on exterior surfaces of the shelter was partially absorbed by the shelter's envelopes. The SHEP program assumed that the absorption of the incident solar radiation occurred at the exterior surface of the shelter. Second, the transmitted solar radiation was evaluated as an instantaneous room cooling load, such as heat generations from the lighting and equipment. When the SHEP program analyzed the transmittance of the incident solar radiation, the value of the total transmittance was used although the actual value of the transmittance varied with the wavelength of the incident solar radiation.

In the SHEP program, all effects of the incident solar radiation were analyzed on the basis of the solar time, which is a slightly different term from the standard time (i.e., civil time). The SHEP program determined the value of the solar time on the basis of the occupancy

schedule and the shelter's longitude. The intensity of the solar radiation that was incident on

exterior surfaces of the shelter was calculated in each time step. The intensity of the incident

solar radiation was calculated by summing values of the intensity of the direct solar radiation and

the diffuse solar radiation. Because the SHEP program assumed that all effects of the reflected

solar radiation were neglected, the intensity of the reflected solar radiation was not included in

the calculation of the total intensity of incident solar radiation. Before calculating the solar

radiation intensity, values of several parameters were determined, which included: the sun's

altitude angle, sun's azimuth angles, solar declination angle, time angle, angle of exterior surface

of the shelter to sun's rays, sunrise values of hour angle and sunset values of hour angle.

For the analysis of the effect of the moisture condensation that resulted in heat energy

removal from the shelter thermal environment and the effect of the moisture evaporation that

resulted in the heat energy input to the shelter thermal environment, the SHEP program assumed

effects of the moisture condensation and the moisture evaporation occurred at an even film on

interior surfaces of the shelter. To determine whether the effect of the moisture condensation or

the moisture evaporation occurred at interior surfaces of the shelter, the vapor pressure (i.e.,

saturation pressure of water vapor) at interior surfaces of the shelter was calculated by using the

dry-bulb temperature at interior surfaces of the shelter. The specific range of the dry-bulb

temperatures from the 50°F to 120°F was assumed for the determination of the effect of the

moisture condensation or evaporation because thermal relation with occupants was defined from

the 50°F to 120°F. To calculate the amount of heat energy transfer by effects of the moisture

condensation and evaporation, Jakob's method (1949) was used in the SHEP program, which

discussed the phenomenon of mass and heat energy transfer. The amount of heat energy transfer

by the effect of the moisture condensation was represented by:

$$Q_{condensation} = 2.825 \; \frac{\lambda h}{\rho_a} \; (\frac{p_o}{p_b - p_o} \; - \; \frac{p_s}{p_b - p_s})$$ (5.14)

Where,

$Q_{condensation}$ = amount of energy transfer due to moisture condensation,

λ = heat of condensation,

h = film heat transfer coefficient,

ρ_a = density of dry air,

p_o = partial pressure of water vapor at shelter temperature,

p_b = barometric pressure, and

p_s = partial pressure of water vapor at wall temperature.

Because the effect of the moisture condensation was assumed as the exact opposite

effect of the moisture evaporation (i.e., equivalent amount of energy and mass transfer in

moisture condensation and evaporation), the equation of the moisture condensation was also

used in the calculation of the moisture evaporation. The effects of the moisture condensation and

the moisture evaporation that occurred at interior surfaces of the shelter were involved in the

evaluation of the shelter thermal environment.

In the SHEP program, the metabolic calculations developed by Houghten (1929) were

used for the analysis of the sensible and latent metabolic loads in the shelter thermal

environment. Houghten's method reflected the effect of the relative humidity for the calculation of metabolic loads in the shelter thermal environment. The equations were given by:

$$Q_{sensible} = -0.06875 \ (T_{db})^2 + 1.625 \ (T_{db}) + 523 \qquad \text{for } T_{db} \geq 50°F \qquad (5.15)$$

$$Q_{total} = -1.482 \ (ET) + 514 \qquad \text{for } 50°F \leq ET \leq 87°F \qquad (5.16)$$

$$= -1.508 \ (ET)^2 + 259.7 \ (ET) - 10795.2 \qquad \text{for } 87°F < ET \leq 102°F \qquad (5.17)$$

$$= 0.0 \ (\text{assumed}) \qquad \text{for } ET > 102°F \qquad (5.18)$$

Where,

$Q_{sensible}$ = amount of sensible heat due to occupants,

Q_{total} = amount of total heat due to occupants,

T_{db} = shelter dry-bulb temperature, and

ET = effective temperature.

To calculate the latent metabolic load in the shelter thermal environment, the relation between the sensible heat and the latent heat was assumed by:

$$Q_{latent} = Q_{total} - Q_{sensible} \qquad (5.19)$$

Where,

Q_{latent} = amount of latent heat due to occupants,

Q_{total} = amount of total heat due to occupants, and

$Q_{sensible}$ = amount of sensible heat due to occupants.

For the analysis of the heat generation by occupants, the SHEP program assumed that the thermal status of occupants' body was equal to the shelter thermal environment (i.e., thermal equilibrium). Therefore, the effect of the heat storage in occupants was neglected in the SHEP program. In the SHEP program, internal heat generations by the lighting and equipment were evaluated as the auxiliary load. To include internal heat generations due to the lighting and equipment as instantaneous heating and cooling loads within the room system, the SHEP program required user to specify the lighting and equipment loads at each hourly time increment as the program's input variable.

For the prediction of the adequacy of shelter thermal environment, the summer season was main concern for the Office of Civil Defense (OCD) because the adequacy of the shelter thermal environment for occupants was critical issue especially in the summers (Kusuda, 2001). Therefore, the SHEP program primarily focused on the analysis of the cooling load that was imposed on the air-conditioning system. For the analysis of the cooling performance of the air-conditioning system (i.e., capabilities of cooling and dehumidifying the shelter air), the coil condition was the key parameter in the SHEP program. Therefore, the SHEP program required users with the specification of the coil, which included: the coil bypass factor, the effective coil surface temperature and the air flow rate through the coil.

To analyze the cooling load that was imposed on the air-conditioning system, the SHEP program used a simplified specification for the coil. First, the temperature of the coils did not depend on the cooling load in the shelter. When the SHEP program calculated the air-conditioning load, the temperature of coils was constant because the design value of temperature of coils (i.e., the effective coil surface temperature) was used. Second, the percentage of air that

didn't pass through cooling coils (i.e., the coil bypass factor) was also constant. Therefore, the design value of the percentage of air was used for the calculation of the air-conditioning load. Because the SHEP program assumed that the performance of coils was a function of the design of the entire air-conditioning system, the characteristics of load dependence with the coil bypass factor and the effective coil surface temperature was neglected.

To evaluate the shelter thermal environment, the SHEP program analyzed the inlet air condition that was supplied to the shelter space. The SHEP program required users to specify three characteristics of the ventilation rates: the ventilation rate of ambient air that entered the air-conditioning system, the ventilation rate of air that passed through the air-conditioning system and the ventilation rate of air that supplied to inside shelter.

5.2.2.2 Thermo-dynamic Analysis Computer System (TACS) Program

In this section, the TACS program is analyzed by studying two articles: "*TACS – A New Approach to System Design*" (Milnark, 1968) and "*TACS – Computer Workhorse for Sale*" (Milnark, 1969). Although program manuals for the TACS program could not be located for this study, these two articles provided the information about the TACS program.

The TACS program was constructed using the FORTRAN IV language and was compatible with IBM, CDC, UNIVAC and Honeywell computers. The TACS program evaluated heating and cooling loads in postal buildings as well as the most economic combination among various fuels (i.e., oil, gas and electricity) and the HVAC equipment performance.   For the analysis of heating and cooling loads in a postal building, the TACS program used the new heating and cooling loads calculation procedure (i.e., Response Factor method and Weighting

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Factor method) that was based on transient conditions. The TACS program calculated more accurate transient values of heating and cooling loads for each time increment under dynamic thermal conditions. At that time, heating and cooling loads in postal buildings often varied with the amount of the mail load that suddenly came in and out through the loading docks, which could be at different temperatures depending on the season and how long the mail sat in a hot truck (Milnark, 1968). Therefore, the new heating and cooling loads calculation procedure that took into account the transient thermal conditions of all loads in the postal building was more suitable for the evaluation of postal buildings.

Based on the data from the dynamic heating and cooling loads, weather conditions and building information, the TACS program performed the HVAC system simulation. To simulate the HVAC system in postal buildings, the TACS program incorporated HVAC systems performance (i.e., compressors, condensers, chillers, pumps, etc.) as well as the control strategies for each hour, which were read on the computer tapes (Milnark, 1968).

The TACS program was a modular program that consisted of sub-programs (i.e., LOADS, SYSTEMS, and ECONOMICS sub-programs) and sub-systems. In order to run the program, users were required to modify the sequence of simulation for the purpose of their simulation. In addition, the TACS program was capable of analyzing other types of buildings other than postal buildings with minor modifications to the computer program, although the purpose of the TACS program was for the analysis of postal buildings (Milnark, 1969).

5.2.2.3 Post Office Program

The Post Office program analyzed the dynamic thermal properties in postal buildings and conducted an HVAC systems simulation and economic analysis. By using the Post Office program, users determined the most economical combinations among various HVAC systems and energy sources (i.e., gas, oil, coal, steam, and electricity) for postal buildings.

Unlike the MATEUS program and the SHEP program, which were constructed using one long continuous algorithm, the Post Office program was constructed using seven sub-programs: the LOADS calculation sub-program, the PUNCH sub-program, the thermal loads PLOT sub-program, the LOADS EDITING sub-program, the SYSTEMS simulation sub-program, the PACKAGED SYSTEMS simulation sub-program and ECONOMICS analysis sub-program. Each sub-program consisted of a number of sub-routines that included the algorithmic equations. For example, specific output values of some of the sub-programs became specific input values of subsequent sub-programs.

Among these seven sub-programs, the major sub-programs included: the LOADS calculation sub-program, the thermal loads PLOT sub-program, the SYSTEMS simulation sub-program and ECONOMICS analysis sub-program. The PUNCH sub-program and the LOADS EDITING sub-program were used together with the thermal loads PLOT sub-program. Each sub-program ran specific sub-routines. The execution of each sub-program was depended on the purpose of simulation as well as the information about the postal building. For example, if the program user directly divided the postal building into fan zones, the thermal loads PLOT sub-program was not used because the purpose of the thermal loads PLOT sub-program was for the

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determination of fan zones in the postal building. By running the required sub-programs, the Post Office program evaluated heating and cooling loads in the postal building, the performance of HVAC systems, the energy requirements for the postal building and the total cost for the postal facility.

The LOADS calculation sub-program was the one of main sub-programs in the Post Office program. The LOADS calculation sub-program calculated the transient hourly heating and cooling loads for each space in the postal building. For the LOADS calculation sub-program, the postal building information (i.e., structure, surroundings, environment, etc.) as well as the climate condition (i.e., local weather, solar geometry, etc.) were required as input variables. Based on these input variables, the LOADS calculation sub-program calculated the hourly sensible and latent thermal loads in the postal building, the hourly weather condition, the hourly psychrometric condition and the power consumption of the equipment as outputs of the LOADS calculation sub-program. The LOADS calculation sub-program was constructed on the basis of the ASHRAE TGER publications: "*Procedure for determining heating and cooling loads for computerized energy calculation – Algorithms for building heat transfer subroutines*" (ASHRAE. 1971), which was edited by Dr. Metin Lokmanhekim at the GARD/GATC (GARD/GATC, 1971a).

For the analysis of the transient heat conduction through multi-layered walls or roofs, the LOADS calculation sub-program first calculates the values of the response factors by using the response factor package sub-routine, which includes: the RESFAC, DER, FALSE, MATRIX, SLOPE and ZERO sub-routines. Based on the calculated values of the response factors, the LOADS calculation sub-program analyzed the transient heat conduction through multi-layered

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walls or roof by using the HD sub-routine. For the analysis of heating and cooling loads in the postal building, the LOADS calculation sub-program calculated values of weighting factors by using the weighting factor package sub-routine, which included: the RMRSS, RMRG, RMRL, RMRLP and RMRX sub-routines (see Figure 5.8). Table 5.3 describes the sub-routines that were used in the Post Office program and the shared characteristics between LOADS calculation sub-routines of the Post Office program and the ASHRAE TGER Committee's recommended heating and cooling loads calculation procedure that was published at 1971.

The twenty-nine sub-routines in the LOADS calculation sub-program analyzed the transient heat conduction through multi-layered walls or roofs and the hourly heating and cooling loads in a postal building. These sub-routines were divided in two categories: a main program and several smaller programs. The main program handled the input data, determined the sequence of sub-routines, and wrote the output of the LOADS calculation sub-program. On the other hand, the other programs in the LOADS calculation sub-program conducted the engineering calculations to determine hourly heating and cooling loads that were imposed on the air-conditioning system by each space at each time increment.

Table 5.3. *The subroutines of the Post Office program and shared characteristics with ASHRAE 1971*

Symbol of Subroutine	Description of Subroutine	Shared Characteristics with ASHRAE 1971
WEATHER	• Subroutine to decode weather tape.	• The Algorithm of WEATHER subroutine in the Post Office program was included in the ASHRAE 1971 as the CLIMATE subroutine.
SUN-1	• Subroutine to calculate daily data on solar radiation.	• The Algorithm of SUN-1 subroutine in the Post Office program was included in the ASHRAE 1971 as the SUN subroutine.
SUN-2	• Subroutine to calculate hourly data on solar radiation.	• The Algorithm of SUN-2 subroutine in the Post Office program was included in the ASHRAE 1971 as the SUN subroutine.
SUN-3	• Subroutine to calculate solar data that depended on orientation of a surface.	• The Algorithm of SUN-3 subroutine in the Post Office program was included in the ASHRAE 1971 as the SUN subroutine.
CCM	• Subroutine to calculate cloud cover modifier.	• The Algorithm of CCM subroutine in the Post Office program was included in the ASHRAE 1971 as the CCM subroutine.
RECTANG	• Subroutine to calculate vertex coordinates of a rectangular surface.	• The RECTANG subroutine in the Post Office program was not included in the ASHRAE 1971.
APOL	• Subroutine to calculate area and orientation of an irregular surface.	• The APOL subroutine in the Post Office program was not included in the ASHRAE 1971.
SHADOW, MATCON	• Subroutine to calculate shadow shapes and areas.	• The Algorithms of SHADOW and MATCON subroutines in the Post Office program were included in the ASHRAE 1971 as the SHADOW subroutine.
SEARCH	• Subroutine to limit shadow pictures to certain times and certain surfaces.	• The SEARCH subroutine in the Post Office program was not included in the ASHRAE 1971.

Table 5.3. *Continued*

Symbol of Subroutine	Description of Subroutine	Shared Characteristics with ASHRAE 1971
SHG	• Subroutine to calculate heat gain through windows.	• The Algorithm of SHG subroutine in the Post Office program was included in the ASHRAE 1971 as the SHG subroutine.
TAR	• Subroutine to calculate glass absorption and transmission factors.	• The Algorithm of TAR subroutine in the Post Office program was included in the ASHRAE 1971 as the TAR subroutine.
FILM	• Subroutine to calculate outside heat transfer film coefficient.	• The Algorithm of FILM subroutine in the Post Office program was included in the ASHRAE 1971 as the FO subroutine.
HQ	• Subroutine to calculate heat gain through quickly responding surfaces (quick surfaces).	• The Algorithm of HQ subroutine in the Post Office program was included in the ASHRAE 1971 as the IHG subroutine.
HD	• Subroutine to calculate heat gain through slowly responding surfaces (delayed surfaces).	• The Algorithm of HD subroutine in the Post Office program was included in the ASHRAE 1971 as the HEATW subroutine.
WALLS, BRICK, CONCR, PINE, STUCO	• Subroutine to determine thermal and physical properties of a selected wall construction.	• The package subroutine for selecting a standard ASHRAE wall in the Post Office program was not included in the ASHRAE 1971.
ROOFS, MSNRY, PITCH, WOOD	• Subroutine to determine thermal and physical properties of a selected roof construction.	• The package subroutine for selecting a standard ASHRAE roof in the Post Office program was not included in the ASHRAE 1971.
RESFAC, DER, FALSE, MATRIX, SLOPE, ZERO	• Subroutine to calculate response factors for walls and roofs.	• The Algorithms of package subroutine for the calculation of response factors in the Post Office program was included in the ASHRAE 1971 as the XYZ subroutine.

Table 5.3. *Continued*

Symbol of Subroutine	Description of Subroutine	Shared Characteristics with ASHRAE 1971
RMRSS, RMRG, RMRL, RMRLP, RMRX	• Subroutine to calculate room hourly weighting factors.	• The Algorithms of package subroutine for the calculation of weighting factors in the Post Office program was included in the ASHRAE 1971 as the RMRT subroutine.
HL	• Subroutine to calculate sensible and plenum return air heating and cooling loads due to a space.	• The HL subroutine in the Post Office program was not included in the ASHRAE 1971.
INF	• Subroutine to calculate infiltration air loads due to a space.	• The Algorithm of INF subroutine in the Post Office program was included in the ASHRAE 1971 as the INFIL subroutine.
SCHED	• Subroutine to determine lighting, people and equipment schedules.	• The Algorithm of SCHED subroutine in the Post Office program was included in the ASHRAE 1971 as the SCHEDULE subroutine.
PSY, PPWVMS	• Subroutine to calculate psychrometric data.	• The Algorithms of PSY and PPWVMS subroutines in the Post Office program were included in the ASHRAE 1971 as the PSY subroutine.
NDOW	• Subroutine to determine day of week.	• The Algorithm of NDOW subroutine in the Post Office program was included in the ASHRAE 1971 as the WKDAY subroutine.
DAYMO	• Subroutine to determine the day of month.	• The DAYMO subroutine in the Post Office program was not included in the ASHRAE 1971.
HOLDAY	• Subroutine to determine holiday.	• The Algorithm of HOLDAY subroutine in the Post Office program was included in the ASHRAE 1971 as the HOLIDAY subroutine.
LEEP	• Subroutine to determine whether the year is a leap-year.	• The LEEP subroutine in the Post Office program was not included in the ASHRAE 1971.

Table 5.3. *Continued*

| Symbol of Subroutine	Description of Subroutine	Shared Characteristics with ASHRAE 1971
DST	• Subroutine to determine daylight saving time.	• The Algorithm of DST subroutine in the Post Office program was included in the ASHRAE 1971 as the DST subroutine.
TABMAK	• Subroutine to tabulate output.	• The TABMAK subroutine in the Post Office program was not included in the ASHRAE 1971.
CENTER	• Subroutine to center the headings of output.	• The CENTER subroutine in the Post Office program was not included in the ASHRAE 1971.
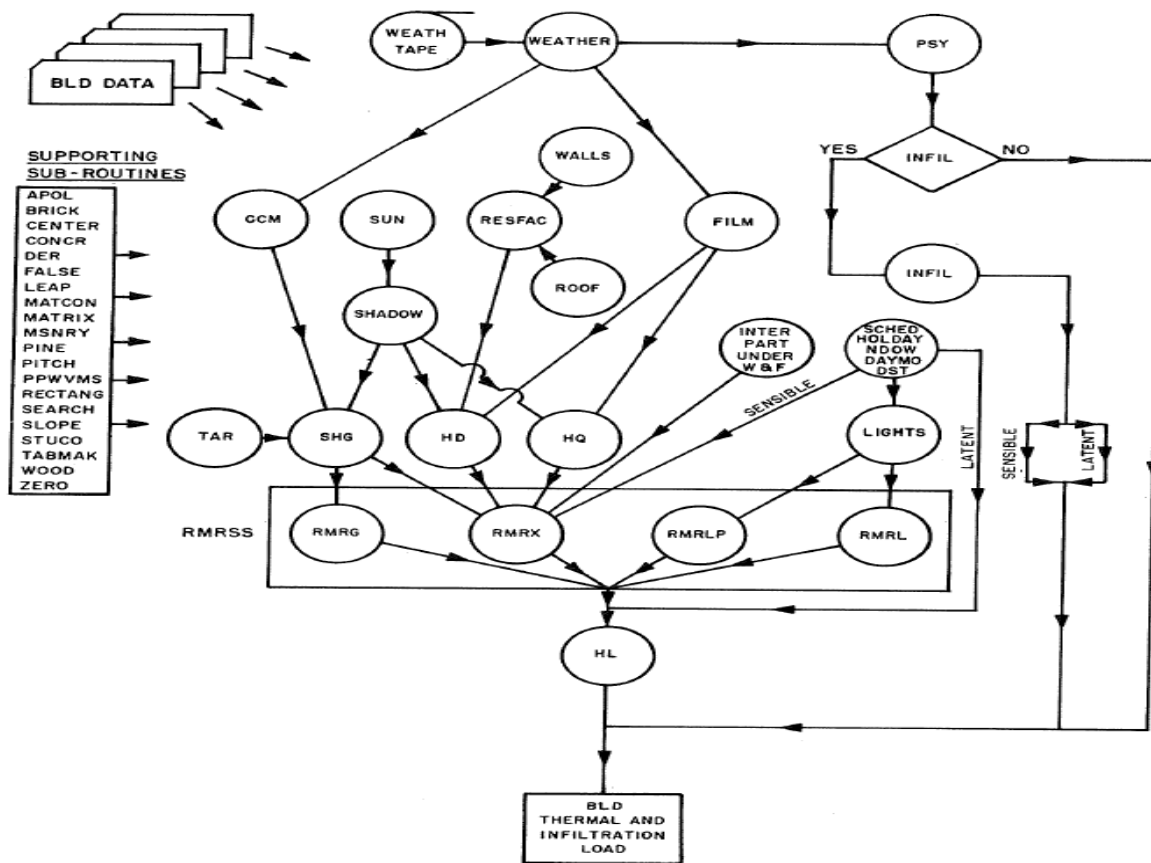
Figure 5.8. Interrelationship of load calculation sub-program sub-routines. Reprinted from U.S. Postal Service Symposium: Computer Program for Analysis of Energy Utilization 1971.

To calculate heating and cooling loads in each space, the Post Office program used the Response Factor method and the Weighting Factor method, which were developed by Mitalas and Stephenson of the National Research Council (NRC) of Canada at 1967. In the Post Office program, the Response Factor method was used for the analysis of the transient heat transfer through multi-layered walls, roofs or floors and the Weighting Factor method was used for the analysis of the heating and cooling loads in each thermal zone. In the shelter simulation programs (i.e., MATEUS program and SHEP program), the Finite Difference method with the one-dimensional network matrix was used for the analysis of the transient heat transfer through shelter's envelopes (i.e., shelter's walls, roofs or floors) instead of using the Response Factor method. In addition, the MATEUS program and the SHEP program used the Heat Balance method for the analysis of the thermal environment in the shelter instead of using the Weighting Factor method.

The MATEUS program and the SHEP program analyzed the heat exchange phenomena within the shelter, which included: interior surfaces, the shelter indoor air and internal sources of the heat generation (i.e., occupants, equipment and lighting). To evaluate the thermal environment in the underground shelter, the MATEUS program and the SHEP program solved the overall heat balance equations that included all the heat exchange within the shelter. On the other hand, the Post Office program used the Weighting Factor method that simplified calculation procedures of many heat balance equations by using pre-calculated values of weighting factors. Using the Response Factor method and the Weighting Factor method, the Post Office program analyzed the dynamic heat transfer phenomena as well as hourly heating and cooling loads in postal buildings in relatively short computation time.

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To analyze the transient heat conduction through multi-layered walls, roof and floor in postal buildings, the Post Office program provided three ways for the calculation of response factors. First, users directly specified values of response factors. Second, users provided physical and thermal properties of multi-layered walls, roof and floor (i.e., thickness of each layer, conductivity, specific heat, etc.), and the Post Office program calculated the values of response factors on the basis of the physical and thermal data. Third, users provided the simplified data (i.e., U-factor, climate conditions and physical properties of multi-layered walls, roof and floor) and the Post Office program calculated approximate values of the response factors.

The thermal loads PLOT sub-program was also one of main sub-programs in the Post Office program. The thermal loads PLOT sub-program was an offline program that graphically plotted the load profile for any space in the postal building for any length of time (i.e., day, week, month or year). Before the Post Office program performed the SYSTEMS simulation sub-program, the Post Office program requested that users to classify similar spaces into fan zones. If users did not have the sufficient building information to directly classify compatible spaces into fan zones, the users operated the thermal loads PLOT sub-program to get the load profile plots for each space and classified spaces into fan zones[1] by comparing load profile plots. For the thermal loads PLOT sub-program, the PUNCH sub-program and the LOAD EDITING sub-program were used as auxiliary sub-programs. The PUNCH sub-program provided punched input cards that were used for the thermal loads PLOT sub-program. To prepare punched input

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[1] The definition of a fan zone in the Post Office program was a group of spaces that were controlled by one thermostat (USPS, 1971).

cards, the PUNCH sub-program analyzed outputs of the LOAD calculation sub-program. The

LOAD EDITING sub-program was used when spaces or fan zones were grouped again.

The SYSTEMS simulation sub-program was the one of main sub-programs in the Post

Office program. The SYSTEMS simulation sub-program mainly conducted three tasks. First, the

SYSTEMS simulation sub-program determined the capacities of the secondary HVAC system

(i.e., thermal distribution systems) as well as the primary HVAC system (i.e., chillers, boilers,

cooling towers, etc.) on the basis of peak heating and cooling zone loads and peak heating and

cooling loads in the postal building. Second, for the hourly analysis of postal building energy

requirements, the SYSTEMS simulation sub-program converted the hourly heating and cooling

space loads in the postal building into hourly thermal requirements that were imposed on the

primary HVAC system (i.e., chillers and boilers). To determine hourly thermal requirements that

were imposed on the primary HVAC system, the performance of the secondary HVAC system

(i.e., thermal distribution systems) was evaluated. Lastly, the SYSTEMS simulation sub-program

converted the hourly thermal requirements that were imposed on the primary HVAC system into

the energy requirements in the postal building. To determine energy requirements in the postal

building, the part-load performance as well as the performance characteristics of the primary

HVAC system were evaluated.

The SYSTEMS simulation sub-program consisted of fifteen sub-routines. Among the

fifteen sub-routines, three sub-routines performed the major parts of the SYSTEMS simulation

sub-program, which included: the SYSIM sub-routine, the HTCON sub-routine, the EQUIP sub-

routine, and the ENGYC sub-routine (see Figure 5.9). The SYSIM sub-routine controlled the

sequence of the SYSTEMS simulation sub-program and evaluated air flow quantities for each

fan zone, capacities of heating and cooling plants as well as on-site generation plants, and

performances of fan systems. The HTCON sub-routine evaluated the performance of heat

conservation system. The heat conservation system were refrigeration machines that included

double-bundled condensers. During the summer, the heat conservation system cooled the interior

air in the postal building as the conventional refrigeration system. During the winter, however,

the heat conservation system heated the interior air in the postal building as the heat pump. The

EQUIP sub-routine determined the actual energy requirements (i.e., gas, oil, steam, electricity,

and diesel fuel) that were imposed on heating and cooling plants, the on-site generation plant and

heat conservation systems. The ENGYC sub-routine prepared the summary of monthly energy
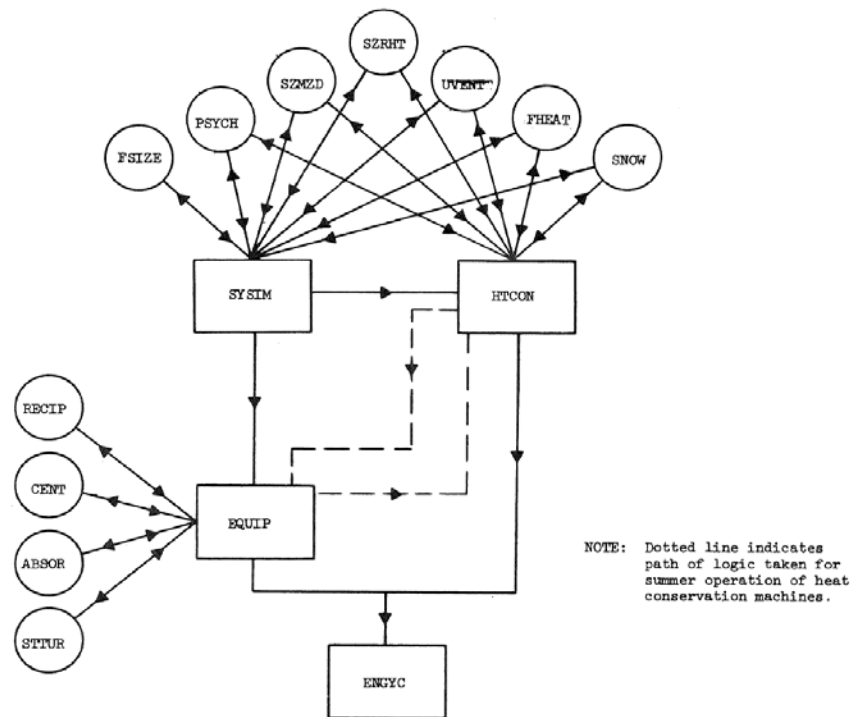
consumptions and demands.

Figure 5.9. Interrelationship of systems simulation sub-program sub-routines. Reprinted from
U.S. Postal Service Symposium: Computer Program for Analysis of Energy Utilization 1971.

The SYSTEMS simulation sub-program consisted of two sub-programs: the central

system simulation sub-program (i.e., SYSTEMS simulation sub-program) and the PACKAGED

SYSTEMS simulation subprogram. The central system simulation sub-program was used for the

large postal buildings (i.e., floor areas of the postal building larger than 35,000 ft^2), and the

PACKAGED SYSTEMS simulation sub-program was used for the small postal building (i.e.,

floor areas of the postal building smaller than 35,000 ft^2).

The central system simulation sub-program simulated seven-types of thermal

distribution systems for the postal building, which included: the single-zone system, the multi-

zone system, the dual duct system, the unit ventilator, the unit heater, the single-zone reheat

system and the radiant floor panel heating. To simulate these thermal distribution systems, the

Post Office program used control schedules for these thermal distribution systems that complied

with specifications of the U.S. Postal Service. Based on the simulation of these thermal

distribution systems with their control analysis, the central system simulation sub-program

evaluated the hourly heating and cooling requirements that were imposed on heating and cooling

plants. The available heating and cooling plants within the central system simulation sub-

program included: the conventional systems, total electric systems, total gas systems, total oil

systems and on-site generation systems.

The PACKAGED SYSTEMS simulation sub-program simulated packaged (i.e., unitary)

heating and cooling systems in the small postal building, which included: packaged air-

conditioning units (i.e., electric air-conditioning and gas air-conditioning) and a reversible cycle

heat pump unit. To determine the hourly energy consumption for the packaged units, the

characteristics of control systems as well as the part-load performance of packaged heating and

cooling systems were evaluated in the PACKAGED SYSTEMS simulation sub-program. Unlike the large post office building that used fan systems or heating and cooling plants, small post office buildings used packaged heating and cooling systems, and each packaged heating and cooling systems only served each space in the postal building. Therefore, for the simulation of small post office building that used packaged heating and cooling systems, the thermal loads PLOT sub-program didn't reflect the output of LOAD calculation sub-program because the Post Office program didn't require it to determine the fan-zone.

The ECONOMICS analysis sub-program was also one of the main sub-programs in the Post Office program. The ECONOMICS analysis sub-program evaluated the total owning and operating costs on the basis of life cycle costs that included the cost of energy, cost of equipment, cost of maintenance, cost of periodic overhaul, cost of floor space and salvage value of equipment. By using the ECONOMICS analysis sub-program, users determined the most economical combination among various building equipment (i.e., cooling equipment, heating equipment, air side equipment, steam turbines and on-site generation engines).

5.2.3 Simulation Programs by the National Research Council (NRC) of Canada

In this section, two computer programs that were developed by the National Research Council (NRC) of Canada are analyzed, which include: the FORTRAN IV program to calculate heat flux response factors for a multi-layer slab (i.e., CP-26 program) and the FORTRAN IV program to calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs (i.e., CP-33 program).

5.2.3.1 FORTRAN IV Program to Calculate Heat Flux Response Factors for a Multi-Layer Slab (CP-26 Program)

In this section, the CP-26 program is analyzed by reviewing the National Research Council (NRC) of Canada paper: "*FORTRAN IV program to calculate heat flux response factors for a multi-layer slab*" (Mitalas and Arseneault, 1967). This NRC paper included many important information about the CP-26 program as the user and engineering manuals of the CP-26 program, which included: the general information about the CP-26 program, the calculation method (i.e., the Response Factor method) that applied to the CP-26 program, input requirements and output formats of the CP-26 program, key studies that contributed to the development of the CP-26 program, the source code of the CP-26 program and samples of inputs and output of the CP-26 program.

The CP-26 program was constructed using the FORTRAN IV language and was compatible with the IBM-360 computer. To calculate the transient heat conduction through a multi-layered slab, the CP-26 program used the Response Factor method. Detailed information about the Response Factor method was provided in two ASHRAE papers: "*Cooling load calculations by thermal response factor method*" (Stephenson and Mitalas, 1967) and "*Room thermal response factors*" (Mitalas and Stephenson, 1967). The CP-26 program calculated three sets of response factors (i.e., X, Y and Z) for multi-layered walls or roof. The three sets of response factors (i.e., X, Y and Z) characterized the transient heat transfer through multi-layered walls or roof. The CP-26 program had the capability to calculate up to two-hundred values for each set of the response factor and had the capability to analyze up to twenty-layers within a wall (i.e., slab).

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The CP-26 program required the input data to use card format. Each card included the information about one layer to be analyzed. The input data of the CP-26 program included: the time interval, thermal properties of each layer (i.e., thermal conductivity, specific heat and thermal resistance) and physical properties of each layer (i.e., thickness and density). Based on these input data, the CP-26 program calculated values of response factors by printing or punching on the results on cards. The algorithms in the CP-26 program for calculating the values of response factors were used for the development of the TACS program, the Post Office program, the NBSLD program, the RESPTK program and the CP-33 program.

5.2.3.2 FORTRAN IV Program to Calculate Z-transfer Functions for the Calculation of Transient Heat Transfer through Walls and Roofs (CP-33 Program)

In this section, the CP-33 program is analyzed by reviewing the National Research Council (NRC) of Canada paper: "*FORTRAN IV Program to Calculate Z-transfer Functions for the Calculation of Transient Heat Transfer through Walls and Roofs*" (Mitalas and Arseneault, 1972). This NRC paper included important information about the CP-33 program, which included: a general description of the CP-33 program, the calculation method (i.e., Conduction Transfer Functions) that applied to the CP-33 program, input requirements and output formats of the CP-33 program, the key studies that contributed to the development of the CP-33 program, flow diagrams that showed the calculation sequences, the source code of the CP-33 program and samples of inputs and outputs of the CP-33 program.

The CP-33 program was constructed by using the FORTRAN IV language and was compatible with the IBM-360 computer. For the analysis of the transient heat conduction through

the multi-layered walls or roofs, the CP-33 program used the Conduction Transfer Functions (CTFs) method. Detailed information about the Conduction Transfer Functions (CTFs) method was provided in the ASHRAE paper: "*Calculation of heat conduction transfer functions for multilayer slabs*" (Stephenson and Mitalas, 1971).

To analyze the transient heat conduction through multi-layered walls or roofs using the CTFs method, z-transfer functions had to be used. The z-transfer functions was similar in characteristics to the response factors. However, the z-transfer functions was further advanced compared to the response factors approach because the application of the z-transfer functions to the analysis of the transient heat conduction reduced the computation time as well as the computer memory (Stephenson and Mitalas, 1971).

The CP-33 program also required the input data to use card format. The input data of the CP-33 program included: the time interval, the description for the output title, thermal properties of each layer (i.e., thermal conductivity, specific heat and resistance of radiation path) and physical properties of each layer (i.e., thickness and density). Using z-transfer functions, the CP-33 program had the capability to analyze up to twenty-layers within a wall or roof. The algorithms that were developed for the CP-33 program were used for the development of the NBSLD program.

5.3 Summary of Results

Chapter V provided detailed information about the Level 0 and Level 1 analysis. From the analysis, this study found shared characteristics between the ASHRAE TGER Committee publications and the early whole-building energy simulation programs (i.e., Post Office program and NBSLD program). In addition, a detailed analysis of early computer programs was conducted by reviewing published documents (i.e., user and engineering manuals or equivalent documents). From the analysis of early computer programs, this study found the additional characteristics of the early computer programs, such as sub-routines, input and output variables, calculation methods, etc. Based on this further analysis, the shared characteristics between early computer programs (i.e., MATEUS, SHEP, TACS, CP-26, RESPTK and CP-33 programs) and early whole-building energy simulation programs (i.e., Post Office and NBSLD programs) were analyzed.

The results of this analysis showed:

1) The MATEUS program was the first building energy simulation program that preceded the SHEP, Post Office and NBSLD programs.

2) The SHEP program was the second building energy simulation program that appeared to share routines from the MATEUS program. For the calculation of the transient heat conduction through multi-layered walls, roofs or floors, the MATEUS and SHEP programs used the Finite Difference method. For the calculation of the heating and cooling load, the MATEUS and SHEP programs used the Heat Balance method.

3) The MATEUS, SHEP and CP-33 programs contributed to the development of the NBSLD program. For the calculation of the heating and cooling loads, the MATEUS, SHEP and NBSLD programs used the Heat Balance method. For the calculation of the transient heat conduction through multi-layered walls, roofs or floors, the CP-33 and NBSLD programs used the Conduction Transfer Functions method.

4) The CP-26, RESPTK and TACS programs contributed to the development of the Post Office program. The TACS program was the original name for the Post Office program. For the calculation of the transient heat conduction through multi-layered walls, roofs or floors, the CP-26, RESPTK, TACS and Post Office programs used the Response Factor method. For the calculation of the heating and cooling load, the TACS and Post Office programs used the Weighting Factor method.

5) The FORTRAN source code was available for the CP-26, SHEP, Post Office, CP-33 and NBSLD programs. However, the source code was not available for the MATEUS, RESPTK and TACS programs. Therefore, an analysis of the source code for all these programs could not be conducted.

6) Shared characteristics between the ASHRAE TGER Committee publications and the early whole-building simulation programs were found. The first ASHRAE TGER Committee publication (1968) contributed to the development of the LOADS calculation portion of the TACS program. The second ASHRAE TGER Committee publication (1971) contributed to the development of the LOADS calculation portion of the Post Office program. Most of the

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sub-routines that were used in the NBSLD program were discussed in the third ASHRAE TGER Committee publication (1975).

7) The interview with Mr. Robert Henninger helped to clarify the origins of whole-building energy simulation programs.

8) Dr. Kusuda's paper (2001) hinted at the existences of the early computer programs (i.e., the MATEUS, SHEP, CP-26, RESPTK and CP-33 program), which were only discussed in one other of the previous historical papers (Gupta et al., 1971).

9) The Gupta's paper (1971) referenced the MATEUS and RESPTK programs, but did not mention the SHEP program.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

This section provides the conclusions of this study, which include: 1) contributions of the ASHRAE TGER Committee to the development of the early building simulation programs (i.e., Post Office program and NBSLD program); 2) identification of early simulation programs that contributed to the development of the Post Office and NBSLD programs; 3) detailed analysis of early simulation programs on the basis of published reports (i.e., program user and engineering manuals or equivalent publications); and 4) identification of any shared characteristics among early simulation programs. This section also provides comments about future work relevant to this study.

6.1 Conclusions

In this study, the early computer programs that were rarely mentioned in the previous historical papers have been discussed. These computer programs were analyzed by reviewing published documents. In addition, the contributions of the ASHRAE TGER Committee to the development of early building energy simulations are analyzed in this study.

To clarify these contributions to whole-building energy simulations, the previous studies that discussed the history of whole-building energy simulations were analyzed, and a comprehensive analysis to identify any gaps or incorrect information in the previous historical studies was conducted by reviewing the published papers and reports. From this analysis, this study found early computer programs that were not mentioned in the previous historical studies,

which included: the MATEUS program, the SHEP program, the TACS program and three miscellaneous programs (i.e., the CP-26 program, the RESPTK program and the CP-33 program). Although all of these early computer programs contributed to the development of early building energy simulation programs (i.e., the Post Office program and the NBSLD program), none of them were explicitly discussed in the previous historical studies. In addition, this study also found that the ASHRAE TGER Committee contributed significantly to the development of early building energy simulation programs (i.e., the Post Office program and the NBSLD program), which was not explicitly mentioned in detail in the previous papers.

To identify the shared characteristics among the early computer programs, the Post Office program and the NBSLD program, published documents (i.e., program user and engineering manuals or equivalent documents) were found and carefully analyzed. From the analysis of the published documents, this study found that the MATEUS program (Achenbach et al., 1962) and the SHEP program (GARD/GATC, 1968) shared very similar analytical methods for the evaluation of the thermal environment in underground fallout shelters. Both programs used the Finite Difference method for the analysis of the transient heat conduction through multi-layered walls, roofs or floors and the Heat Balance method to evaluate the thermal environment in the underground shelter spaces.

This study found that these shelter simulation programs contributed to the development of the NBSLD program.   Although the NBSLD program used the Conduction Transfer Functions (CTFs) for the analysis of the transient heat conduction through multi-layered walls, roofs or floors instead of the Finite Difference method, the MATEUS program, the SHEP program and the NBSLD program shared a very similar analytical base (i.e., the Heat Balance

method) for the determination of heating and cooling loads in a space. In addition, this study found that the RESPTK program and the CP-33 program also contributed to the development of the NBSLD program because the NBSLD program's algorithms for the calculation of conduction transfer functions were derived from the RESPTK program and the CP-33 program. Finally, this study found that most of the sub-routines that were used in the NBSLD program were explained in detail in the ASHRAE TGER Committee publication (ASHRAE, 1975).

This study also found that the TACS program was developed and tested by Jim Anders before the Post Office program was released. The Post Office program used the Response Factor method for the analysis of the transient heat conduction through multi-layered walls, roof or floor and the Weighting Factor method for the calculation of heating and cooling loads in postal buildings.

Finally, this study found that the CP-26 program and the RESPTK program contributed to the development of the Post Office program because the Post Office program's algorithms for the calculation of response factors were derived from the CP-26 program and the RESPTK program. In addition, this study found that the ASHRAE TGER Committee publication (ASHRAE, 1971) contributed significantly to the development of the LOADS calculation portion of the Post Office program. To check and review these findings, this study conducted an interview with one of the key experts who was involved in the development of these early whole-building energy simulation programs.

Figure 6.1 shows the proposed revisions to genealogy charts that show the lineage of the MATEUS, SHEP, TACS, CP-26, RESPTK, CP-33, Post Office and NBSLD programs, as well as

the contributions from ASHRAE TGER Committee. In the figure, the MATEUS program can be clearly seen as the original building energy simulation program. The SHEP program followed the MATEUS program and shared several features with the program. The CP-26, RESPTK and CP-33 programs' progression can be seen from 1967 to 1972. The TACS and Post Office programs' relationship is also shown during the period from 1968 to 1971. Finally, the three ASHRAE TGER Committee publications can be seen from 1968 to 1975. The first ASHRAE TGER Committee publication in 1968 informed the TACS program and the second ASHRAE TGER publication (1971). This second ASHRAE TGER publication informed the Post Office program. The third ASHRAE TGER publication informed the NBSLD program. This detailed genealogy chart provides a much needed revision to all previous genealogy charts.
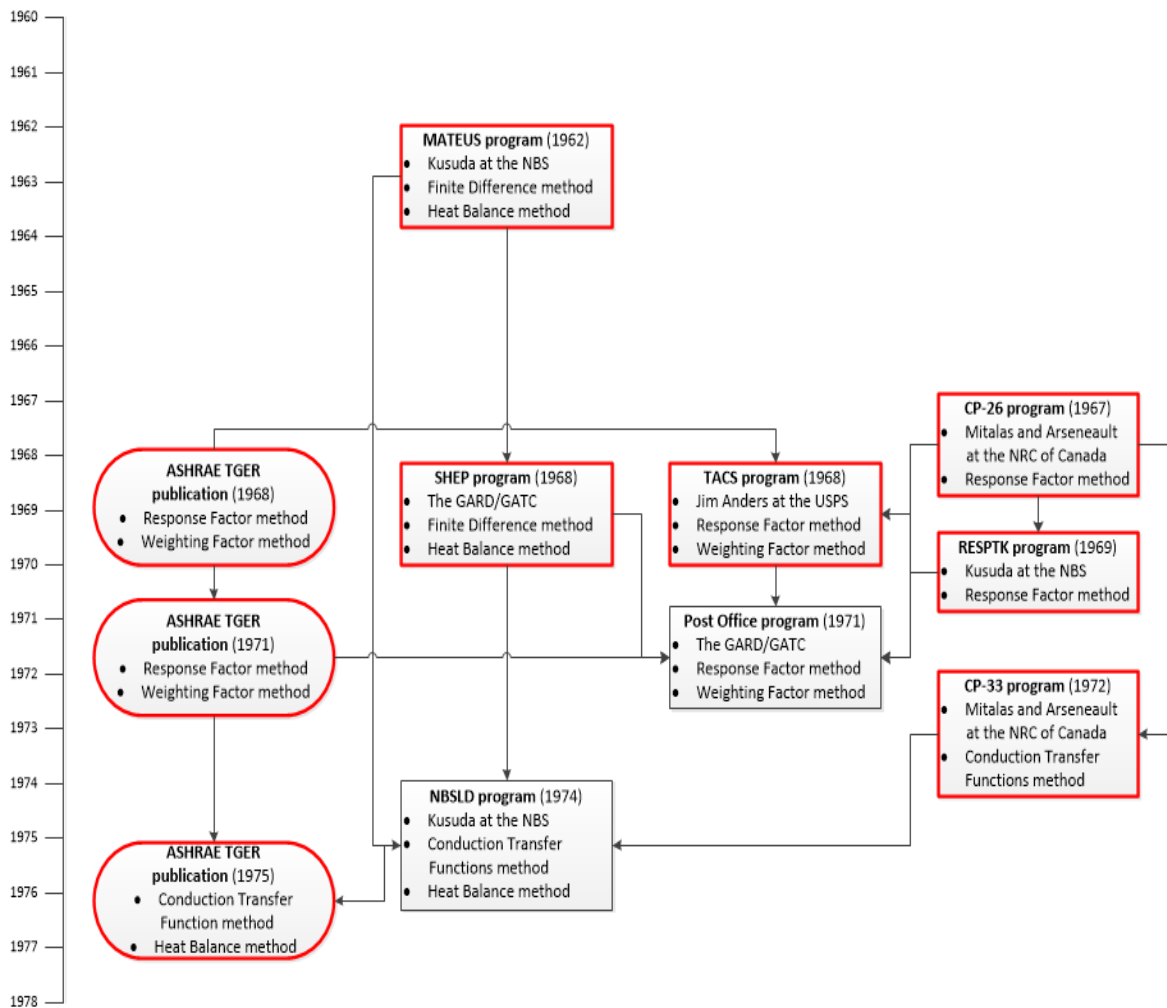
Figure 6.1. Updated genealogy chart from the 1960's to 1970's.

6.2 Future Work

During this study, the following future work is highly recommended:

- A detailed analysis of HVAC systems simulation needs to be conducted to determine the origins of specific algorithms and trace those routines to today's programs (i.e., DOE-2, eQUEST, TRNSYS and EnergyPlus).

- The origins of whole-building energy simulations need to be analyzed by reviewing the program's FORTRAN source code.

- Working versions of the FORTRAN program source code for the MATEUS, SHEP, TACS, Post Office, NBSLD, CP-26, RESPTK, and CP-33 programs need to be compiled and run (i.e., executed) so a comparative analysis can be performed to see how the accuracy of the early programs compares to today's programs.

- Electronic (i.e., digital text) versions of the previous source codes need to be assembled in a public place on the internet for wide distribution so others can learn from the early codes.

- Specific contributions by individuals need to be determined so recognition can be given to those who contributed to today's programs.

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APPENDIX A

APPROVAL FROM THE INSTITUTIONAL REVIEW BOARD (IRB)

DIVISION OF RESEARCH

A͘M | TEXAS A&M
UNIVERSITY

NOT HUMAN RESEARCH DETERMINATION

May 30, 2018

Type of Review:	Initial Review Submission Form
Title:	Origins of analysis methods used to design high-performance commercial buildings: HVAC system simulation
Investigator:	Jeff Haberl
IRB ID:	IRB2018-0583
Reference Number:	076726
Documents Received:	IRB Application (Human Research) - (Version 1.0) - Proposal - (Version 1.0) -

Dear Jeff Haberl:

The Institution determined that the proposed activity is not research involving human subjects as defined by DHHS and FDA regulations.

Further IRB review and approval by this organization is not required because this is not human research. This determination applies only to the activities described in this IRB submission and does not apply should any changes be made. If changes are made you must immediately contact the IRB about whether these activities are research involving humans in which the organization is engaged. You will also be required to submit a new request to the IRB for a determination.

Please be aware that receiving a 'Not Human Research Determination' is not the same as IRB review and approval of the activity. You are not to use IRB consent forms or templates for these activities.

If you have any questions, please contact the IRB Administrative Office at 1-979-458-4067, toll free at 1-855-795-8636.

Sincerely,
IRB Administration

750 Agronomy Road, Suite 2701

1186 TAMU
College Station, TX 77843-1186

Tel. 979.458.1467 Fax. 979.862.3176
http://rcb.tamu.edu

Figure A.1. The Institutional Review Board (IRB) letter for this study.

APPENDIX B

INTERVIEW WITH MR. ROBERT HENNINGER

1) Can you tell me about your life, education, occupation and so forth?

I was born here in Chicago. In 1964, I received my Bachelor's degree in Mechanical Engineering and then followed with a Master's degree in 1965. I had the privileged during that time of interacting with Professor Wilbert Stoecker from the University of Illinois who had a long history of involvement with ASHRAE.

When I graduated in June 1965, I immediately took a job with the General American Research Division (GARD) of the GATX corporation. The General American Transportation Corporation was a transportation company involved in real world business. At the time that I joined the GARD, I joined their environment engineering department. They had been involved in quite a bit doing research contract, research work with the Office of Civil Defense (OCD) people that were part of the Department of the Army at that time. When I came to GARD, the Office of Civil Defense (OCD) was a big funder of research works.

There were a lot of work being done and I was in fallout shelters work at that time. When I joined them, I participated in several tasks. They were doing around country with fallout shelters. They had equipped one shelter with simulated occupants, and we are trying to determine what kind of natural ventilation rates could be produced by wind forces, thermal forces and so forth.

2) Do you recall what sort of projects you did at the GARD/GATC?

When I joined the GARD, they were doing some fallout shelters testing like I said. One of the first test I was involved in was the one that took place at North Western University here in Illinois. The tower at a stadium there which was several stories had windows on each side. I needed to size an ideal shelter for using natural ventilation.

Two weeks after joining the GARD, I got married so it was my privilege to work the midnight to eight-o clock shift to take down the data at that site for a couple of months. That was my first experience with real work. I tried to measure the natural ventilation rate. I think a lot of work was used to develop and verify the SHEP program which you may reference to. However, much of that work done before I came. Thus, I didn't know much about the SHEP program.

3) Are you aware of the Mathematical Analysis of Thermal Environment in Underground Shelters (MATEUS) program?

I was not aware of the MATEUS program. I never heard of the program until I read the note here. Since the reference is to an underground shelter, I expected that was probably also funded by the OCD as part of their fallout shelter research.

4) Are you aware of the the SHelter Environmental Prediction (SHEP) program?

I never really ever got the chance to use the SHEP program although I had copies of the report about the SHEP program. I really don't know much about the SHEP program. I never used it, never really looked at the code, never really read the SHEP report. That was the work done before I came.

5) Are you aware of the Fortran IV program to calculate heat flux response factors for a multi-layer slab (i.e., CP-26) program?

I was not aware of the CP-26 program. I remember that ASHRAE formed a task group on LOAD calculations. I remember that I think there was a photograph at one of meetings showing about thirty people sitting around table. The task group was headed by Bob coming up with algorithms for LOAD calculations. Mitalas and Stepheson from NRC of Canada, Kusuda from NBS and Metin from GARD were really involved in developing of these algorithms.

6) Are you aware of the Thermo-dynamic Analysis Computer System (TACS) program and Jim Anders who developed the TACS program?

Jim Anders was the gentleman that wrote the scope of work that was offered as bidding. Several companies responded bidding and the GARD fortunately won the contract. Jim was very forward thinking kind of person at the post office. At that time, it was involved in doing a lot of post office building design and energy was becoming to be important thing. The post office was

starting to realize that the heating and cooling equipment was oversized in buildings. Jim was

interested in going ahead and trying to develop some kind of computerized program doing the

LOAD calculation and SYSTEM simulation to help their design group at post office in

Washington D.C. to help design more energy efficient buildings.

Sam Milnark at that time was an editor from heating, piping and air-conditioning magazine. He

wrote several articles in conjunction with Jim. The term TACS may have been developed by Sam

Milnark and Jim. They wanted to go ahead and publish articles. The term calling at the post

office program was not really very enticing so they wanted to come up with this name Thermo

Dynamic Analysis Computer System (TACS). The TACS got fixed through these scope of works

basically in the wish list they were looking forward to developing.

7) Are you aware of the Post Office program?

When the Post Office program was developed, I really had no involvement in the development of

the LOAD program that was all part of Metin Lokmanhikim and Charles Groth is work. They

really did most of the work on that. My involvement was more in the SYSTEM and

EQUIPMENT area. I don't know how much the SHEP program really played in the role in the

development of the LOAD program. But, I think maybe some of the work done was from

development of the SHEP program. It was generally known GARD had a big part of the

involvement in the SHEP program.

The level of the sophistication between the LOAD, SYSTEM and EQUIPMENT was very

different because as the part of the LOAD program, Metin Lokmanhekim and Charles Groth

developed the shadow analysis program which even printed shadow pattern from surfaces.

Charles Groth was headed to all of cording to develop all the algorithms and necessarily shadow analysis.

You had to realize that I was just a newbie out of the university. They gave me a responsibility for going ahead and trying to develop parts of the SYSTEM and EQUIPMENT programs for the Post Office program. It was always ideal approach just using straight heat balance so far. Because post office purchased a lot of heating and cooling equipment, Jim Anders was able to get some performance data from manufactures which were able to go and computerize. When I came to GARD, every cording was done with punched cards. At the GARD, we had IBM 1130 machine that had 16K memory.

8) Are you aware of the NECAP program?

I really don't remember much about my assignment exactly for the Post Office program but I was the project engineer on the NECAP program so I did have more involvement there. But, at that time, Metin left the company so we did kind of our own work. At that time, we competed with Metin for the NECAP contract and fortunately we successfully got in it.

I remember I spent awful time developing the NECAP engineering manuals putting the awful details into that thing. I tried to develop documents more exactly what's going on with the program. The NECAP program was basically from the Post Office program which was the enhanced program from the Post Office program.

9) Are you aware of the *Documentation of system and equipment simulation program – engineering manual with flowcharts* (GARD/GATX, 1975)

After we had finished developing the Post Office program, Sliwinski, one of research engineers at the Construction Engineering Research Laboratory (CERL) asked us to bring the Post Office program down to install equipment. The document was created for their speciality. We enhanced the documentation because post office documentation we created wasn't really great and NECAP documentation was much more detailed. The documentation of the Post Office program was pretty scant. The document that CERL asked us included what we wanted to develop. We already got better idea as to how the program was structured and how the logic was flowed. All became input then into the NECAP program later. This work we had done for the CERL was a kind of precursor to their BLAST program which came after later.

APPENDIX C

THE ANALYSIS OF THE FIRST 1968 ASHRAE TGER PUBLICATION

Table C.1. *The analysis of the ASHRAE TGER 1968 publication (ASHRAE, 1968)*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
CLIMATE	• A sub-routine to process climatic parameters that were required for hourly load calculations. • The CLIMATE sub-routine used climatic data from National Weather Record Center as input variables.	Punch card or magnetic tape form from the National Weather Record Center	**DB**: Dry-bulb temperature **DP**: Dew-point temperature **WB**: Wet-bulb temperature **TC**: Total cloud amount **CT**: Cloud type **V**: Wind velocity **DIR**: Wind direction **I**: Total hemispherical radiation over the horizontal surface **PB**: Barometric pressure **Rain or Snow Fall**: Precipitation data	X
SUN	• A sub-routine to identify solar position. • A sub-routine to evaluate solar radiation intensity that was incident on surfaces of buildings.	**L**: Latitude **l**: Longitude **TZN**: Time zone number **d**: Date **t**: Time **DST**: Daylight saving time indicator (output of DST sub-routine) **ρg**: Ground reflectivity **CCM**: Cloud cover modifier (output of CCM sub-routine) **CN**: Clearness number **WA**: Wall azimuth angle **WT**: Wall tilt angle	**h'**: Sunrise and sunset time **COS(Z), COS(W), COS(S)**: Direction cosines of direct solar beam **α, β, γ**: Direction cosines of normal to surface **COS(η)**: Cosine of angle of incidence η **SALT**: Solar altitude **SAZM**: Solar azimuth **BS**: Sky brightness **BG**: Ground brightness **IDN**: Intensity of direct normal solar radiation **I**: Intensity of total solar radiation incident on surface **Id,sky**: Intensity of sky diffuse radiation incident on surface **Id,ground**: Intensity of ground diffuse radiation incident on surface	O

Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
SAT	• A sub-routine to calculate the sol-air temperature for a surface. • The SAT sub-routine wasn't used if heat conduction through multi-layered walls and roof was analyzed by using the Response Factor method.	**a**: Solar absorptance of the outside surface **RO**: Combined convective and radiative thermal resistance at the outside surface (output of FO sub-routine) **DB**: Outside dry-bulb temperature at time t (output of CLIMATE sub-routine) **I**: Total solar radiation incident on surface at time t (output of SUN sub-routine) **α**: Cosine of angle between zenith and normal to surface (output of SUN sub-routine) **TC**: Total cloud amount at time t (output of CLIMATE sub-routine)	Sol-air temperature for the surface at time t	O
CCM	• A sub-routine to calculate the cloud cover modifier. • The CCM sub-routine at 1968 did not include calculation sequence.	**SALT**: Solar altitude angle (output of SUN sub-routine) **NTYPE**: Cloud type (output of CLIMATE sub-routine) **TC**: Weather Bureau total cloud amount index (output of CLIMATE sub-routine)	**CCM**: Cloud cover modifier	X
TAR	• A sub-routine to calculate factors for windows (i.e., transmission factors, absorption factors, and reflection factors).	**COS(η)**: Cosine of angle of incidence η (output of SUN sub-routine) **k*l**: Extinction coefficient*thickness	**Tη, Td**: Transmission factors **Aθ,outer, Ad,outer, Aθ,inner, Ad,inner**: Absorption factors	O

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Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
SHG	• A sub-routine to calculate solar heat gain through windows.	**IDN**: Intensity of direct normal solar radiation (output of SUN sub-routine) **BS**: Sky brightness (output of SUN sub-routine) **BG**: Ground brightness (output of SUN sub-routine) **COS(η)**: Cosine of the angle of incidence of direct solar radiation (output of SUN sub-routine) **FWS**: Form factor between the window and the sky **FWG**: Form factor between the window and the ground **RO, RA, RI**: Thermal resistances at outside surface, air space, and inside surface **SLA**: Sunlit area factor (output of SHADOW sub-routine) **SC**: Shading coefficient **Tη, Td**: Transmission factors of direct and diffuse radiation for windows (output of TAR sub-routine) **Aη,outer, Aη,inner, Ad,outer, Ad,inner**: Absorption factors of direct solar and diffuse radiation through outer and inner window panes (output of TAR sub-routine)	**SHG**: Solar heat gain through glass	O
SHADOW	• A sub-routine to evaluate the shadow effects on buildings. • The SHADOW sub-routine consisted of three sub sub-routines, which included: the WINDOW, ADJBLDG, and SPRP sub sub-routines. • The input variable of Transmissivity of SP was only used in the SPRP sub sub-routine. • The output variable of PIC was only used in the SPRP sub sub-routine.	Coordinates and dimensions of shading devices and their relationship to the exterior surface Coordinates and dimensions of the exterior surface **SALT**: Solar altitude (output of SUN sub-routine) **SAZM**: Solar azimuth angles (output of SUN sub-routine) Transmissivity of Sending Polygons(SP)	**SLA**: Sunlit area factor **PIC**: Pictorial representation of shadow shapes	X

Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
FO	• A sub-routine to calculate outside surface heat transfer coefficient. • The FO sub-routine used coefficients data that was given in the 1967 ASHRAE Handbook of Fundamentals.	**V**: Wind velocity (output of CLIMATE sub-routine) **IS**: Exterior surface index	**FO**: Outside surface heat transfer coefficient	O
ACR	• A sub-routine to calculate air cavity thermal resistance within walls and roofs. • The polynomial equations for determining air cavity thermal resistance (RES) was derived from Robinson's research (Robinson et al., 1957).	**DT**: Temperature difference across the air space **L**: Thickness of the air space **IDIR**: Direction index of the heat flow **ε-1, ε-2**: Emittance of the surfaces facing the air cavity **ATC**: Average temperature of the air space	**RES**: Air cavity thermal resistance	O
XYZ	• A sub-routine to calculate response factors. • To calculate response factors by using the XYZ sub-routine, the sequence of input variables followed the direction from the exterior surface to the inside air.	**N**: Number of layers of wall or roof **K(I)**: Thermal conductivity of each layer **ρ(I)**: Density of each layer **C(I)**: Specific heat of each layer **L(I)**: Thickness of each layer **RES(I)**: Thermal resistance of the layer that had no thermal mass **DT**: Time increment for the response factors calculation	**X(j), Y(j), Z(j)**: Response factors **R**: Common ratio between successive terms of each series beyond M	X

Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
HEATW	• A sub-routine to evaluate transient heat conduction through opaque walls or roofs using response factors.	**X(j), Y(j), Z(j)**: Response factors (output of XYZ sub-routine) **FOt**: Outside surface heat transfer coefficient (output of FO sub-routine) **It**: Intensity of total solar radiation incident on the outer surface of wall or roof at time t (output of SUN sub-routine) **TOt-j**: History of outside surface temperatures at times t-1, t-2, t-3 ... t-NT **DBt-j**: History of outside air temperature at time t, t-1, t-2 ... t-NT **TZt-j**: History of room air temperature at times t, t-1, t-2 ... t-NT **a**: Solar absorptance of the outside surface **ε**: Emittance of the outside surface **α**: Cosine of angle between the zenith and normal to the surface (output of SUN sub-routine) **TCt**: Total cloud amount at time t (output of CLIMATE sub-routine)	**TOt**: Outside surface temperature at time t **HEATWt**: Heat gain to the room air at time t	O
RMRT	• A sub-routine to calculate weighting factors that related cooling load of a room to changes in air temperature of a room. • The Z-factors that were calculated by the XYZ sub-routine were used in the RMRT sub-routine.	X	X	O
RMRIS	• A sub-routine to calculate weighting factors that related cooling load of a room to the power supplied to the lights. • A research by Kimura and Stephenson (1968) contributed to the development of the RMRIS sub-routine.	X	X	O

Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
HLC	• A sub-routine to calculate heating and cooling loads (i.e., sensible and latent loads) of a space. • The HLC sub-routine was one of main sub-routines in the ASHRAE load calculation at 1968.	**HEATVSt**: Sensible heat gain due to air infiltration (output of IHG sub-routine) **HEATLt**: Latent heat gain due to internal heat sources and infiltration (output of IHG sub-routine) **HEATGt-j**: History of hourly values of solar heat gain through windows with no interior shading devices (output of IHG sub-routine) **HEATG't-j**: History of hourly values of solar heat gain through windows with interior shading devices (output of IHG sub-routine) **HEATXt-j**: History of hourly values of heat gain through exterior walls and roofs (output of IHG sub-routine) **HEATISt-j**: History of power input to lights (output of IHG sub-routine) **HEATDPt-j**: History of heat gain through doors, partition walls, underground walls and floors and that due to internal sensible heat sources other than lights (output of IHG sub-routine) **θ't-j**: History of deviation of space temperature TZ from the assumed constant value TM used for calculating all the instantaneous heat gain (θ'= TZ-TM) **RMRGj**: Weighting factors for use with HEATGj **RMRXj**: Weighting factors for use with HEATXt-j, HEATG't-j, and HEATDPt-j **RMRIS**: Weighting factors for use with HEATISt-j **RMRTj**: Weighting factors for use with θ't-j	**HRLODSt**: Total hourly sensible heating/cooling load at time t **HRLODLt**: Total hourly latent heating/cooling load at time t	O
RMRX	• A sub-routine to calculate weighting factors that related cooling load of a room to the heat gain through walls and roofs.	X	X	X

Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
IHG	• A sub-routine to calculate instantaneous heat gains (i.e., sensible and latent heat gains) of a space. • The IHG sub-routine was one of main sub-routines in the ASHRAE load calculation at 1968.	For Windows **NY**: Number of windows **AYk**: Area of each window **UYk**: Overall heat transfer coefficient for each window **SHGk**: Solar heat gain through each window (output of SHG sub-routine) For Exterior walls and roofs **NX**: Number of exterior walls and roofs **AXk**: Area of each exterior wall and roof **HEATWk**: Heat gain through each exterior wall and roof (output of HEATW sub-routine) For Lights **NS**: Number of different types of lights (output of SCHEDULE sub-routine) **QSk**: Power input to each type of light (output of SCHEDULE sub-routine) For Inside doors **ND**: Number of inside doors **ADk**: Area of each inside door **UDk**: Overall heat transfer coefficient of each inside door For Outside doors **ND'**: Number of outside doors **AD'k**: Area of each outside door **UD'k**: Overall heat transfer coefficient of each outside door	For Sensible heat gains **HEATG, HEATG'**: Total hourly solar heat gain through windows **HEATX**: Total hourly heat gain through exterior walls and roofs **HEATIS**: Total power input to lights **HEATDP**: Overall sensible heat gain due to heat transfer through doors, partitions, underground walls and floors and due to internal heat sources other than lights **HEATVS**: Sensible heat gain due to air leakage For Latent heat gain **HEATL**: Latent heat gain due to internal heat generating sources and due to air infiltration	O

Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
IHG	• A sub-routine to calculate instantaneous heat gains (i.e., sensible and latent heat gains) of a space. • The IHG sub-routine was one of main sub-routines in the ASHRAE load calculation at 1968.	For Partitions **NP**: Number of partitions which separated the space from other spaces at different temperatures **APk**: Area of each of these partitions **UPk**: Overall heat transfer coefficient for each of these partition walls For Underground walls **NG**: Number of underground walls **AGk**: Area of each underground wall **UGk**: Overall heat transfer coefficient of each underground wall For Underground floors **NGF**: Number of underground floors **AGFk**: Area of each underground floor **UGFk**: Overall heat transfer coefficient of each underground floor For Internal Infiltration **NLK**: Number of internal air leakage sources **LEAKk**: Air leakage from each source (output of INFILTRATION sub-routine) For External Infiltration **NLK'**: Number of external air leakage sources **LEAK'k**: Air leakage from each external source (output of INFILTRATION sub-routine)	For Sensible heat gains **HEATG, HEATG'**: Total hourly solar heat gain through windows **HEATX**: Total hourly heat gain through exterior walls and roofs **HEATIS**: Total power input to lights **HEATDP**: Overall sensible heat gain due to heat transfer through doors, partitions, underground walls and floors and due to internal heat sources other than lights **HEATVS**: Sensible heat gain due to air leakage For Latent heat gain **HEATL**: Latent heat gain due to internal heat generating sources and due to air infiltration	O

Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
IHG	• A sub-routine to calculate instantaneous heat gains (i.e., sensible and latent heat gains) of a space. • The IHG sub-routine was one of main sub-routines in the ASHRAE load calculation at 1968.	For Temperatures **TAk**: Dry-bulb temperature of each adjacent space **DB**: Dry-bulb temperature of outdoor air (output of CLIMATE sub-routine) **TG**: Average ground water temperature at half underground basement depth **TGW**: Ground water temperature **TZ**: Space dry-bulb temperature (output of SCHEDULE sub-routine) For Humidity ratios **WAk**: Humidity ratio of adjacent space **WO**: Humidity ratio of outdoor air (output of PSY sub-routine) **WZ**: Humidity ratio of indoor space (output of SCHEDULE sub-routine)	For Sensible heat gains **HEATG, HEATG'**: Total hourly solar heat gain through windows **HEATX**: Total hourly heat gain through exterior walls and roofs **HEATIS**: Total power input to lights **HEATDP**: Overall sensible heat gain due to heat transfer through doors, partitions, underground walls and floors and due to internal heat sources other than lights **HEATVS**: Sensible heat gain due to air leakage For Latent heat gain **HEATL**: Latent heat gain due to internal heat generating sources and due to air infiltration	O

Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
RMRG	•A sub-routine to calculate weighting factors that related cooling load of a room to the solar heat gain through windows. • The heat gain through windows with inside shading devices (i.e., blind, curtain, etc.) was converted to cooling load by using RMRX sub-routine. • The heat gain through windows without inside shading devices was converted to cooling load by using RMRG sub-routine.	X	X	X
DST	• A sub-routine to identify dates of the daylight saving time.	**YR**: Year **MO**: Month of the year **DAY**: Day of the Month	**DSTX**: The day when the daylight saving time commenced **DSTY**: The day when the standard time resumed **DST**: The daylight saving time indicator	O
WKDAY	• A sub-routine to identify the day of the week. • The WKDAY sub-routine only identified the date of the year from 1901 to 2000.	**YR**: Year **MO**: Month of the year **DAY**: Day of the Month	**WKDAY**: Weekday indicators	O
HOLIDAY	• A sub-routine to identify the national holidays of the United States. • Modifications were allowed for any holidays in any country.	**YR**: Year **MO**: Month of the year **DAY**: Day of the Month	**HOL**: Holiday indicator	O

Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
PSY	• A sub-routine to conduct approximate psychrometric calculations. • A sub-routine to evaluate the psychrometric properties of moist air. • The PSY sub-routine was used if the Goff-Gratch method was not warranted.	**DB**: Dry-bulb temperature (output of CLIMATE sub-routine) **WB**: Wet-bulb temperature (output of CLIMATE sub-routine) **DP**: Dew-point temperature (output of CLIMATE sub-routine) **PB**: Barometric pressure (output of CLIMATE sub-routine) **H**: Enthalpy of moist air **PVS**: Partial pressure of water vapor in moisture saturated air **t**: Temperature (either DB, WB, or DP)	**PVS**: Partial pressure of water vapor in moisture saturated air **PV**: Partial pressure of water vapor in moist air **W**: Humidity ratio of moist air **H**: Enthalpy of moist air **V**: Volume of moist air **WB**: Wet-bulb temperature **DP**: Dew-point temperature	O
SCHEDULE	• A sub-routine to determine the characteristics of heat generations (i.e., occupancy, lighting, equipment, outdoor ventilation air, and indoor design conditions) in the space on a daily basis.	**DAY**: Day of the year **OCCUPANCY**: Daily schedules in terms of number, activity levels and heat generating characteristics of people **LIGHTING**: Daily schedules of lighting, types of various lighting fixtures, number of each type of light, power input to each light **EQUIPMENT**: Daily schedules of usage of motors, appliances, office machines, computers, etc., heat-generating characteristics of each source **OUTDOOR AIR SUPPLY**: Daily schedules and quantity of outdoor ventilation air **INDOOR DESIGN CONDITIONS**: Daily schedules of space temperature and relative humidity	**NS**: Total number of different daily lighting schedules **(QS)t,k**: Daily schedule of power input for each lighting schedule **NS'**: Total number of sensible heat schedule other than lighting **(QS')t,k**: Daily schedule of heat output for each sensible heat schedule other than lights **NL**: Total number of latent heat schedules **(QL)t,k**: Daily schedule of heat generation for each latent heat schedule **NT**: Total number of space temperature and humidity schedules **(TZ)t,k, (WZ)t,k**: Daily schedule for each space temperature and humidity schedule	X

Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
INFILTRATION	• A sub-routine to calculate infiltration rate (i.e., air leakage through each exposure). • Flow characteristics of openings that were used for INF input variable calculation were derived from 1967 ASHRAE Handbook of Fundamentals. • Infiltration characteristics through walls that were used for WALEAK input variable calculation were derived from 1967 ASHRAE Handbook of Fundamentals.	For Outdoor conditions **V**: Wind velocity (output of CLIMATE sub-routine) **DIR**: Wind direction (output of CLIMATE sub-routine) **DB**: Outdoor dry-bulb temperature (output of CLIMATE sub-routine) **PB**: Atmospheric pressure (output of CLIMATE sub-routine) For Building description **(HT)k**: Height of building floor (k) above grade **HTT**: Total height of building above grade **NF**: Number of floors above grade **k**: Floor number **NZB**: Neutral zone of building **NZS**: Neutral zone of elevator and service shaft **TZ**: Indoor space dry-bulb temperature **TS**: Elevator and service shaft temperature **WA'**: Direction measured clockwise from north to normal of exterior wall surface For Windows and doors **NY**: Number of windows **LY**: Crack length of each window **TY**: Type of window **LF**: Crack length of frame **TF**: Type of frame **ND**: Number of doors **LD**: Crack length of door **TD**: Type of door **INF**: Flow through opening	**LEAKYk,x**: Infiltration through window crack **LEAKFk,x**: Infiltration through frame crack **LEAKDk,x**: Infiltration through doors **WALEAKk,x**: Infiltration through walls **SWINGDk,x**: Infiltration through swinging doors	O

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Table C.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
INFILTRATION	• A sub-routine to calculate infiltration rate (i.e., air leakage through each exposure). • Flow characteristics of openings that were used for INF input variable calculation were derived from 1967 ASHRAE Handbook of Fundamentals. • Infiltration characteristics through walls that were used for WALEAK input variable calculation were derived from 1967 ASHRAE Handbook of Fundamentals.	For Outside walls **AW**: Area of wall **TW**: Type of wall **WALEAK**: Flow through wall For Swinging doors **NDS**: Number of swinging door entrances **NTYPE**: Type of entrance **TRT**: Number of persons per hour per door **SWINGD**: Swinging door entrance infiltration For Surrounding buildings **TB**: Type of surrounding building **NSB**: Ratio of distance between buildings and width of conditioned building in direction of wind For Interior separations **CF**: Equivalent opening of stairway door **CS**: Equivalent opening of elevator doors and service shafts **TF**: Type of opening in stairway door **TS**: Type of opening on elevator doors and service shafts	**LEAKYk,x**: Infiltration through window crack **LEAKFk,x**: Infiltration through frame crack **LEAKDk,x**: Infiltration through doors **WALEAKk,x**: Infiltration through walls **SWINGDk,x**: Infiltration through swinging doors	O

APPENDIX D

THE ANALYSIS OF THE SECOND 1971 ASHRAE TGER PUBLICATION

Table D.1. *The analysis of the ASHRAE TGER 1971 publication (ASHRAE, 1971)*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
CLIMATE	• A sub-routine to process climatic parameters that were required for hourly load calculations. • The CLIMATE sub-routine used climatic data from National Weather Record Center (i.e., U.S. Weather Bureau 144 weather card deck or U.S. Weather Bureau 1440 magnetic weather tape) as input variables.	U.S. Weather Bureau 144 weather card deck U.S. Weather Bureau 1440 weather tape	**DB**: Dry-bulb temperature **DP**: Dew-point temperature **WB**: Wet-bulb temperature **TC**: Total cloud amount **CT**: Cloud type **V**: Wind velocity **DIR**: Wind direction **ID**: Direct solar radiation **Id,sky**: Sky diffuse radiation **Id,ground**: Ground diffuse radiation **PB**: Barometric pressure **Rain or Snow Fall**: Precipitation data	X
SUN	• A sub-routine to identify solar position. • A sub-routine to evaluate solar radiation intensity that was incident on surfaces of buildings.	**L,I**: Latitude and longitude **TZN**: Time zone number **d,t**: Date and time **DST**: Daylight saving time indicator (output of DST sub-routine) **ρg**: Ground reflectivity **CCM**: Cloud cover modifier (output of CCM sub-routine) **CN**: Clearness number **WA**: Surface azimuth angle **WT**: Surface tilt angle	**SRT, SST**: Sunrise and sunset time **COS(Z), COS(W), COS(S)**: Direction cosines of direct solar beam **α, β, γ**: Direction cosines of normal to surface **COS(η)**: Cosine of angle of incidence of direct solar radiation **SALT, SAZM**: Solar altitude and solar azimuth **BS, BG**: Sky brightness and ground brightness **IDN**: Intensity of direct normal solar radiation **I**: Intensity of total solar radiation incident on surface **Id,sky**: Intensity of sky diffuse radiation incident on surface **Id,ground**: Intensity of ground diffuse radiation incident on surface	O

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Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
SAT	• A sub-routine to calculate the sol-air temperature for a surface. • The SAT sub-routine wasn't used if heat conduction through multi-layered walls or roof was analyzed by using the Response Factor method.	**a**: Solar absorptance of the outside surface **RO**: Combined convective and radiative thermal resistance at the outside surface (output of FO sub-routine) **DB**: Outside dry-bulb temperature at time t (output of CLIMATE sub-routine) **I**: Total solar radiation incident on surface at time t (output of SUN sub-routine) **α**: Cosine of angle between vertical and normal to surface (output of SUN sub-routine) **TC**: Total cloud amount at time t (output of CLIMATE sub-routine)	Sol-air temperature for the surface at time t	O
CCM	• A sub-routine to calculate the cloud cover modifier.	**SALT**: Solar altitude angle (output of SUN sub-routine) **CT**: Cloud type (output of CLIMATE sub-routine) **TC**: Total cloud amount at time t (output of CLIMATE sub-routine)	**CCM**: Cloud cover modifier	O
TAR	• A sub-routine to calculate several factors (i.e., transmission factors, absorption factors, and reflection factors) for windows.	**COS(η)**: Cosine of angle of incidence of direct solar radiation (output of SUN sub-routine) **k*l**: Extinction coefficient*thickness	**Tη, Td**: Transmission factors of direct solar and diffuse radiation for windows **Aη,outer, Ad,outer, Aη,inner, Ad,inner**: Absorption factors of direct solar and diffuse radiation through outer and inner window pane	O

Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
SHG	• A sub-routine to calculate solar heat gain through windows.	**IDN**: Intensity of direct normal solar radiation (output of SUN sub-routine) **BS**: Sky brightness (output of SUN sub-routine) **BG**: Ground brightness (output of SUN sub-routine) **COS(η)**: Cosine of the angle of incidence of direct solar radiation (output of SUN sub-routine) **FWS**: Form factor between the window and the sky **FWG**: Form factor between the window and the ground **RO, RA, RI**: Thermal resistances at outside surface, air space, and inside surface **SLA**: Sunlit area factor (output of SHADOW sub-routine) **SC**: Shading coefficient **Tη**, **Td**: Transmission factors of direct and diffuse radiation for windows (output of TAR sub-routine) **Aη,outer, Aη,inner, Ad,outer, Ad,inner**: Absorption factors of direct solar and diffuse radiation through outer and inner window panes (output of TAR sub-routine)	**SHG**: Solar heat gain through glass	O

Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
SHADOW	• A sub-routine to evaluate the shadow effects on buildings. • The SHADOW sub-routine consisted of three sub sub-routines, which included: the WINDOW, ADJBLDG, and SHADOW sub sub-routines. • The SHADOW sub sub-routines was developed by GARD/GATC. • The input variable of Transmissivity of SP was only used in the SHADOW sub sub-routine. • The output variable of PIC was only used in the SHADOW sub sub-routine.	Coordinates and dimensions of shading devices and their relationship to the exterior surface Coordinates and dimensions of the exterior surface **SALT**: Solar altitude (output of SUN sub-routine) **SAZM**: Solar azimuth angles (output of SUN sub-routine) Transmissivity of Sending Polygon (SP)	**SLA**: Sunlit area factor **PIC**: Pictorial representation of shadow shapes	X
FI	• A sub-routine to calculate inside surface heat transfer coefficient. • The FI sub-routine formalized tabular data of the 1967 ASHRAE Handbook of Fundamentals to approximate inside surface heat transfer coefficients.	**IDIR**: Heat flow direction index **ε**: Emittance of the surface **IV**: Moving air index	**FI**: Inside surface heat transfer coefficient	O
FO	• A sub-routine to calculate outside surface heat transfer coefficient. • The FO sub-routine used coefficients data that was given in the 1967 ASHRAE Handbook of Fundamentals.	**V**: Wind velocity (output of CLIMATE sub-routine) **IS**: Exterior surface index **DIR**: Wind direction (output of CLIMATE sub-routine) **WA**: Wall azimuth angle	**FO**: Outside surface heat transfer coefficient **FOC**: Convective component of the outside surface heat transfer coefficient	O

Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
ACR	• A sub-routine to calculate air cavity thermal resistance within walls and roofs. • The polynomial equations for determining air cavity thermal resistance (RES) was derived from Robinson's research (Robinson et al., 1957).	**DT**: Temperature difference across the air space **L**: Thickness of the air space **IDIR**: Direction index of the heat flow **ε-1, ε-2**: Emittance of the surfaces facing the air cavity **ATC**: Average temperature of the air space	**RES**: Air cavity thermal resistance	O
XYZ	• A sub-routine to calculate response factors. • To calculate response factors by using the XYZ sub-routine, the sequence of input variables followed the direction from the exterior surface to the inside air. • The CP-26 program and the Response Factor Calculation program calculated response factors for multi-layered walls, roofs and floors.	**N**: Number of layers of wall or roof **Ki**: Thermal conductivity of each layer **ρi**: Density of each layer **Ci**: Specific heat of each layer **Li**: Thickness of each layer **RESi**: Thermal resistance of the layer that had no thermal mass **DT**: Time increment for the response factors calculation	**Ai, Bi, Ci, Di**: Response factors	X
HEXT	• A sub-routine to calculate the sensible heat extraction rate from the space. • The HEXT sub-routine was one of main sub-routines in the ASHRAE load calculation at 1971. • The HEXT sub-routine used heat balance equation to calculate space air temperature deviation (i.e., θt).	**SCLt**: Sensible cooling load at time t, which was calculated for a constant space design temperature of TM (output of HCL sub-routine) **Xj, Yj**: Weighting factors for use with θt-j (output of RMRT sub-routine) **θt-j**: History of hourly space air temperature deviation from the assumed constant value TM **C**: Average heat extraction rate of the apparatus in a space when the space air temperature is TM **D**: Change in the rate of heat extraction of the apparatus caused by one degree change in space air temperature **HEt-j**: History of heat extracted from the space	**HEt**: Heat extracted from the space at time t	O

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Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
HEATW	• A sub-routine to evaluate transient heat conduction through opaque walls or roof using response factors.	**Aj, Bj, Dj**: Response factors (output of XYZ sub-routine) **FOt**: Outside surface heat transfer coefficient (output of FO sub-routine) **It**: Intensity of total solar radiation incident on the outer surface of wall or roof at time t (output of SUN sub-routine) **TOt-j**: History of outside surface temperatures at times t-1, t-2, t-3 ... t-M **DBt-j**: History of outside air dry-bulb temperature at time t, t-1, t-2 ... t-M **HEATt-j, QOt-j**: History of heat gain at times t, t-1, t-2 ... t-M at interior and exterior surfaces of the walls or roofs **a**: Solar absorptance of the outside surface **ε**: Emittance of the outside surface **α**: Cosine of angle between the zenith and normal to the surface (output of SUN sub-routine) **TCt**: Total cloud amount at time t (output of CLIMATE sub-routine) **TM**: Inside design or any other convenient reference temperature	**TOt**: Outside surface temperature at time t **HEATj**: Heat gain at interior surface of walls and roof at time t	O

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Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
IHG	• A sub-routine to calculate instantaneous heat gains (i.e., sensible and latent heat gains) of a space.	For Windows **NY**: Number of windows **AYk**: Area of each window **UYk**: Overall heat transfer coefficient for each window **SHGk**: Solar heat gain through each window (output of SHG sub-routine) For Exterior walls and roofs **NX**: Number of exterior walls and roofs **AXk**: Area of each exterior wall and roof **HEATk**: Heat gain through each exterior wall and roof (output of HEATW sub-routine) For Lights **NS**: Number of different types of lights (output of SCHEDULE sub-routine) **QSk**: Power input to each type of light (output of SCHEDULE sub-routine) For Internal heat source other than lights **NS'**: Number of different types of internal sensible heat sources other than lights (output of SCHEDULE sub-routine) **QS'k**: Heat generation from each internal sensible heat source (output of SCHEDULE sub-routine) **NL**: Number of different types of internal latent heat sources (output of SCHEDULE sub-routine) **QLk**: Latent heat gain from each internal latent heat source (output of SCHEDULE sub-routine)	For Sensible heat gains **HEATG, HEATG'**: Total hourly solar heat gain through windows **HEATX**: Total hourly heat gain through exterior walls and roofs **HEATIS**: Total power input to lights **HEATDP**: Total sensible heat gain due to heat transfer through doors, partitions, underground walls and floors and due to internal heat sources other than lights **HEATVS**: Total hourly sensible heat gain due to infiltration For Latent heat gain **HEATL**: Total hourly latent heat gain due to internal heat generating sources and due to infiltration	O

Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
IHG	• A sub-routine to calculate instantaneous heat gains (i.e., sensible and latent heat gains) of a space.	For Inside doors **ND**: Number of inside doors **ADk**: Area of each inside door **UDk**: Overall heat transfer coefficient of each inside door For Outside doors **ND'**: Number of outside doors **AD'k**: Area of each outside door **UD'k**: Overall heat transfer coefficient of each outside door For Partitions **NP**: Number of partitions which separated the space from other spaces at different temperatures **APk**: Area of each of these partitions **UPk**: Overall heat transfer coefficient for each of these partition walls For Underground walls **NG**: Number of underground walls **AGk**: Area of each underground wall **UGk**: Overall heat transfer coefficient of each underground wall For Underground floors **NGF**: Number of underground floors **AGFk**: Area of each underground floor **UGFk**: Overall heat transfer coefficient of each underground floor	For Sensible heat gains **HEATG, HEATG'**: Total hourly solar heat gain through windows **HEATX**: Total hourly heat gain through exterior walls and roofs **HEATIS**: Total power input to lights **HEATDP**: Total sensible heat gain due to heat transfer through doors, partitions, underground walls and floors and due to internal heat sources other than lights **HEATVS**: Total hourly sensible heat gain due to infiltration For Latent heat gain **HEATL**: Total hourly latent heat gain due to internal heat generating sources and due to infiltration	O

Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
IHG	• A sub-routine to calculate instantaneous heat gains (i.e., sensible and latent heat gains) of a space.	For Internal Infiltration **NLK**: Number of internal air leakage sources **LEAKk**: Air leakage from each source (output of INFIL sub-routine) For External Infiltration **NLK'**: Number of external air leakage sources **LEAK'k**: Air leakage from each external source (output of INFIL sub-routine) For Temperatures **TAk**: Dry-bulb temperature of each adjacent space **DB**: Dry-bulb temperature of outdoor air (output of CLIMATE sub-routine) **TG**: Average ground water temperature at half underground basement depth **TGW**: Ground water temperature **TZ**: Space dry-bulb temperature (output of SCHEDULE sub-routine) For Humidity ratios **WAk**: Humidity ratio of adjacent space **WO**: Humidity ratio of outdoor air (output of PSY sub-routine) **WZ**: Humidity ratio of indoor space (output of SCHEDULE sub-routine)	For Sensible heat gains **HEATG, HEATG'**: Total hourly solar heat gain through windows **HEATX**: Total hourly heat gain through exterior walls and roofs **HEATIS**: Total power input to lights **HEATDP**: Total sensible heat gain due to heat transfer through doors, partitions, underground walls and floors and due to internal heat sources other than lights **HEATVS**: Total hourly sensible heat gain due to infiltration For Latent heat gain **HEATL**: Total hourly latent heat gain due to internal heat generating sources and due to infiltration	O

Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
HLC	• A sub-routine to calculate heating and cooling loads (i.e., sensible and latent loads) of a space for a constant space temperature. • The HLC sub-routine was one of main sub-routines in the ASHRAE load calculation at 1971. • Suspendid lighting fixture data for weighting factors for the HEATIS variable was derived from 1967 ASHRAE Book of Fundamentals. • The HLC sub-routine used data of pre-calculated weighting factors (i.e., weighting factors for typical office spaces with heavy, medium, or light structure). • The HLC sub-routine was developed by Mitalas and Stephenson's research (Stephenson and Mitalas, 1967; Mitalas and Stephenson, 1967).	**HEATGt-j**: History of hourly values of solar heat gain through windows with no interior shading devices (output of IHG sub-routine) **HEATG't-j**: History of hourly values of solar heat gain through windows with interior shading devices (output of IHG sub-routine) **HEATXt-j**: History of hourly values of heat gain through exterior walls and roofs (output of IHG sub-routine) **HEATISt-j**: History of power input to lights (output of IHG sub-routine) **HEATDPt-j**: History of heat gain through doors, partition walls, underground walls and floors and that due to internal sensible heat sources other than lights (output of IHG sub-routine) **HEATVSt**: Sensible heat gain due to air infiltration (output of IHG sub-routine) **HEATLt**: Latent heat gain due to internal heat sources and infiltration (output of IHG sub-routine) **HLCGt-j**: History of hourly load due to HEATG **HLCXt-j**: History of hourly load due to HEATG', HEATX and HEATDP **HLCISt-j**: History of hourly load due to HEATIS	**SCLt**: Sensible heating and cooling loads of the space **LCLt**: Latent heating and cooling loads of the space	O

Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
RMRT	• A sub-routine to calculate weighting factors that related cooling load of a room to changes in air temperature of a room.	**AF, AC**: Floor area, Ceiling area **AP, AW**: Interior partition wall area, Exterior wall area **AG, AD**: Window glass area, Door area **AFN**: Internal furnishings area **BFj, CFj, DFj**: Thermal response factors for floor (output of XYZ sub-routine) **BCj, CCj, DCj**: Thermal response factors for ceiling (output of XYZ sub-routine) **BPj, CPj, DPj**: Thermal response factors for interior partition walls (output of XYZ sub-routine) **CWj, DWj,**: Thermal response factors for exterior walls (output of XYZ sub-routine) **CDj, DDj**: Thermal response factors for doors (output of XYZ sub-routine) **CFNj, DFNj**: Thermal response factors for internal furnishings (output of XYZ sub-routine) **UG**: Heat transmission coefficient of window glass **CFM**: Rate of supply air	**Xj, Yj**: Weighting factors for the hourly space air temperature deviations from the design value	O
DST	• A sub-routine to identify dates of the daylight saving time.	**YR**: Year **MO**: Month of the year **DAY**: Day of the Month	**DSTX**: The day when the daylight saving time commenced **DSTY**: The day when the standard time resumed **DST**: The daylight saving time indicator	O
WKDAY	• A sub-routine to identify the day of the week.	**YR**: Year **MO**: Month of the year **DAY**: Day of the Month	**WKDAY**: Weekday indicators	O
HOLIDAY	• A sub-routine to identify the national holidays of the United States. • Modifications were allowed for any holidays in any country.	**YR**: Year **MO**: Month of the year **DAY**: Day of the Month	**HOL**: Holiday indicator	O

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Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
PSY	• A sub-routine to conduct approximate psychrometric calculations. • A sub-routine to evaluate the psychrometric properties of moist air. • The PSY sub-routine was used if the Goff-Gratch method (Kusuda, 1969) was not warranted.	**DB**: Dry-bulb temperature (output of CLIMATE sub-routine) **WB**: Wet-bulb temperature (output of CLIMATE sub-routine) **DP**: Dew-point temperature (output of CLIMATE sub-routine) **PB**: Barometric pressure (output of CLIMATE sub-routine) **H**: Enthalpy of moist air **PV**: Partial pressure of water vapor in moist air **t**: Temperature (either DB, WB, or DP)	**PVS**: Partial pressure of water vapor in moisture saturated air **PV**: Partial pressure of water vapor in moist air **W**: Humidity ratio of moist air **H**: Enthalpy of moist air **V**: Volume of moist air **WB**: Wet-bulb temperature **DP**: Dew-point temperature	O
SCHEDULE	• A sub-routine to determine the characteristics of heat generations (i.e., occupancy, lighting, equipment, outdoor ventilation air, and indoor design conditions) in the space on a daily basis.	**DAY**: Day of the year **OCCUPANCY**: Daily schedules in terms of number, activity levels and heat generating characteristics of people **LIGHTING**: Daily schedules of lighting, types of various lighting fixtures, number of each type of light, power input to each light **EQUIPMENT**: Daily schedules of usage of motors, appliances, office machines, computers, etc., heat-generating characteristics of each source **OUTDOOR AIR SUPPLY**: Daily schedules and quantity of outdoor ventilation air **INDOOR DESIGN CONDITIONS**: Daily schedules of space temperature and relative humidity	**NS**: Total number of different daily lighting schedules **(QS)t,k**: Daily schedule of power input for each lighting schedule **NS'**: Total number of sensible heat schedule other than lighting **(QS')t,k**: Daily schedule of heat generation for each sensible heat schedule other than lights **NL**: Total number of latent heat schedules **(QL)t,k**: Daily schedule of heat generation for each latent heat schedule **NT**: Total number of space temperature and humidity schedules **(TZ)t,k, (WZ)t,k**: Daily schedule for each space temperature and humidity schedule **(QVS)t**: Sensible heat gain and loss due to the ventilation air **(QVL)t**: Latent heat gain and loss due to the ventilation air	X

Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
INFIL	• A sub-routine to calculate infiltration rate (i.e., air leakage through each exposure). • Flow characteristics of openings that were used for INF input variable calculation were derived from 1967 ASHRAE Handbook of Fundamentals. • Infiltration characteristics through walls that were used for WALEAK input variable calculation were derived from 1967 ASHRAE Handbook of Fundamentals.	For Outdoor conditions **V**: Wind velocity (output of CLIMATE sub-routine) **DIR**: Wind direction (output of CLIMATE sub-routine) **DB**: Outdoor air dry-bulb temperature (output of CLIMATE sub-routine) **PB**: Barometric pressure (output of CLIMATE sub-routine) For Building description **(HT)k**: Height of building floor (k) above grade **(CFHsupply)k**: Ventilation air supplied to kth floor **(CFHexhaust)k**: Ventilation air exhausted from kth floor **HTT**: Total height of building above grade **NF**: Number of floors above grade **NZB**: Neutral zone of building **NZS**: Neutral zone of elevator and service shaft **TZ**: Indoor air dry-bulb temperature **TS**: Elevator and service shaft temperature **WA'**: Direction measured clockwise from north to normal of exterior wall surface	**LEAKYk,x**: Infiltration through window crack **LEAKFk,x**: Infiltration through frame crack **LEAKDk,x**: Infiltration through doors **WALEAKk,x**: Infiltration through walls **SWINGDk,x**: Infiltration through swinging doors	O

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Table D.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
INFIL	• A sub-routine to calculate infiltration rate (i.e., air leakage through each exposure). • Flow characteristics of openings that were used for INF input variable calculation were derived from 1967 ASHRAE Handbook of Fundamentals. • Infiltration characteristics through walls that were used for WALEAK input variable calculation were derived from 1967 ASHRAE Handbook of Fundamentals.	For Windows and doors **NY**: Number of windows **LY**: Crack length of each window **TY**: Type of window **LF**: Crack length of frame **TF**: Type of frame **ND**: Number of doors **LD**: Crack length of door **TD**: Type of door **INF**: Flow through opening For Outside walls **AW, TW**: Area of wall, Type of wall **WALEAK**: Flow through wall For Swinging doors **NDS**: Number of same type swinging door entrances **NTYPE**: Type of entrance **TRT**: Number of persons per hour per door **SWINGD**: Swinging door entrance infiltration For Surrounding buildings **TB**: Type of surrounding building **NSB**: Ratio of distance between buildings and width of conditioned building in direction of wind For Interior separations **CF**: Equivalent opening of stairway door **CS**: Equivalent opening of elevator doors and service shafts **TM**: Type of opening in stairway door **TE**: Type of opening on elevator doors and service shafts	**LEAKYk,x**: Infiltration through window crack **LEAKFk,x**: Infiltration through frame crack **LEAKDk,x**: Infiltration through doors **WALEAKk,x**: Infiltration through walls **SWINGDk,x**: Infiltration through swinging doors	O

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APPENDIX E

THE ANALYSIS OF THE THIRD 1975 ASHRAE TGER PUBLICATION

Table E.1. *The analysis of the ASHRAE TGER 1975 publication (ASHRAE, 1975)*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
CLIMATE	• A sub-routine to process climatic parameters that were required for hourly load calculations. • The CLIMAT sub-routine used climatic data from National Climatic Center (i.e., data series 144) as input variables. • The CLIMAT sub-routine included the FORTRAN listing form that decoded weather tapes.	Data series 144 (i.e., National Climatic Center's magnetic weather tapes)	**DB**: Dry-bulb temperature **DP**: Dew-point temperature **WB**: Wet-bulb temperature **TC**: Total cloud amount **CT**: Cloud type **V**: Wind velocity **DIR**: Wind direction **ID**: Direct solar radiation **Id,sky**: Sky diffuse radiation **Id,ground**: Ground diffuse radiation **PB**: Barometric pressure **Rain or Snow Fall**: Precipitation data	X
SUN	• A sub-routine to identify solar position. • A sub-routine to calculate intensity of direct normal and diffuse radiation. • The SUN sub-routine used values of declination angle, equation of time, apparent solar constant, atmospheric extinction coefficient, and sky diffuse factor, which was derived from the 1972 ASHRAE Handbook of Fundamentals.	**L**: Latitude **l**: Longitude **TZN**: Time zone number **d**: Date **t**: Time **DST**: Daylight saving time indicator (output of DST sub-routine) **ρg**: Ground reflectivity **CN**: Clearness number	**SRT, SST**: Sunrise and sunset time **COS(Z), COS(W), COS(S)**: Direction cosines of direct solar beam **COS(η)**: Cosine of angle of incidence of direct solar radiation **SALT**: Solar altitude **SAZM**: Solar azimuth **IDN**: Intensity of direct solar radiation for a cloudless condition **BS**: Diffuse sky radiation (sky brightness) **BG**: Ground reflected radiation (ground brightness)	O

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
SOLAD	• A sub-routine to calculate direct and diffuse solar radiation incident on a surface. • The SOLAD sub-routine didn't provide the calculation of diffuse radiation on a surface under cloudless sky because of insufficient research.	**P, C**: Cloudless sky factor, Standard diffuse sky factor **CC**: Cloud cover **CCF**: Cloud cover factor (output of CCF sub-routine) **WA**: Azimuth angle of the surface **WT**: Tilt angle of the surface **COS(Z), COS(W), COS(S)**: Direction cosines of direct radiation **IDN**: Intensity of the direct normal solar radiation for a cloudless condition **BS**: Diffuse radiation from the cloudless sky **BG**: Diffuse radiation from ground **SALT**: Solar altitude angle	**ID**: Direct radiation on a surface under cloudless sky **IDC**: Direct radiation on a surface under cloudy sky **Idc**: Diffuse radiation on a surface under cloudy sky **ITC**: Total radiation on a surface under cloudy sky	O
CCF	• A sub-routine to calculate the cloudy day solar radiation.	**IS**: Season index **CAj, TCA**: Cloud amount and total cloud amount **TOCj**: Type of cloud	**CCF**: Cloud cover factor	O
TAR	• A sub-routine to calculate several factors (i.e., transmission factors, absorption factors, and reflection factors) for windows. • The TAR sub-routine included the alternative calculation of transmissivity and absorptivity, which was developed by Stephenson (Stephenson, 1967).	**COS(η)**: Cosine of angle of incidence of direct solar radiation (output of SUN sub-routine) **k*l**: Extinction coefficient*thickness	Single-pane glass **Aη**: Absorptivity for direct radiation **Tη**: Transmissivity for direct radiation **Ad**: Absorptivity for diffuse radiation **Td**: Transmissivity for diffuse radiation Double-pane glass **R1η, R2η, R1d, R2d**: Reflectivity of inner and outer panes **Aη,outer, Aη,inner**: Absorptivity for direct radiation **Ad,outer, Ad,inner**: Absorptivity for diffuse radiation **Tη**: Transmissivity for direct radiation **Td**: Transmissivity for diffuse radiation	O

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Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
SHG	• A sub-routine to calculate solar heat gain through windows.	**IDN**: Intensity of direct normal solar radiation (output of SUN sub-routine) **BS**: Sky brightness (output of SUN sub-routine) **BG**: Ground brightness (output of SUN sub-routine) **COS(η)**: Cosine of the angle of incidence of direct solar radiation (output of SUN sub-routine) **FWS**: Form factor between the window and the sky **FWG**: Form factor between the window and the ground **RO, RA, RI**: Thermal resistances at outside surface, air space, and inside surface **SLA**: Sunlit area factor (output of SHADOW sub-routine) **SC**: Shading coefficient **Tη, Td**: Transmission factors of direct and diffuse radiation for windows (output of TAR sub-routine) **Aη,outer, Aη,inner, Ad,outer, Ad,inner**: Absorption factors of direct solar and diffuse radiation through outer and inner window panes (output of TAR sub-routine)	**SHG**: Solar heat gain through glass	O
SHADOW	• A sub-routine to calculate external shadows on a building. • The Groth and Lokmanhekim's research (1969) contributed to the development of SHADOW sub-routine.	Coordinates and dimensions of the exterior surface **SALT**: Solar altitude (output of SUN sub-routine) **SAZM**: Solar azimuth angles (output of SUN sub-routine) Transmissivity of Sending Polygons (SP)	**SLA**: Sunlit area factor **PIC**: Pictorial representation of shadow shapes	O

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Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
SHADOW-1	• A sub-routine to calculate the ratio of the sunlit and shaded area of a given window that was cast by overhang and side fins. • The FORTRAN listing form for SHADOW-1 sub-routine was included. • Tseng-Yao Sun, Ayres and Hayakawa contributed to the development of SHADOW-1 sub-routine. • The calculation sequence of SHADOW-1 sub-routine was derived from the Tseng-Yao's research (Tseng-Yao, 1968).	**HT, FL**: Window height, Window width **FP**: Depth of the overhang **AW**: Distance from top of the window to the overhang **BWL**: Distance of the overhang extended beyond the left edge of the window **BWR**: Distance of the overhang extended beyond the right edge of the window **D**: Depth of vertical projection at the end of the overhang **FP-1**: Depth of the left fin **A-1**: Distance of the left fin extended above the top of the window **B-1**: Distance from the left edge of the window to the left fin **C-1**: Distance of the left fin stop short above the bottom of the window **FP-2**: Depth of the right fin **A-2**: Distance of the right fin extended above the top of the window **B-2**: Distance from the right edge of the window to the right fin **C-2**: Distance of the right fin stop short above the bottom of the window **PHI**: Solar azimuth angle **WAZI**: Window azimuth angle **COSZ**: Cosine of solar zenith angle	**SHRAT**: Ratio of sunlit area to the total window area	X
SHADOW-2	• A sub-routine to determine whether a given window was shaded by a remote object. • The SHADOW-2 sub-routine didn't result in specific output variables, but determined whether a given window was shaded or not. • Tseng-Yao Sun, Ayres, Cohen and Hayakawa contributed to the development of SHADOW-2 sub-routine.	**α-1**, **α-2**: Azimuth shadow limit angles **β-1**, **β-2**: Altitude shadow limit angles **WAZI**: Window azimuth angle **PHI**: Solar azimuth angle **BETA**: Solar altitude angle		O

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
FIJ	• A sub-routine to calculate radiation shape factors between inside surfaces of a room. • The FIJ sub-routine was developed by D.M. Burch and B. A. Peavy at the National Bureau of Standards (NBS). • The FORTRAN listing form for FIJ sub-routine was included.	**L**: Length of room **W**: Width of room **H**: Height of room **A**: Height of windows or doors **B**: Width of windows or doors **C**: Distance of left edge of window from left wall **D**: Height of lower edge of window from floor	**Fm-n**: Radiation shape factors between various inside surfaces of a room	O
FIJ-1	• A sub-routine to calculate radiation shape factors between attic surfaces where the attic had a gabled room. • The FIJ-1 sub-routine was developed by B. A. Peavy and D.M. Burch at the National Bureau of Standards (NBS).	**L**: Length of attic floor **W**: Width of attic	**Fm-n**: Radiation shape factors between various inside surfaces of an attic with a gabled roof	O
FI	• A sub-routine to calculate inside surface heat transfer coefficient. • The FI sub-routine formalized tabular data of the 1972 ASHRAE Handbook of Fundamentals to approximate inside surface heat transfer coefficients.	**IDIR**: Heat flow direction index **ε**: Emittance of the surface **IV**: Moving air index	**FI**: Inside surface heat transfer coefficient	O
FO	• A sub-routine to calculate outside surface heat transfer coefficient.	**V**: Wind velocity (output of CLIMATE sub-routine) **IS**: Outside surface index **DIR**: Wind direction (output of CLIMATE sub-routine) **WA**: Wall azimuth angle	**FO**: Outside surface heat transfer coefficient **FOC**: Convective component of the outside surface heat transfer coefficient	O

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
ACR	• A sub-routine to calculate air cavity thermal resistance within walls and roofs. • The polynomial equations for determining air cavity thermal resistance (RES) was derived from Robinson's research (Robinson et al., 1957).	**DT**: Temperature difference across the air space **L**: Thickness of the air space **IDIR**: Heat flow direction index **ε-1**, **ε-2**: Emittance of the surfaces facing the air cavity **ATC**: Average temperature of the air cavity	**RES**: Air cavity thermal resistance	O
XYZ	• A sub-routine to calculate Conduction Transfer Functions (CTFs). • The research of Stephenson and Mitalas (1971) that discussed modified conduction transfer functions contributed to the development of XYZ sub-routine. • To calculate conduction transfer functions by using the XYZ sub-routine, the sequence of input variables followed the particular direction that was adopted for the specific calculation convention (i.e., from the inside layer to the outside layer or vice versa). • The CP-26 program and the Response Factor Calculation program calculated conduction transfer functions for multi-layered walls, roofs and floors.	**NL**: Number of layers of a given structure **Ki**: Thermal conductivity of i-th layer **ρi**: Density of i-th layer **Ci**: Specific heat of i-th layer **Li**: Thickness of i-th layer **RESi**: Thermal resistance of air cavities and surface resistance layers **DT**: Time increment for the conduction transfer functions	**Xj, Yj, Zj**: Conduction Transfer Functions (CTFs)	X

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
HEATW	• A sub-routine to evaluate transient heat conduction through opaque walls or roofs using Conduction Transfer Functions (CTFs). • To calculate the input variable of R (i.e., common ratio of the response factors), the response factors and conduction transfer functions followed equations that represented specific relationships to each other. • The equation for determining heat loss to the sky was derived from Hoglund's research (Hoglund et al., 1967). • The method to calculate heat loss to the ground through the floor on grade was applicable to the floor over the un-vented crawl space.	**Xj, Yj, Zj**: Conduction transfer functions (output of XYZ sub-routine) **R**: Common ratio of the response factors **N**: Number of the significant terms to be used for the conduction heat transfer calculation (output of XYZ sub-routine) **FOt**: Outside surface heat transfer coefficient **ITt**: Total solar radiation intensity on the outside surface (output of SOLAD sub-routine) **TISt-j**: History of inside surface temperatures at times t-1, t-2, t-3 ... t-N **TOSt-j**: History of outside surface temperatures at times t-1, t-2, t-3 ... t-N **DBt**: Outdoor air dry-bulb temperature **HEATt-l**: Heat loss at the interior surface to the outdoor environment at the previous hour **QOt-l**: Heat loss at the exterior surface to the outdoor environment at the previous hour **a**: Solar absorption coefficient at the exterior surface **α**: Cosine of angle subtended by a vertical line and the surface normal (output of SUN sub-routine) **TCt**: Total cloud amount (output of CLIMATE sub-routine) **TM**: A reference temperature	**HEATt**: Heat gain at exterior walls and roofs **HEATt**: Heat gain at interior walls and floor/ceiling sandwich **HEATt**: Heat loss to the ground through the floor on grade **HEATt**: Heat gain at floor over the vented crawl space	O
HEXT	• A sub-routine to calculate the sensible heat extraction rate from the space.	**SCLt**: Sensible cooling load at time t, which was calculated for a constant space design temperature of TM (output of HCL sub-routine) **Xj, Yj**: Weighting factors for use with θt-j (output of RMRT sub-routine) **θt-j**: History of hourly space air temperature deviation from the assumed constant value TM **C**: Average heat extraction rate of the apparatus in a space when the space air temperature was TM **D**: Change in the rate of heat extraction of the apparatus caused by one degree change in space air temperature **HEt-j**: History of heat extracted from the space	**HEt**: Heat extracted from the space at time t	X

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
IHG	• A sub-routine to calculate instantaneous heat gains (i.e., sensible and latent heat gains) of a space.	**For Windows** **NY**: Number of windows **AYk**: Area of each window **UYk**: Overall heat transfer coefficient for each window **SHGk**: Solar heat gain through each window (output of SHG sub-routine) **For Exterior walls and roofs** **NX**: Number of exterior walls and roofs **AXk**: Area of each exterior wall and roof **HEATk**: Heat gain through each exterior wall and roof (output of HEATW sub-routine) **For Lights** **NS**: Number of different types of lights **QSk**: Power input to each type of light **For Internal heat source other than lights** **NS'**: Number of different types of internal sensible heat sources other than lights **QS'k**: Heat generation from each internal sensible heat source **NL**: Number of different types of internal latent heat sources **QLk**: Latent heat gain from each internal latent heat source **For Inside doors** **ND**: Number of inside doors **ADk**: Area of each inside door **UDk**: Overall heat transfer coefficient of each inside door	For Sensible heat gains **HEATG, HEATG'**: Total hourly solar heat gain through windows **HEATK**: Total hourly heat gain through exterior walls and roofs **HEATIS**: Total power input to lights **HEATDP**: Total sensible heat gain due to heat transfer through doors, partitions, underground walls and floors and internal heat sources other than lights **HEATVS**: Total hourly sensible heat gain due to infiltration For Latent heat gain **HEATL**: Total hourly latent heat gain due to internal heat generating sources and infiltration	O

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
IHG	• A sub-routine to calculate instantaneous heat gains (i.e., sensible and latent heat gains) of a space.	For Outside doors **ND'**: Number of outside doors **AD'k**: Area of each outside door **UD'k**: Overall heat transfer coefficient of each outside door For Partitions **NP**: Number of partitions which separated the space from other spaces at different temperatures **APk**: Area of each of these partitions **UPk**: Overall heat transfer coefficient for each of these partition walls For Underground walls **NG**: Number of underground walls **AGk**: Area of each underground wall **UGk**: Overall heat transfer coefficient of each underground wall For Underground floors **NGF**: Number of underground floors **AGFk**: Area of each underground floor **UGFk**: Overall heat transfer coefficient of each underground floor For Internal Infiltration **NLK**: Number of internal air leakage sources **LEAKk**: Air leakage from each source (output of INFIL sub-routine)	For Sensible heat gains **HEATG, HEATG'**: Total hourly solar heat gain through windows **HEATK**: Total hourly heat gain through exterior walls and roofs **HEATIS**: Total power input to lights **HEATDP**: Total sensible heat gain due to heat transfer through doors, partitions, underground walls and floors and internal heat sources other than lights **HEATVS**: Total hourly sensible heat gain due to infiltration For Latent heat gain **HEATL**: Total hourly latent heat gain due to internal heat generating sources and infiltration	O

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
IHG	• A sub-routine to calculate instantaneous heat gains (i.e., sensible and latent heat gains) of a space.	For External Infiltration **NLK'**: Number of external air leakage sources **LEAK'k**: Air leakage from each external source (output of INFIL sub-routine) For Temperatures **TAk**: Dry-bulb temperature of each adjacent space **DB**: Outside dry-bulb temperature (output of CLIMATE sub-routine) **TG**: Average ground water temperature at half underground basement depth **TGW**: Ground water temperature **TZ**: Space dry-bulb temperature For Humidity ratios **WAk**: Humidity ratio of adjacent space **WO**: Outside air humidity ratio (output of PSY sub-routine) **WZ**: Space humidity ratio	For Sensible heat gains **HEATG, HEATG'**: Total hourly solar heat gain through windows **HEATK**: Total hourly heat gain through exterior walls and roofs **HEATIS**: Total power input to lights **HEATDP**: Total sensible heat gain due to heat transfer through doors, partitions, underground walls and floors and internal heat sources other than lights **HEATVS**: Total hourly sensible heat gain due to infiltration For Latent heat gain **HEATL**: Total hourly latent heat gain due to internal heat generating sources and infiltration	O
DST	• A sub-routine to identify dates of the daylight saving time.	**YR**: Year **MO**: Month of the year **DAY**: Day of the Month	**DSTX**: The day when the daylight saving time commenced **DSTY**: The day when the standard time resumed **DST**: The daylight saving time indicator	O
WKDAY	• A sub-routine to identify the day of the week.	**YR**: Year **MO**: Month of the year **DAY**: Day of the Month	**WKDAY**: Weekday indicators	O

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
HOLDAY	• A sub-routine to identify the national holidays of the United States. • Modifications were allowed for any holidays in any country.	**YR**: Year **MO**: Month of the year **DAY**: Day of the Month	**HOL**: Holiday indicator	O
ATTIC	• A sub-routine to calculate heating and cooling loads for an attic space. • The ATTIC sub-routine at 1975 didn't include exact information about input variables, output variables, and calculation sequence, but included general information about the ATTIC sub-routine. • To evaluate the non-ventilated attic space, the ATTIC sub-routine used Conduction Transfer Functions (CTFs). • To evaluate the ventilated attic space, the ATTIC sub-routine used RMTMP sub-routine.	X	X	X

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
HLC	• A sub-routine to calculate approximate heating and cooling loads (i.e., sensible and latent loads) by using weighting factors. • The HLC sub-routine used data of pre-calculated weighting factors (i.e., weighting factors for typical office spaces with heavy, medium, or light structure). • The HLC sub-routine was developed by Mitalas and Stephenson's research (Stephenson and Mitalas, 1967; Mitalas and Stephenson, 1967).	**HEATGt-j**: History of hourly values of solar heat gain through windows with no interior shading devices (output of IHG sub-routine) **HEATG't-j**: History of hourly values of solar heat gain through windows with interior shading devices (output of IHG sub-routine) **HEATXt-j**: History of hourly values of heat gain through exterior walls and roofs (output of IHG sub-routine) **HEATISt-j**: History of power input to lights (output of IHG sub-routine) **HEATDPt-j**: History of heat gain through doors, partition walls, underground walls and floors and that due to internal sensible heat sources other than lights (output of IHG sub-routine) **HEATVSt**: Sensible heat gain due to air infiltration (output of IHG sub-routine) **HEATLt**: Latent heat gain due to internal heat sources and infiltration (output of IHG sub-routine) **HLCGt-j**: History of hourly load due to HEATG **HLCXt-j**: History of hourly load due to HEATG', HEATX and HEATDP **HLCISt-j**: History of hourly load due to HEATIS	**SCLt**: Sensible heating and cooling loads of the space **LCLt**: Latent heating and cooling loads of the space	O

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Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
RMTMP	• A sub-routine to calculate heating and cooling loads (i.e., sensible and latent loads) or room temperature.	**NS**: Total number of heat transfer surfaces contributing to the room heat balance **Si**: Area of i-th heat transfer surface **Xi,j, Yi,j, Zi,j**: Conduction transfer functions of i-th surface (output of XYZ sub-routine) **Ni**: Number of conduction transfer function terms **Ri**: Common ratio for the conduction transfer function **TOSi,t-j**: Outside surface temperature history **TISi,t-j**: Inside surface temperature history **TAt**: Air temperature of the room at time t **DBt**: Outdoor air temperature **TSt**: Supply air temperature from the central system **Hi**: Inside surface convection heat transfer coefficient **Fi,k**: Radiation heat exchange view factor **Ei**: Emissivity **Ri,t**: Radiant heat flux impinging upon i-th surface from various sources (i.e., solar radiation, radiation from lights, occupants, and equipment) **Qi,t**: Heat conducted into i-th surface **GLt**: Mass air flow rate due to air leakage **GSt**: Mass air flow rate of the supply air from the central system **QEQUP**: Internal heat generated from equipment **QOCPS**: Internal heat (sensible) generated from occupants **QLITE**: Heat from lights **RE**: Fraction of convective internal heat gain from equipment **RO**: Fraction of convective internal heat gain from occupants **RL**: Fraction of convective internal heat gain from lights **SHGi,t**: Solar incident radiation on i-th surface	**QHLS**: Sensible heating load of the space **QHLL**: Latent heating load of the space **QCLS**: Sensible cooling load of the space **QCLL**: Latent cooling load of the space **TA**: Space temperature **WA**: Space humidity ratio	O

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
RMRT	• A sub-routine to calculate weighting factors for deviation of space air temperature from the design value.	**AF**: Floor area **AC**: Ceiling area **AP**: Interior partition wall area **AK**: Corridor wall area **AW**: Exterior wall area **AG**: Window glass area **AD**: Door area **AFN**: Internal furnishings area **BFj, CFj, DFj**: Transfer functions for floor (output of XYZ sub-routine) **BCj, CCj, DCj**: Transfer functions for ceiling (output of XYZ sub-routine) **BKj, DKj**: Transfer functions for corridor wall (output of XYZ sub-routine) **BPj, CPj, DPj**: Transfer functions for interior partition walls (output of XYZ sub-routine) **CWj, DWj,**: Transfer functions for exterior walls (output of XYZ sub-routine) **CDj, DDj**: Transfer functions for outside door (output of XYZ sub-routine) **CFNj, DFNj**: Transfer functions for internal furnishings (output of XYZ sub-routine) **UG**: Heat transmission coefficient of window glass **CFM**: Rate of air flow through the room	**Xj, Yj**: Weighting factors for the deviation of space temperature	O

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
PSY	• A sub-routine to conduct approximate psychrometric calculations. • A sub-routine to evaluate the psychrometric properties of moist air. • The PSY sub-routine was used if the Goff-Gratch method (Kusuda, 1969) was not warranted. • The FORTRAN listing form for PSY sub-routine was included, which was developed by the National Bureau of Standards.	**DB**: Dry-bulb temperature (output of CLIMATE sub-routine) **WB**: Wet-bulb temperature (output of CLIMATE sub-routine) **DP**: Dew-point temperature (output of CLIMATE sub-routine) **PB**: Barometric pressure (output of CLIMATE sub-routine) **H**: Enthalpy of moist air **PV**: Partial pressure of water vapor in moist air **t**: Temperature (either DB, WB, or DP)	**PVS**: Partial pressure of water vapor in moisture saturated air **PV**: Partial pressure of water vapor in moist air **W**: Humidity ratio of moist air **H**: Enthalpy of moist air **V**: Volume of moist air **WB**: Wet-bulb temperature **DP**: Dew-point temperature	O
INFIL	• A sub-routine to calculate air infiltration. • Air leakage data for the equivalent flow coefficient and pressure exponent was derived from 1972 ASHRAE Handbook of Fundamentals. • The CP-35 program included algorithm to calculate the air infiltration in buildings, which was described in the INFIL sub-routine.	**V**: Wind speed **DIR**: Wind direction **DB**: Outdoor air dry-bulb temperature **PB**: Barometric pressure **NF**: Number of above-grade floors **HTT**: Total height of building (from above-grade) **TZ**: Indoor air temperature **TS**: Elevator and service shaft temperature **WA'**: Direction angle of the building **HTk**: Height of floor **CFMSPk**: Ventilation air supplied to the floor **CFMEXk**: Ventilation air exhausted from the floor	**LEAKWDk,j**: Window leakage **LEAKFMk,j**: Window frame leakage **LEAKDRk,j**: Door leakage **LEAKWLk,j**: Wall leakage **LEAKCLk**: Ceiling leakage **LEAKFLk**: Floor leakage **LEAKELk**: Elevator leakage **LEAKSSk**: Service shafts leakage **LEAKFSk, LEAKESk**: Leakages between the floor levels within the shafts	O

Table E.1. *Continued*

Symbol	Description / Note	Input Variables	Output Variables	Calculation Sequence
SCHEDULE	• A sub-routine to calculate heat gains from lighting, equipment, occupancy and ventilation.	**QLITEi,j**: Lighting schedules **QEQUPi,j**: Equipment use schedules **QOCUPi,j**: Occupancy schedule **QVENTi,j**: Ventilation fan operating schedule **ROOMDBi,j**: Space thermostat setting schedule **ROOMRHi,j**: Space humidistat setting schedule **QLITX**: Maximum electric power demand for lighting for the 24 hour **QEQUPX**: Maximum electric power demand for appliances for the 24 hour **QOCUPX**: Maximum number of equivalent sedentary adult occupants during the 24 hour **QVENTX**: Maximum amount of ventilation air supply during the 24 hour **QHTWTX**: Maximum amount of hot water demand during the 24 hour **Day**: Day of the year **QOS**: Sensible heat loss of a sedentary adult **QOL**: Latent heat loss of a sedentary adult **WO**: Humidity ratio of the outdoor air **WI**: Humidity ratio of the indoor air **QWT**: Heat needed to generate one gallon of hot water	**QSi,j**: Heat generated from lights **QS'i,j**: Sensible heat generated from equipment and occupants **QLi,j** Latent heat generated from occupants **LEAKi,j**: Sensible heat gain due to ventilation air **LEAK'i,j**: Latent heat gain due to ventilation air	O

APPENDIX F

THE ANALYSIS OF THE PROCEEDINGS OF THE FIRST INTERNATIONAL SYMPOSIUM THAT

WAS HELD BY KUSUDA

Table F.1. *The analysis of the proceedings of the first international symposium on the application of computer to building environmental system simulations (Kusuda ed., 1971)*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
1	Welcome Address	F. K. Willenbrock	National Bureau of Standards (USA)	• Explained the purpose of this First Symposium on the Use of Computers for Environmental Engineering Related to Buildings • Provided the historical information about how the computer was applied to building system research	• Discussed the history of development of building research and technology from 1900 to 1970
2	Keynote Address: Some Objectives for the Technological Man	Bruce J. Graham	Skidmore, Owings and Merrill (USA)	• Covered the purpose of the first symposium which discussed important Issues that faced big cities in the 1970's	• Discussed the issues which were caused by the occurrence of big cities in the 1970's
3	An Insight Into Three Dimensional Graphics	A. R. Paradis	Dynamic Graphics, Inc. (USA)	• Discussed the three dimensional computer graphics program which was a cost-effective and time saving tool for perspective drawings	• Discussed the technical aspects of the computer graphics program, which included: software, hardware, program structure and algorithms for solving the hidden line

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
4	The Use of Graphics in the Development of Computer-Aided Environmental Design for Two-Stories Houses	A. Bijl, T. Renshaw and D. F. Barnard	University of Edinburgh (Scotland)	• Provided the information about the important factors and relevance of existing precedent in the design practice for house design and production • Discussed how these key factors and relevance of the house design practice were properly applied to a computer design system	• Provided the information about the design process of houses, which based on graphic stages • Discussed the key input elements for house computer design
5	Anticipatory Techniques for Enhancing Remote Computer Graphics	T. N. Pyke	National Bureau of Standards (USA)	• Discussed the anticipatory techniques for improving the performance of graphical display terminals which were located remotely from a central computer system	• Provided the information about the methods (i.e., communication line) which enabled users to communicate from the remote terminal to the central system
6	Computer Graphic Data Structures for Building Design	M. Abrams	National Bureau of Standards (USA)	• Discussed the key variables of graphical data structures for the digital representation of graphical information in building design	• Provided the comprehensive information about the computer graphic data for building design, which included: key factors, limitation, application and examples • Provided the several conceptual models of graphical data structures by utilizing diagrams and flow charts
7	A Systems Model for Environmental Design of Buildings	C. L. Gupta	CSIRO (Australia)	• Discussed improved method which considered the interactive aspects of thermal and lighting in building to achieve optimum thermal design	• Covered important variables for thermal design and lighting design • Provided algorithms for the environmental system optimization
8	Design Considerations for a Practical Heat Gain Computer Code	S. F. Normann and N. E. Mutka	DERAC Consultants, Inc. (USA)	• Discussed improved method for heat gain and design condition computation	• Covered key variables which affected heat gain calculations • Provided algorithms of computational sequence which displayed correlation of sub-routines

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Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
9	Solving the Communication Problem in a Computer-Controlled Environmental System	T. Prickett, J. L. Seymour, D. L. Willson and R. W. Haines	Collins Radio Company (USA)	• Discussed traditional methods of the data communication, which included: hardwiring, frequency multiplexing and electro-mechanical multiplexing • Discussed improved method (i.e., time-division multiplexing), which was a digital communication system using time-division concept	• Provided information about the use of analog and digital computer for the HVAC systems control • Discussed the history of supervisory HVAC systems control
10	A Linear Programming Model for Analyzing Preliminary Design Criteria for Multizone Air Distributions Systems	R. A. Gordon	Cornell, Howland, Hayes and Merryfield (USA)	• Discussed linear programming model to evaluate conceptual design systems (i.e., air volume, duct sizing, spatial description, unit costs and duct costs) of multi-zone air distribution systems	• Covered key variables for the computation of multi-zone air distributions systems through a series of sub-systems
11	A Conceptual Survey of Computer-oriented Thermal Calculation Methods	C. L. Gupta, J. Spencer R. Muncey	CSIRO (Australia)	• Provided detailed information about the cooling and heating loads calculation methods, which included: numerical methods, harmonic methods and response factor methods	• Discussed the origins, key equations and procedure of numerical methods • Discussed key documents which explained the origin of response factor method
12	Method for Thermal Calculations Using Total Building Response Factors	R. Muncey, J. Spencer and C. Gupta	CSIRO (Australia)	• Discussed the method which determined the response factor for the total building	• Covered the improved response factor method which was suitable for computer application than previous response factor methods

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
13	Calculation of Building Thermal Response Factors as Wiener Filter Coefficients	T. Kusuda	National Bureau of Standards (USA)	• Provided detailed explanation of the building thermal response factors • Compared the output of building response factors with those of Post Office program	• Provided detailed explanation of the building thermal response factors, which included: applied key equations, sample calculations, advantages and limitations of the method
14	Thermal Studies by Electrical Simulation. Application example to the study of the heating equipment of an apartment building heated by electricity	J. Anquez L. Bertolo	CSTB (France)	• Discussed the simulator which was able to evaluate heat transfer in buildings by utilizing RC network method • Covered case study of the electric heating device of an apartment building	• Provided detailed explanation about RC network method • Discussed an analog computer simulator with detailed explanation
15	Analog Computer Simulation of an Air Conditioning System in a Commercial Building Incorporating Yearly Weather Data	J. Magnussen	Honeywell, Inc. (USA)	• Discussed the method which determined system operating costs by utilizing analog computer simulation	• Covered an overall simulation process by using analog computer • Provided information about important analysis methods, which included: lumped nodal point method, electrical circuit and transfer function

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
16	Experience with a Thermal Network Analysis Program Applied to Heat Flow in Buildings	N. Sheridan	University of Queensland (Australia)	• Discussed the network analysis program to calculate heat flow in building • Covered analysis methods for heat flow calculations as well as algorithm ,which were applied to the program	• Provided detailed explanation about thermal models and thermal network, which included: heat flow in boundary conditions, thermal response method, finite difference method and node concepts
17	A Method of Computer Simulation Through Modified Signal Flow Graphs and Operator Concepts and Its Application to Syntheses of Heating Equipment Capacities	S. Matsuura	Hokkaido University (Japan)	• Discussed the new method for physical system simulation, which was based on concepts of signal flow graphs and operator	• Discussed the characteristics of simulation procedures of analog and digital computers for building environmental design
18	Shared Time System Computer Programs for Heating and Cooling Energy Analysis of Building Air Conditioning Systems	C. J. R. McClure and J. C. Vorbeck	Mechanical Engineering Data Services, Inc. (MEDSI) (USA)	• Provided detailed information about MEDSI program • Contained input data form, basic logic diagram, and three logic diagrams for system programs	• Provided detailed analysis of one of the first HVAC system simulation programs (i.e., MEDSI program) • Contained diagrams for HVAC system simulations (i.e., reheat system, heat-cool-off system, and multi-zone or double duct system)

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
19	The Program of the ASHRAE Task Group on the Determination of Energy Requirements for Heating and Cooling Buildings	R. H. Tull	ASHRAE Task Group on Energy Requirements for Heating and Cooling Buildings (USA)	• Provided information about the activities of ASHRAE Task Group around 1970 regarding building energy requirement	• Contained information about the Task Group subcommittee #2 and #3, which had the task of HVAC system simulation
20	Successful Application of Energy Analysis Programs	K. M. Graham	Southern Counties Gas Company (USA)	• Discussed the important factors to implement new energy analysis programs • Provided information about the origin of GATE program, HCC program, and APEC	• Provided the information about one of the earliest building energy analysis programs (i.e., GATE program) which had HVAC system simulation as a part of a series of the program
21	Comparison of a Short Form Load and Energy Program with the Detailed Westinghouse Load and Energy Programs	B. G. Liebtag and J. R. Sarver	Duquesne Light Company (USA)	• Compared the short form energy programs which were developed by Duquesne Light Company and Westinghouse energy program	• Contained the information about the Westinghouse Electric Company's energy program which was one of the earliest energy program in the U.S. and had HVAC system simulation as a part of a series of the program • Discussed one of the methods to calculate air conditioning energy consumption (i.e. equivalent full load hour method) which was applied to the short form energy programs
22	Energy Estimating - How Accurate?	R. Romanchek	Pensylvanic Power and Light Company (USA)	• Discussed new program which calculated thermal loads and total energy use by utilizing the degree-day method • Discussed the validity of application of simplified procedure to estimate energy consumption	• Discussed key variables of this program to calculate heating and cooling loads • Contained comprehensive information about the field of building simulation around 1970, which included: organizations, analog computer and technical problems

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
23	Instantaneous Cooling Loads by Computer Based on ASHRAE's Time Average Method	R. V. Thomas	Naval Facilities Engineering Command (USA)	• Discussed the instantaneous cooling loads calculation which was based on ASHRAE's time averaging method	• Discussed important variables for instantaneous cooling loads calculation, which were applied to this program (i.e., fenestration area, walls, roof and latent heat) • Provided a diagram, which explained the difference between instantaneous heat gain and instantaneous cooling load
24	Computer Method for Estimating Net Energy Requirement for Heating Buildings	N. E. Hager	Armstrong Cork Company (USA)	• Discussed new analysis method (i.e., net energy method) for heating load calculation, which was based on conventional methods (i.e., degree-day method and NEMA method) and internal heat gain	• Provided detailed explanation about the net energy method with key equations, reference data, comparison with conventional methods and program output
25	The Practical Application of Small Computers for Heating and Air Conditioning Load Evaluation	T. Romine	Romine and Slaughter, Inc. (USA)	• Discussed technical problems of consulting firms which evaluated heating and air conditioning load around 1970 • Provided detailed information about the APEC HCC program	• Covered key variables for peak load calculation, which were used in the APEC HCC programs
26	Accuracy Requirements for Computer Analysis of Environmental Systems	R. Cook and J. A. Serfass	Westinghouse Electric Corporation (USA)	• Provided the information about the accuracy requirements for this program to select between alternative competing systems (i.e., energy source, energy conservation system, etc.)	• Provided the information about how to determine quantification of accuracy required by computer programs

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Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
27	Calculation of Energy Requirements with the Proposed ASHRAE Algorithms for U. S. Postal Buildings	M. Lokmanhekim	GARD/GATC (USA)	• Provided the information about the Computer Program for Analysis of Energy Utilization in Postal Facilities which was developed by GARD/ GATC	• Discussed the post office program, which was one of the earliest energy program in the U.S. and had HVAC system simulation as a part of a series of the program • Provided explanation about each sub-program and flow chart of sub-program sequence which were used in the post office program
28	An Accurate Computing Method for the Analysis of the Non-Steady Thermal Behavior of Office Buildings	S. Oegema and P. Euser	Institute of Applied Physics, TNO-TN (Netherlands)	• Discussed the computation method, which was based on implicit difference method, to calculate non-steady heat transfer in a room of office building	• Provided detailed explanation about the methods for heat transfer simulation (i.e., conduction, convection and radiation) in a room • Discussed the thermal models of heat transfer and unit room for simulating non-steady thermal behavior in office building
29	A Successive Integration Method for the Analysis of the Thermal Environment of Building	N. Aratani, N. Sasaki and M. Enai	Hokkaido University (Japan)	• Discussed new method (i.e., successive integration method) to calculate room air temperature or thermal loads variations for each time interval	• Covered the thermal environment evaluation method in various thermal conditions and time intervals, which was based on successive integration method
30	Digital Simulation of Building Thermal Behavior	M. J. Wooldridge	CSIRO (Australia)	• Discussed a mathematical model of building thermal environment, which calculated internal air temperatures and humidity	• Discussed the heat transfer calculation through walls ,which was based on finite difference numerical procedures • Discussed key variables which affected sensible heat transfer to the indoor air within a zone

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
31	A Computer Program for the Calculation of Individual Room Air Temperature of Multi-Roomed Buildings	K. Rao and P. Chandra	Central Building Research Institute (India)	• Discussed the calculation and computation method of individual room air temperature in multi-roomed buildings • Discussed key variable which affected thermal load calculations • Discussed simulation procedure which was suitable for small machine	• Discussed the computational method for heat transfer calculation (i.e., Matrix method), which was suitable for high speed computer (i.e., digital computer)
32	A Practical Method for Calculating Room Temperature Heating Load and Cooling Load of a Multi-room	K. Ochifuji	Hokkaido University (Japan)	• Discussed the practical method for calculating room temperature of a multi-room system by means of a digital computer of relatively small capacity at reasonable cost	• Discussed reliable and simplified simulation method for calculating indoor air temperature • Discussed how to simplify the mathematical models which calculated room air temperature
33	Simulation by Digital Computer Program of the Temperature Variation in a Room	G. Brown	The Royal Institute of Technology (Sweden)	• Discussed the computer program which calculated time variation of temperature in a room by utilizing heat balance equations • Provided application examples to verify temperature variation in a room	• Provided detailed explanation about the heat balance equations for material layers, windows and room air to calculate un-uniform indoor temperature

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
34	Optimization of and Air-Supply Duct System	W. F. Stoecker, R. C. Winn and C. O. Pedersen	University of Illinois (USA)	• Discussed the computer program which determined the minimum cost of air-supply system by utilizing the optimum duct system pressures	• Discussed the procedure for optimizing the first cost of an air-supply system • Discussed key variables which affected the cost of air-supply duct system
35	Computerized Calculation of Duct Friction	H. F. Behls	Sargent and Lundy, Engineers (USA)	• Discussed the duct system simulation program which determined balanced duct systems • Discussed the Newton-Raphson method for solving Colebrooks' equation (i.e., a function that determined friction factors), which required the minimum computer execution time • Discussed subroutines to calculate the pressure drop in straight air ducts	• Discussed the procedure for modeling of duct and pipe systems • Discussed key variables of the pressure drop calculations, which included: friction factors, pressure drop in straight ducts and moist air properties
36	Pressure Loss Coefficients for the 45-Degree Return Air Tee	H. F. Behls and W. K. Brown	Sargent and Lundy, Engineers (USA)	• Discussed the correlation of experimental data (i.e., data for through flow and branch flow loss coefficients) for the 45-degree return air tee	• Provided the information about tee loss coefficients which affected total pressure drop and air quantities design
37	Automatic Design of Optimal Duct Systems	M. Kovarik	CSIRO (Australia)	• Discussed the computer program which was based on the concept of Lagrange multipliers and the Newton-Raphson iterative method	• Provided the detailed information about the procedure and key variables to determine optimal duct systems

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
38	A System of Computer Programs Widely Used In Europe for Designing, Selecting and Analyzing Different Air Conditioning Systems	A. Boeke and S. Larm	Technische Hogeschool, Leerstoel (Holland)	• Discussed the computer programs which evaluated heating and cooling loads for different kinds of air conditioning systems (i.e., 2-pipe induction system, 4-pipe induction system and dual duct system) as well as determined complete duct systems	• Provided the information about key factors for air conditioning system installation and operation, which included: room temperature variations, heating and cooling loads, dimensions of duct systems and fan pressure
39	Standardized Method for Optimizing Building Construction and Heating and Ventilating Installations for Various Indoor Climate Criteria	A. Boysen and S. Mandorff	National Swedish Institute for Building Research (Sweden)	• Discussed the method which calculated class room temperature (i.e., operative temperature) • Provided the information about key variables which affected classroom thermal environment	• Provided the information about calculations of class room temperature as a function of different parameters, which included: distance from window, classroom structures, sizes of window, different ventilation systems, outdoor temperature and combinations of structure and ventilation systems
40	Designing Installations by Computer In Sweden	L. Sundberg	Wahling's Installation and Development Company (Sweden)	• Discussed key factors for computer installations to design buildings	• Provided the information about the inventory of existing computer programs which designed various building systems
41	A Cost Analysis Service Helps Optimize Building Costs and Environmental Benefits	J. T. Malarky	PPG Industries (USA)	• Discussed the program (i.e., Cost Analysis Service) which evaluated cost comparison of the effect of improved fenestration on overall building costs	• Provided the information about the effect of glass performance on construction and operating costs

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Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
42	Comparative Computer Analysis of the Thermal Cost Performance of Building Enclosures	W. A. Oberdick	University of Michigan (USA)	• Discussed the computer programs on thermal-cost performance of building systems as to program logic (i.e., thermal neutralization, solar climatic simulation and cost) • Provided examples of specific building thermal system simulations, which compared the prediction of energy consumption with that metered	• Discussed key variables (i.e., wall type, wall conditions, solar climatic conditions, mechanical systems and economic data) which were applied to early total building energy simulations • Discussed key variables of heat transfer in buildings
43	A Numerical Method for Computing the Non-Linear, Time Dependent, Buoyant Circulation of Air in Rooms	J. E. Fromm	IBM Corporation (USA)	• Discussed the numerical method (i.e., finite difference method) which computed air circulation at environmental room temperature	• Provided the detailed information about the numerical methods as well as required algorithms for the methods by utilizing the concept of approximations • Provided the information about variation of air flows in rooms
44	FORTRAN IV Program to Calculate Absorption and Transmission of Thermal Radiation by Single and Double-glazed Windows	G. P. Mitalas and J. G. Arseneault	National Research Council (Canada)	• Discussed the program (i.e., FORTRAN IV program) which evaluated the absorptivity and transmissivity of windows	• Provided the detailed information about calculations of absorptivity and transmissivity of windows by utilizing Fresnel's formula, Snell's law and Exponential extinction law
45	A Computer Analysis of Window Shading Coefficients by Calculating Optical and Thermal Transmission	I. Isfalt	The Royal Institute of Technology (Sweden)	• Discussed the program (i.e., ALGOL-program) which evaluated the transmission of sunlight and solar heat gain through different layers of a window from the optical data	• Provided the information about the solar heat transfer through a window, which included: radiation and convection

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
46	Optimum Shape of External Shade for the Window to Minimize Annual Solar Heat Gain and to Maximize View Factor	K. Kimura	Waseda University (Japan)	• Discussed the procedure to determine the optimum shape of sun shade, which provided minimum direct radiation and maximum view for occupants	• Discussed key variables and design process to determine optimum shape of sun shade • Provided the diagram which explained the overall phase of solar radiation that converted into heat gain
47	Calculation of Smoke Movement in Buildings	T. Wakamatsu	Building Research Institute (Japan)	• Discussed the computer program which calculated smoke movement (i.e., mass rate of smoke, air flow, smoke spread and concentration) for smoke protection design system	• Provided the fundamental knowledge of the smoke protection design system and computer techniques for calculating smoke movement
48	Use of Actual Observed Solar Radiation Values in the Determination of Building Energy Requirements	J. Thies	Southern Services, Inc. (USA)	• Discussed the approach to estimate the effect of solar radiation on a building's heat loss or heat gain by utilizing measured solar radiation data	• Discussed advantages and disadvantages of theoretical (i.e., calculated) and practical (i.e., measured) approaches for evaluating solar radiation
49	Design of Direct-Expansion Evaporator Coils by Digital Computer	D. G. Rich and J. B. Chaddock	Duke University (USA)	• Discussed the program which simulated direct-expansion evaporator coils for air conditioning by digital computer	• Provided the detailed information about simulating evaporator coil, which included: key variables, program procedure, decision points and thermal behavior • Discussed key factors of the direct-expansion evaporator coils, which must be applied to simulation of the air-conditioning

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Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
50	Simulation of a Multicylinder Reciprocating Refrigeration System with Chilled Water Coil and Evaporative Condenser	E. Stamper and M. Greenberger	Newark College of Engineering (USA)	• Discussed the procedure to simulate multi cylinder reciprocating refrigeration system which consisted of cooling coil, chiller and evaporative condenser	• Discussed the procedures for thermal loads and HVAC system simulation, which were recommended procedures by ASHRAE • Provided the information about how to select and simulate HVAC system components by utilizing load data
51	Use of Digital Computers for the Heat and Mass Transfer Analyses of Controlled Environment Greenhouses	M. K. Selcuk	Orta Dogu Teknik Universitesi (Turkey)	• Discussed computation methods of the heat and mass balances for controlled environment greenhouse	• Provided the detailed information about the heat and mass transfer and important physical phenomena in the greenhouse
52	Automated Design Program for Air-Handling Apparatus	M. Nagatomo, S. Tanaka and N. Tohda	Kajima Institute of Construction Technology (Japan)	• Discussed the program which consistently treated the entire design process, which included: heating and cooling loads calculation, supply air volume calculation and selection of air-handling equipment	• Discussed the formula and procedure, which determined the state of moist air and supply air volume for selecting appropriate HVAC system equipment
53	Computer-aided System for Preliminary Air Conditioning Design	E. Maki and Y. Okuda	Nikken Sekkei Komu Company, Ltd. (Japan)	• Discussed the programs (i.e., COSMA and SPACE) which computed continuous processing of heat load, equipment selection, pipe and duct design for preliminary design stage of air conditioning system	• Discussed key factors to compute continuous processing from thermal load calculations to HVAC system estimation • Provided comprehensive information about the simulation of air-conditioning system

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Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
54	Computer Selection and Evaluation of Design Weather Data	E. N. Van Deventer	National Building Research Institute, CSIR (South Africa)	• Discussed the computational procedure to produce design weather data which was typified by large diurnal variations in air temperature • Discussed four methods to select and evaluate weather data	• Discussed key equations and factors to compute design weather data, which included: sol-air temperature, solar radiation, etc.
55	Quality Rules for Thermal Performance of Low Cost Dwellings (Building Climatology for Argentine)	R. Alvarez Forn and I. Lotersztain	INTI (Argentina)	• Provided the information about a research which analyzed climatic parameters of Argentina for building purpose	• Discussed the procedure to determine design weather data • Discussed how to simplify raw weather data for use in computer program
56	FORTRAN IV Program to Calculate z-Transfer Function for the Calculation of Transient Heat Transfer Through Walls and Roofs	C. P. Mitalas and J. G. Arseneault	National Research Council of Canada (Canada)	• Discussed the program (i.e., FORTRAN IV program) which evaluated the coefficients of a set of z-transfer functions to compute heat transfer	• Provided the detailed information about the calculation of z-transfer functions for a multi-layer wall
57	Application of Multilayer Periodic Heat Flow Theory to the Design and Optimization of Roofing Systems	C. Smolenski, E. Halteman and E. M. Krokosky	Pittsburgh Corning Corporation (USA)	• Discussed the analytical model for heat transfer and optimization scheme to design protected membrane roofing systems • Discussed the method to evaluate suitable thermal barrier at a reasonable cost	• Discussed the procedure which designed suitable roofing system to protect the membrane roof insulation system from thermal fluctuations

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
58	Pulse Transfer Function and Its Application Related to Buildings	H. Yamazaki	Kyushu Institute of Design (Japan)	• Discussed the method which produced z-transform transfer function • Discussed how the z-transform transfer function is applied to calculation of room air temperature	• Discussed the pulse transfer function method to calculate dynamic changes of room air temperature and thermal loads, which was based on the z-transform transfer function
59	A Calculating Method for Heating Loads of Buildings	Y. Nakazawa	Kyoto Technical University (Japan)	• Discussed the calculation methods for the intermittent heating or cooling load in the multi-room building, which was based on the matrix calculation method	• Discussed the procedure to determine the thermal properties of multi-layers, which was based on matrix equations • Discussed the procedure to determine the system, which was based on heat balance equations and matrix equations • Discussed the method to solve large unknown values of building thermal environment, which was based on iterative method
60	An Example of Heating and Cooling Load Calculation Method for Air-Conditioning of Building by Digital Computer	S. Kuramochi	Taisei Construction Company, Ltxd. (Japan)	• Discussed the method to calculate actual load for air-conditioning, which considered the heat from the equipment operation	• Discussed the output of heat in regarding to the HVAC system operation, which included: heat from equipment and heat from thermal medium transportation system • Covered important factors which must be applied to actual load calculation for air-conditioning

Table F.1. *Continued*

Paper Number	Paper Title	Author	Organization (Country)	What did the paper discuss?	Why was it important for my research?
61	Heating and Cooling Load Calculations by Means of Periodic Window Function	K. Eguchi	Building Research Institute Ministry of Construction (Japan)	• Discussed the calculation procedures for the determination of periodic heating and cooling loads, which were based on the time series method, the concept of window function and the heat flow matrix	• Provided the information about the window function (i.e., transient type and periodical type) as combining function of the time series method • Discussed the calculation procedure for periodical heat flow which was based on the concept of superposition
62	Banquet Address: Computers and the Building Industry	S. Daryanani	Syska and Hennessy, Inc. (USA)	• Discussed the limitations of computer application in the building industry around 1970 • Discussed important reasons why computers should be used in the building industry	• Cover the important issues in the field of building industry around 1970 • Discussed how computer contributed to the field of building industry

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APPENDIX G

THE ANALYSIS OF THE PROCEEDINGS OF THE U.S. POSTAL SERVICE SYMPOSIUM

Table G.1. *The analysis of the U. S. Postal Service Symposium Computer Program for Analysis of Energy Utilization (USPS, 1971)*

Paper Title	Speaker	Organization	What did the section discuss?	Why was it important for my research?
Call to Order / Welcoming Remarks	J. Kenneth Fleetwood / Robert E. Isaacs	United States Postal Service (USA)	•Discussed historical aspects of the United States postal service around 1970	•Discussed the reasons why the U.S. postal service invented postal service computer program
United States Postal Service Construction Program	George A. Rebh	U.S. Army Corps of Engineers (USA)	• Provided the information about how the U.S. army was related to and contributed to the U.S. postal service construction program	• Discussed the U.S. army's key contributions to the U.S. postal service construction program, which included: real estate acquisition, construction service, etc.
Introduction to the Program	Sam W. Milnark	Air Conditioning & Refrigeration Business (USA)	• Discussed the reasons why the postal service developed the postal service computer program • Discussed the usefulness of the postal service computer program to determine the most economical systems and energy in a building	• Discussed motivations for developing the postal service computer program, which included: renaissance period of the postal service and energy crisis in the U.S.
Position of the American Society of Heating, Refrigeration and Air Conditioning Engineers, INC.	Robert H. Tull	ASHRAE Task Group (USA)	• Discussed ASHRAE's position in regard to energy calculation in buildings	• Discussed ASHRAE's activities for energy calculation in buildings, which included: Task Group on Energy Requirement, development of procedures for calculating thermal loads, HVAC systems performance • Provided the information about which algorithms were applied to postal service computer program
Description of the Program and Details of the Load Program	Metin Lokman-hekim	General American Research Division (USA)	• Provided the information about the basic structure of the postal service computer program, which included: load calculation, thermal loads plot, systems simulation and economic analysis	• Discussed the convolution principle which was applied to simulation of transient heat conduction through a thick wall (i.e., building structures) • Covered key knowledge about transient heat flow in a building envelope, which included: response factor and weighting factor

Table G.1. *Continued*

Paper Title	Speaker	Organization	What did the section discuss?	Why was it important for my research?
Description of Systems Simulation and Economic Sub-Programs	Robert H. Henninger	General American Research Division (USA)	• Provided the detailed information about systems simulation sub-program, economic analysis sub-program, sequence of sub-programs' use and examples of input and output of each sub- program	• Provided important diagram and flow charts, which explained inter-relationship of sub-program subroutines
Utilization of the Program for Other Than Postal Facilities	T. Kusuda	National Bureau of Standards	• Due to recording difficulties, T. Kusuda's presentation couldn't be included in the proceedings	
Application of the Program in Specific Projects - Use in a 250 Bed Hospital and 6 Smaller Buildings	Z. Cumali	Consultants Computation Bureau (USA)	• Shared the experiences that how the postal service computer program simulated actual buildings which included: a hospital and small office buildings	• Discussed actual issues about simulating a building by using postal service computer program, which included: input variables, computation time, running cost, computer memory and future development
Application of the Program in Specific Projects - Use in the New IBM 52 Story Building In Chicago	Richard Stillman	IBM Corporation (USA)	• Shared the experience of simulating new IBM building in Chicago	• Discussed the overall procedure for simulating a large building • Discussed critical issue about running system simulation subroutine
Application of the Program in Specific Projects - Use In Canadian Public Buildings	Robert S. Bycraft	Department of Public Works (Canada)	• Shared the experience of simulating public office buildings in Canada	• Discussed problems on simulating a building, which included: simplified modeling, weather data, fan system zoning and electrical energy calculation
Questions and Answers			• Provided answers to audience's questions	• Provided various point of views about the postal service computer program
Registrants			• Provided a list of the symposium registrants	• Provided the information about which organization was interested in the postal service computer program

APPENDIX H

THE ANALYSIS OF 2001 KUSUDA PAPER

Table H.1. *The analysis of Kusuda's paper (Kusuda, 2001)*

Section Title	What did this section discuss?	Why was it important for my research?
Abstract/Introduction	• Described the purpose of this paper.	• Described key events in the field of building simulations from the late 1950s to 1970s.
Pre-computer Days	• Described the HVAC system research that Kusuda was involved in during the 1950s and 1960s.	• Discussed the very early HVAC system simulation that Kusuda was involved in during the 1950s and 1960s.
First Encounter with Computers	• Described the moment when Kusuda used the digital computer for the first time to evaluate the coil performance.	• Discussed characteristics of the one of digital computers (i.e., Bendix G-15).
The First ASHRAE Paper based on Computer Simulation	• Discussed the first ASHRAE journal paper that analyzed the one of HVAC systems (i.e., compressor) by using the digital computer.	• Provided information about the origins of HVAC systems simulation. • Discussed practical difficulties in use of the assembly language before the development of FORTRAN language.
Survival Shelter Simulation	• Provided information about the shelter simulation program (i.e., MATEUS program) that was developed by Kusuda at 1962.	• Discussed the purpose of development of the MATEUS program. • Provided detailed information about the MATEUS program, which included: the program language, mathematical models of the MATEUS program (i.e., Finite Difference method and Heat Balance method), etc. • Discussed the validation test of the MATEUS program.
Trials and Tribulations	• Discussed difficulties in the development of the MATEUS program.	• Provided information about major outputs of the MATEUS program, which included: the hourly shelter air temperature, relative humidity and effective temperature. • Provided information about characteristics of Finite Difference method that was used in the MATEUS program. • Provided information about the key publication that discussed the development and validation of the MATEUS program. • Provided the evidence that the MATEUS program possibly contributed to the development of the SHEP program.

Table H.1. *Continued*

Section Title	What did this section discuss?	Why was it important for my research?
Psychrometric Calculations	• Discussed the psychrometric calculation routine that was developed by Kusuda.	• Described the moment when Kusuda changed the field of research from the underground shelter to the entire-building above ground.
Room Air Motion by CFD	• Discussed the research of the air flow motion in the room that Kusuda was involved in.	• Discussed characteristics of the room air floor motion research by using the CFD technique.
Thermal Response Factor (Conduction Transfer Functions)	• Discussed characteristics of the Response Factor method, the Weighting Factor method and the Conduction Transfer Functions (CTFs).	• Discussed advantages of the Response Factor method by comparison with the Finite Difference method. • Provided information about key documents that discussed the Response Factor method, the Weighting Factor method and the Conduction Transfer Functions (CTFs). • Provided information about the Response Factor Calculation program that was developed by Kusuda at 1969. • Provided possible reason why the NBSLD program used the Conduction Transfer Functions (CTFs) and the Heat Balance method.
Heating and Cooling Load Calculations	• Discussed the Heating and Cooling load Calculation (HCC) program and the Group to Advance Total Energy (GATE) program that were developed in the 1960s.	• Provided information about private building simulation programs in the 1960s, which included: the HCC program that was developed by the Automated Procedures for Engineering Consultants (i.e., APEC) and the GATE program that was developed by the Group to Advance Total Energy (i.e., GATE). • Discussed characteristics of the Total Equivalent Temperature Differential (i.e., TETD) method and the Time-Averaging (i.e., TA) method. • Provided the evidence that the GATE program significantly contributed to the field of whole-building energy simulation programs.

Table H.1. *Continued*

Section Title	What did this section discuss?	Why was it important for my research?
ASHRAE Task Group on Energy Requirements	• Discussed the establishment of the ASHRAE Task Group on Energy Requirements at 1965.	• Discussed key members of the ASHRAE Task Group on Energy Requirements at 1965. • Discussed the Post Office program that was developed by the GARD/GATC. • Provided information about the ASHRAE recommended algorithms for the heating and cooling loads calculation and the HVAC systems simulation.
International Symposium on the Use of Computers for Environmental Engineering Related to Buildings	• Discussed the first international symposium on the application of computer to the building environmental system simulation, which was organized by Kusuda at 1970.	• Provided information about various applications of computer to the analysis of building environmental systems around the 1970s. • Provided information about the CP-33 program that possibly contributed to the development of the NBSLD program.
NBSLD	• Provided detailed explanation about the NBSLD program that was developed by Kusuda at 1974.	• Provided information about key studies that contributed to the development of the NBSLD program. • Provided the evidence that the MATEUS program possibly contributed to the development of the NBSLD program. • Provided the evidence that miscellaneous simulation programs (i.e., CP-26 program, Response Factor Calculation program and CP-33 program) possibly contributed to the development of the NBSLD program. • Discussed the Heat Balance method that was used in the NBSLD program.
NBSLD Energy Program	• Discussed the NBSLD Energy program that derived from the NBSLD program for the analysis of the building energy calculation.	• Discussed historical events in the field of building energy simulation in the United States around the 1970s. • Discussed the NBSLD Energy program that was possibly first public building energy simulation program with Heat Balance method.

Table H.1. *Continued*

Section Title	What did this section discuss?	Why was it important for my research?
DOE-2 and BLAST	• Discussed the origins of the DOE-2 program and the BLAST program.	• Discussed the Shadow Calculation program and its subsequent enhancements, the Post Office program, the CAL-ERDA program and the DOE-2 program. • Provided the evidence that the development of the Post Office program was based on the draft publication of the ASHRAE TGER.
HVAC System and Component Simulation	• Discussed characteristics of the HVAC system and component simulation.	• Discussed characteristics of the Quasi-steady state model that was used for the HVAC systems simulation portion of the whole-building energy simulation at that time. • Discussed characteristics of the dynamic HVAC systems simulation (i.e., minute by minute simulation) that was not suitable for the application to the whole-building energy simulation at that time.
Ground Contact Heat Transfer	• Discussed research for the analysis of the ground contact heat transfer that Kusuda was involved in.	• Provided information about the steady state 2-D FEM program and the knowledge of pseudo-thermal diffusivity, which was developed by Kusuda. • Discussed the analysis of the ground contact heat transfer for the building energy simulation.
Air Infiltration	• Discussed research for the analysis of the air infiltration from the 1960s to 1970s.	• Discussed calculation methods for the analysis of the air infiltration: the Crack method, the Air-change method and the SF_6 method in combination with the blower-door technique. • Discussed the future improvement for air infiltration analysis methods that were widely used at that time.
Future Prospects	• Discussed future improvement for the analysis of the building performance.	• Discussed the integrated building simulation and the predicted building habitability index as the future improvement for the evaluation of building performance.

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