EARLY HISTORY AND FUTURE PROSPECTS OF BUILDING SYSTEM SIMULATION

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ABSTRACT

In the USA, full scale computer applications for HVAC related problems started in the early '60s when the author was involved in the US government's projects to evaluate the thermal environment in fallout shelters by an hour by hour simulation of heat and moisture transfer process between human occupants and shelter walls under limited ventilation conditions. General building thermal simulations based on hour by hour calculations were started at that time by gas and electric industries. This led to the formation of the ASHRAE Task Group on Energy Requirements to develop a comprehensive hourly energy performance simulation of buildings as well as the APEC (Automated Procedure for Engineering Consultants) activities for cooling load calculation. These activities were linked to the four successful international symposia (Gaithersburg, Banff, Paris, and Tokyo) on the use of computers for environmental engineering related to buildings, the forerunner of IBPSA. A considerable amount of effort went into the earlier thermal simulation programs to improve the physical and empirical modeling of air and moisture and heat transfer processes in and through a complex building structure under varying weather conditions and building use conditions. Although the thermal physics aspects of building environmental simulation have sufficiently been explored in recent years, the author contends that there are still several areas that need further improvements and developments.

INTRODUCTION

Good morning, ladies and gentlemen, building simulation specialists, Prof. Nakahara, Prof. Degelman, some of my gray-haired diehard engineers with whom my path crossed during the ‘60s and ‘70s. When I saw the preprints of this conference, they made me feel so ancient. Since I have not been at the forefront of these particular activities for more than decade, I feel extremely humble in addressing this gathering of international authorities on building system simulation. A lot of water has flowed under my bridge especially in the applications of new computer science technologies and numerical analyses. Yet I feel somewhat assured to find old familiar names like DOE2, BLAST, TRNSYS, HVACSIM$^+$ etc. still raising their heads among many new programs. New authors are still addressing the age old familiar problems of ground coupling, daylighting, moisture transfer, etc. My presentation today centers around what the building thermal system simulation activities were like in the late ‘50s, early ‘60s and ‘70s when computers were large in physical size, but tiny in memory, slow in speed, and difficult to approach. My presentation is not strictly confined to computer simulation, but encompasses general building physics research that I was involved in during my professional career. I am keenly aware of the fact that all of you are on or are trying to catch the fast moving train into cyberspace with no time to look back. I, therefore, feel somewhat guilty for taking your valuable time by having you listen to an old man talk about what was like to be a building system simulator or a building thermal physicist before the powerful PCs or Macintosh computers were on every engineer’s desk.

PRECOMPUTER DAYS

During the ‘50s and ‘60s, many engineering calculations were still done by slide rules and desktop electromechanical calculators such as Monroe, Frieden and Tiger. Before dealing with computer simulation, however, I would like to explain how I became involved in building environmental problems, since it has direct bearing on my history of computer applications for HVAC related problems. I was being trained to be an ordinance engineer at the University of Tokyo when World War II ended, and was looking for something exciting but not directly related to war efforts. I found the HVAC and environmental engineering field very interesting when I took the first air conditioning and refrigeration courses at the University of Washington in l950. My graduate advisor at the university told me that there was a hot-box project looking for a research assistant. My job was to construct a guarded hot box and measure the U value of standard wood frame walls. As you all know, the guarded hot box consists of, in addition to the hot box which provides a simulated indoor environment, a test wall, and a cold box to simulate the cold outdoor environment. The project required me to design and construct a refrigeration system to pull-down the cold box temperature to as low as 0ºF. Without knowing much about the refrigeration system, I had a hard time comprehending why my refrigeration system was not cooling the cold box at all when the suction pressure of the Freon 12 compressor was indicating the saturation suction temperature equivalent of -20ºF. What puzzled me most at that time was why the cooling capacity decreased so fast when the suction temperature went down. Upon opening the cold box, I found the evaporator coil solidly covered with ice yet the cold box never achieved 0ºF, and in fact it took a long time to reach 30ºF. After struggling for two years, I was able to modify the system and complete a MS thesis comparing the measured U value with the calculated value based on the ASHVE Guide formula, which is, of course, a simplified formula neglecting the effect of two and three dimensional heat flow path or thermal bridges. I became more interested in understanding the refrigeration system, especially predicting its pull-down temperature performance as a function of refrigeration system capacity and the heat gain to the cold box. When I moved to the University of Minnesota, where a lot of advanced research on building thermal systems was being conducted, I also found my mentor in Prof. James Threlkeld of the refrigeration laboratory. Prof. Threlkeld just completed his PhD at the university, one of the first in the HVAC area in the United States, and was a pioneer in the theoretical analysis of refrigeration systems. You must understand that in those days, most HVAC&R engineers were practical engineers and not interested in thermodynamics or heat transfer beyond what they had studied through the undergraduate years. As far as I was concerned, a book entitled Thermal Environmental Engineering (Prentice Hall) that Prof. Threlkeld later published was a first in the United States presenting a comprehensive mathematical background for many HVAC&R related subjects including psychrometrics, advanced refrigeration cycles, solar energy, transient heat conduction through multi-layer walls, etc. All of these analyses were very much relevant to computer simulation in the later years. Prof. Threlkeld had a small refrigeration test chamber connected to a calibrated refrigeration system for students to measure and record its system performance including those during the temperature pull-down period of the test chamber. He was trying to develop a mathematical formula to predict the pull-down performance of refrigerated warehouses, but finding it difficult to include the refrigeration system performance into the equation. We resorted to the use of a graphical method called the Schmidt Plot to couple the transient heat transfer through the multilayered structure to the performance curve of the refrigeration system. Our graphical method was able to simulate the heat balance among the transient heat conduction gain through the envelope of the test chamber, air cooling coil capacity, and refrigeration compressor cooling capacity to predict the temperature pull-down. The predicted value for the test chamber very closely agreed with the pull-down temperature data that students had collected. Needless to say that we were very much excited about the results and submitted a paper describing the method to Refrigerating Engineering (Vol. 64, No.7, l956) of the ASRE, the forerunner of the ASHRAE. This paper later received the coveted Wolverine award, the best technical paper, in l957. This was my first success in the mathematical simulation of a HVAC system, and I was hooked ever since.

The second success came when I was working at the Worthington Air Conditioning company after graduating from the University of Minnesota. I was assigned to design finned tube coils for condensers and evaporators of the heat pumps. It was straight forward catalog engineering those days to select heating or cooling coils, which are a refrigeration condenser or the evaporator respectively, for a given set of design inlet and outlet air conditions and design condensing and evaporating temperatures. The engineer's task was to determine the face areas and the number of finned tube rows of the coil from the tables in the manufacturer's catalog for required air flow rate and heating capacity or the cooling capacity of the coils. But when the heating cycle of the heat pump is switched to the cooling mode, the same heating coil or the condenser coil becomes the cooling and dehumidifying coil, and the evaporator coil becomes the condenser coil. Engineers who were adept in designing (or selecting) coils had no way of being assured that the size of the condenser coil that was selected could meet the design cooling and dehumidifying requirements. In other words, engineers lacked the capability to predict or simulate the performance of a coil under conditions that were different from the design conditions. There was no method available in those days to determine the performance of cooling and dehumidifying coils except for the contact factor method of Goodman of the Trane company, which was based on the apparatus dewpoint temperature or the wet surface temperature of the coil. I devised a graphical method to obtain the surface temperature of the cooling and dehumidifying coil on the psychrometric chart by balancing the heat conduction from the finned surface to the refrigerant and the heat and moisture transfer from the air at the finned surface. This method, called the surface temperature determination line method, was also presented to

Refrigerating Engineering (Vol. 65, No. 5, l957), and later revised to include the chilled water coil performance calculation based on the effectiveness concept, and the accuracy of which was amply validated by Prof. Trapanese of the University of Turin later. Remember, the graphical method was one good alternative we had those days for realistic simulation calculations. Many engineering papers those days dealt with the graphical solutions of complex mathematical equations.

FIRST ENCOUNTER WITH COMPUTERS

My first exposure to a digital computer came when I was developing a coil performance table for the Worthington Corporation. The company just purchased a Bendix G-15 computer, which had a mechanical drum storage and its programming was done by the assembly language. It, however, was able to do simple arithmetic calculations much faster than desk calculators. I used this machine to produce a table of air temperature rise through the hot water circulated heating coils under various air and water flow conditions when the inlet air and water temperatures were known. I remember that one of the difficult challenges in this computer was how to handle the exponential function needed for coil effectiveness calculations.

THE FIRST ASHRAE PAPER BASED ON COMPUTER SIMULATION

The chief engineer of the compressor development and design at Worthington, and Prof. Ditfach of the University of Massachusetts were working on the bearing force distribution around the crankshaft of multiple cylinder refrigeration compressors. The gas pressures in each of the compressor cylinders had to be determined with respect to various crank angles as the pistons of the compressor going through the suction, compression, and discharge strokes. Remember, this was before the FORTRAN days. The programming for the Bendix G-15 was so primitive, that a sizable efforts were required to determine the cylinder pressure during the adiabatic compression cycle that follows the $pv^{\gamma} = const.$ equation. Computer calculations were justified since each of the six cylinders are at different stroke stage at a given crank angle. This was a major accomplishment worthy enough in those days for a paper in the ASHRAE Journal (1959), and as far as I know, this was the first ASHRAE journal paper based on the use of a digital computer on HVAC related problems.

SURVIVAL SHELTER SIMULATION

When I joined the research staff at the Building Research Division (BRD) of the National Bureau of Standards (later its name was changed to the Center for Building Technology and then to the Building and Fire Research Laboratories of NIST) in early l962, the nation was preoccupied with the nuclear threat from the USSR from its missile sites in Cuba. Citizens were digging backyard fallout shelters stocked with food and supplies. Many large scale fallout shelters for communities were also being built. Although substantial information was available as to the protection from nuclear radiation in these shelters, little was known as to adequacy of the thermal environment within these shelters, which were designed for high occupancy (10 square feet of floor per person) with a limited amount of ventilation air (3 cfm per person) for at least two weeks until the outdoor air was free of the radiation effect. The major concern of the Office of Civil Defense (OCD) was the shelter thermal environment in summer. The Heating and Ventilating Section and the Heat Transfer Section of the BRD had several large projects sponsored by the OCD to study the thermal environment in these shelters and to develop the design handbook data for shelters: shapes and sizes, depths, locations, ground temperature, required floor area and ventilation air per person, the need for air conditioning, predicted temperature and humidity, predicted comfort index, etc. Because of these numerous parameters, NBS scientists had been working on several analytical solutions to include these parameters that could be used to provide a habitable thermal environment in the shelters. Unfortunately, many of the heat transfer solutions available in the conventional engineering textbooks such as Carslaw and Jaeger (Oxford University Press, l959) were applicable only for deep underground shelters (either cylindrical or spherical) surrounded by homogeneous earth of constant temperature. NBS researchers had been working with the development of analytical solutions using the powerful IBM 7094 Computers to deal with the Bessel functions and/or the complementary error functions to predict the shelter temperature rise. Most shelters were rectangular in shape, and had the earth cover of as shallow as several feet, analytical solutions for which were not available. In addition, the analytical heat transfer solutions could not handle the humidity condition in the shelter, one of the major concerns in the crowded underground shelters during the summer. Not many buildings in those days were air conditioned, let alone underground fallout shelters designed for a short stay. Coming from a company which had just begun to use a small mechanical storage type Bendix G-15 computer to the IBM 7094 dominated NBS computer environment with FORTRAN was really eye-opening to me, and I was excited about making active use of the computer.

When I suggested a computer simulation based on heat conduction analysis using the finite difference method, many established NBS heat transfer researchers scoffed as if I was invading their sacrosanct mathematical domain with something less than honorable (they called it a brute force method). They had been working on the Fourier series or Laplace Transfer domain analysis of heat conduction problems and publishing their papers in applied mathematical journals or in the prestigious NBS Circular or on the Journal of Research. In order to dispel the bias of these analytical skeptics by the power of numerical simulation, I decided to simulate the performance of a test underground survival shelter designed for a family of four simulated occupants (SIMOC). NBS researchers had built a family size fallout shelter on their grounds, and placed within it four simulated occupants, or SIMOCs. The sensible and latent heat generated by the SIMOCs were simulated by warm metallic cylinders covered by wet cloths and having their surface areas equal to the surface area of an average human being. These SIMOCs were heated to generate heat and water vapor as functions of air temperature around the body as indicated in accordance with the data shown in the ASHVE Guide, but with the total heat input to be controlled at 400 Btu/hour of the SIMOC simulating the total metabolic heat generated by a sedentary adult. The hour by hour data for the shelter air temperature and relative humidly were recorded dutifully for fourteen days. NBS scientists also installed numerous thermocouples within the soil surrounding the shelter at selected distances normal to all walls, floor and ceiling to measure the soil temperature change during the test. These ground temperature and ambient dry-and wet-bulb temperature were also recorded hourly. In order to show the capability of my model, I constructed a 3-D finite difference model (FEM was not available those days) that no one even dreamed of considering in those days. My computer model closely simulated the earth profile around a rectangular concrete shelter by a 3-D finite difference grids. I wrote the heat balance equations between the shelter air, SIMOCs, and shelter interior surfaces (ceiling, floor and walls), ventilation air and lighting fixtures. In addition, using the Lewis relation and the psychrometric routines I developed, I also included a mass balance equation for water vapor exchange among the shelter air, ventilation air, SIMOC, and the shelter interior surface not only to determine the shelter's relative humidity, but also the water condensed on the shelter's interior surfaces. Although I was able to consider the moisture condensation on the interior surfaces by checking the surface temperature and dewpoint of the shelter air, I did not include moisture absorption by the concrete. Although all input data used for these heat balance equation are from the ASHVE Guide and Data book, ASRE Handbook, and other heat transfer books such as that of Eckert, every one of these data I used could be challenged by the later and more refined values, especially the surface heat transfer coefficients and soil thermal properties.

TRIALS AND TRIBULATIONS

The IBM 7094 was located at the bottom of a hill at the far and opposite corner of the NBS campus from my office in Washington DC. It required a long trek up and down many steps every time I discovered bugs in the program and data. Many users carried a long and heavy metallic box containing sets of IBM cards. Since each card represented one line of the FORTRAN code, some programs required more than one box. My program was quite bulky. First, the program printout was checked and rechecked for corrections before the cards were carried to the computer lab where corrections had to be punched on the IBM cards. The run control cards were prepared and attached before the run was submitted to the operator who had to prepare a circuit patch board designed for each run. Computer users would leave the run instructions to the operator, for example, how long would be the expected run time, and where to call in case of a problem, etc. Instead of waiting for the run to be completed, most computer users left the run there and trekked back to their offices and waited or forgot about the program while doing something else until the next morning. Frequently anxious programmers would call the computer lab to check if the run was ready. Walking back to the computer lab with high expectations, the users found almost always something was wrong in their runs: some runs were outright rejected simply because of trivial errors in the run control card, or due to careless errors in card corrections that were made in a hurry, such as the misplaced decimal points or commas, or the misspelling of words. Nowadays these trivial errors can be corrected instantly on the screen and many trial runs can be made on the desktop computer. Yet, in those days, these little things were the major events that controlled the mental well being of the computer users. I was lucky enough to be within walking distance of the computer, compared with many others who had to drive or take a long train ride to their computers. You can imagine, the devastated feeling of the computer users when their runs were rejected because of trivial errors. Even after all the careless errors were corrected, my run did not produce any meaningful results for a long time due to programming logic errors and due to the stability problems in the finite difference calculations. When the stability problems were finally solved, I found that my finite difference calculation required a long computer time sometimes as long as 10 hours for the 14 day calculation. My computer bill became so high even before any meaningful results were obtained which shocked Mr. Achenbach, my supervisor at BRD. He had to ask for more funding from the OCD. My struggle continued almost a year before the first successful 14 day run was completed.

After all these trials and tribulations, and with some luck, my simulated diurnal cycles of the hourly shelter air temperature and relative humidity agreed extremely well, except for those in the first few days. The difficulties in the first days were believed to be due to the uncertainties of the initial soil temperature distribution around the shelter, especially around the corner regions. This was because the measured soil temperatures were available only along the central axes normal to the walls, ceiling and floor. I also had a routine to determine the effective temperature (ET) based on the simulated temperature and relative humidity with assumed clothing and air velocity around the shelter occupants. These results impressed my superior and colleagues at NBS as well as the OCD sponsors so much that I was asked to continue the simulation of other much larger shelters that were being tested under the OCD by several other institutions, such as the University of Florida, the Army Laboratory at Ft. Belvoir, and GARD/GATX. All of these shelters showed good agreements between the simulated and measured thermal environment. One serious problem was that my simulation program took up too much computer time. Even after repeated modification of the program, the fourteen day simulation calculation required many hours of computer time, and was not practical in developing parametric studies which would be required for the development of the design guidelines for shelters of different shapes, sizes, occupant densities, ventilation rates, depths of earth cover, types of soils (in terms of thermal conductivities and thermal diffusivities), soil temperatures, etc. Nevertheless we tooted our own horns by publishing this finite difference model and the validation results on the ASHRAE Journal (Vol. 69, 1964). The paper was aptly titled "Numerical Analysis of the Thermal Environment of Occupied Underground Space with Finite Cover Using a Digital Computer." This was the first ASHRAE Journal paper bearing "digital computer" in its title. This success in simulating thermal environment by digital computer encouraged several computer oriented engineers, one of whom was Metin Lokmanhekim at the GARD/GATX, who played a major role in the development of the original version of DOE2 later at the Lawrence Berkeley Laboratory.

PSYCHROMETRIC CALCULATIONS

The work in the survival shelters led me into several different directions, including earth temperature data, soil thermal properties, weather data, and the calculation routines for solar radiation, psychrometric data, and natural convection in the enclosed room size cavities. Remember not many researchers in the United States were working in these areas in those days since most talented researchers in mechanical engineering who had free access to high speed computers were busy either in the nuclear or aerospace areas leaving the entire building physics areas to very few of us to explore. In order to improve my psychrometric routines for indoor humidity calculations, I visited Prof. John Goff at the University of Pennsylvania, who kindly gave me papers in which the equations he developed to generate the moist air table on the ASHVE Guide and Data book. I found out that those moist air tables were based on the very rigorous statistical mechanics, and had been calculated by a roomful of women who ran the desk calculators. Later I was able to surprise Prof. Goff that I could duplicate his tables within a few minutes in its entirety. Later, these Goff and Gratch tables were revised by Dr. Hyland of NBS based on even more rigorous calculations. During these activities, I also worked with several researchers in the thermophysical section of NBS, who had been generating thermodynamic properties and the transport properties of gases and gas mixtures (some were for refrigerants) based on statistical mechanics. I found out that the transport properties of air also are strongly affected by its moisture content. I often wondered the need of these exact values in engineering calculations.

ROOM AIR MOTION BY CFD

In order to improve ventilation effectiveness in the crowded survival shelters, it was important to know how the limited amount of the outdoor air that was filtered through the high efficiency filter was distributed effectively throughout the shelter. By attending some of scientific meetings which were held frequently in Washington DC, I met Jacob Fromm of IBM who presented the simulated air flows around cylinders and air foils using his powerful super computer. I challenged him with the problem of predicting the natural convection in rectangular cavities. Modifying his program, Fromm was able to produce beautiful stream functions, vorticities and the isotherms of the flow in a two dimensional rectangular cavities by the numerical solution of the Navier Stokes equation and energy equation. But his solution became unstable at the Rayleigh number of around 1000. I wondered if we can do the same for shelter environment, but quickly found out that the Rayleigh number for the room size cavity was in the order of $10^{10} \sim 10^{15}$, much much higher than those represented by Fromm's numerical calculations. As to the room size air convection, I was first interested in the flow visualization work carried out by the Fire Research Section of NBS to study the fire plume using metaldehyde. Mr. E. M. Barber and I constructed a model chamber of approximately a 12 inch cube first to get acquainted with the flow visualization technology. One side of the box was made of special Corning glass coated with a transparent heating film and other five sides were all made of regular glass plates. The glass box was placed in a dark chamber. A collimated sheet of light was introduced first through a thick water lens to absorb its IR component, and then through the transparent and heated glass plate into the chamber. When metaldehyde particles were generated within the chamber, we could observe the beautiful natural convection flow patterns with the distinct laminar flow boundary layer of approximately 1/4 inch thick along the heated surface. The air flow outside the boundary layer was very irregular made up of many fine vortices and was more or less stagnant compared to the fast moving boundary layer. Mr. Barber was able to photograph this flow pattern, which was quite different from those shown by Fromm at the low Rayleigh number. In fact our 1 ft cubical chamber represented the Rayleigh number of 10^8. Instead of building a full scale test room for metaldehyde visualization study, we turned our attention to the natural convection flow equations and found that the major parameters controlling the Rayleigh number are the Prandtl number and the Grashof number. By examining the properties of various fluids, we discovered that the scale model of approximately 1/14 filled with hot water of approximately 500°F can be used for simulating the natural convection in a large space. Although the Prandtl number of water is ten times higher than that of air at the normal temperature, it becomes very close to that of the air if it is heated to 500 °F, yet its kinematic viscosity remains 133 times larger than that of the air at the room temperature. Barber and I built a high pressure chamber of a 6 inch cube with a high pressure view window and light source slit to visualize the flow pattern in the hot water chamber, which was supposed to represent a room of 10 ft x 10 ft x 10 ft having a Reyleigh number of 10^{11}. We used special and fine hollow glass beads as the flow tracing media. This interesting experiment (reported in the NBS Report No. 10689, l971) had to be terminated, however, due mostly to our inability to produce good visualization photographs to convince the sponsor. Besides, the experiment was extremely dangerous and was difficult to control. When I see many advanced CFD simulations based on turbulent flow models and full scale model studies on the subject of room convection, I wish that someone in the future would reexamine the validity and usefulness of the hot water model with much more advanced and innovative instrumentation techniques.

THERMAL RESPONSE FACTORS

While I was busy with room convection studies, Stephenson and Mitalas of NRC Canada were publishing many papers based on the use of computers, one of which dealt with the thermal response factors (later modified to conduction transfer functions) of multi-layer wall structures (1967 ASHRAE Transactions). As far as I was concerned, this was the most exciting development in building thermal physics. The mathematical background involved in determining these thermal response factors was precise and elegant. Even the most hard-headed NBS mathematicians had to concede the effectiveness and accuracy of the method. The method eliminated the need for the cumbersome and time-consuming finite difference calculations. The method was free of numerical instabilities. The whole concept of transfer functions to use an autoregressive or a convolution scheme to handle the effect of heat storage and time delay problem was very exciting to me at that time. It represented the pinnacle of computer applications for building thermal physics. I jumped on the bandwagon to develop computer programs to determine the thermal response factors for multi-layer cylinders and spheres also. (Thermal Response Factors for Multi-layer Structures of Various Heat Conduction Systems, ASHRAE Transactions, l969). Once determined for specific multi-layer configurations, thermal response factors eliminated the need for numerical wall simulation for the next time steps, and were ideally suited for the detailed hour by hour heat balance calculations in which conductive heat gain from envelope had to be matched with other heat gains from occupants, windows, equipment, and infiltration to determine the room temperature or the room cooling load, depending upon the purpose of the calculations. Repeating the room heat balance calculations for typical room constructions, Stephenson and Mitalas were also able to develop the so called weighting factors (ASHRAE Transaction, l972) to further simplify the room cooling load calculations.

The concept that every building element and every building system has its unique transfer functions was most fascinating. Theoretically this concept is valid only for the linear systems, and will not work for room convection or air infiltration or room convection problems. Nevertheless, many non-linear systems can be linearized to fit the transfer function model. Since most input time series could be represented by a train of overlapping triangular pulses, the transfer functions were generated for the pulse type input, usually by a triangular pulse. If the exact mechanism of a system that generates the output responding to a triangular pulse input is known, it is theoretically possible that its transfer functions can be generated. With the autoregressive scheme between the transfer functions and the input time series, one can then determine the output corresponding to the input. This autoregressive scheme cannot be used, however, to generate meaningful transfer functions by solving the set of autoregressive equations with the known output at the different time steps. This deconvolution technique has been tried by using several filter techniques and equation solvers, and has failed. This implies that it is extremely difficult to determine experimental transfer functions by deconvolving an arbitrary set of measured output. One can generate the solutions for these set of equations by any matrix equation solver, but the transfer function generated by these set of equation will be a meaningless set of numbers and will not be applicable to the input data beyond what was used in generating them. Even a simple wall heat conduction problem using a calibrated hot box to measure the heat conduction under a well defined pulse type heat input, the determination of experimental conduction function required a considerable amount of mathematical manipulation. Existing thermal response factors (or conduction transfer function) are all based on the one-dimensional heat conduction through multilayer structure without 2-D and/or 3-D thermal bridges. With the successful deconvolution algorithm, I believe it should be possible to determine the conduction transfer functions based on the output heat flow that corresponds to a triangular temperature input pulse by using the finite difference or finite element heat conduction calculations for these complex structure. I am surprised that if this has not been done yet.

HEATING AND COOLING LOAD CALCULATIONS

Although the use of computers for building thermal environmental calculations have been confined to universities and national laboratories where computers were readily accessible in the early 1960s, consulting engineers had begun to use computers for HVAC designs, the most notable was the APEC (Automated Procedures for Engineering Consultants) which developed a cooling load calculation program based on the TMTD method, the time averaging of hourly heat gain over a designated time period. The TMTD is basically a similar concept as the weighting factor method, except that all weighting factors are unity with the time regression length depending upon the weight of the building construction. The heavier the mass of the structure, the more historical heat gain terms were added to account for the longer time lag effect. It was a simple method, but was still an improved concept as compared to the conventional method in which the instantaneous heat gain was considered the cooling load without regard to the building thermal mass effect. The TMTD method suited the small computers that were found in engineering offices.

In the late 1960s, several hourly energy simulation programs were being developed by electric utilities and gas companies. The GATE (Gas Application to Total Energy) group developed an hourly simulation of total energy system to advocate the advantage of on-site power generation coupled with the utilization, of gas engine/generator waste heat for heating/cooling and domestic hot water generation. Although the program was based on relatively straight forward and steady state mathematical simulation of hour by hour building heat transfer processes and mechanical system performance, as compared to those which came later, such as DOE2, TRNSYS, BLAST, etc., the GATE program pointed out the usefulness and the importance of HVAC system simulation for annual energy calculations of large buildings and systems.

ASHRAE TASK GROUP ON ENERGY REQUIREMENTS

In the late 1960s, the ASHRAE recognized the importance of energy calculations, and approved the formation of the Task Group on Energy Requirements with a former ASHRAE president Robert Tull as its chairman. As I recall, the first formal meeting of the Task Group for Energy Requirements was held in Morristown, NJ, Tull’s home town. If my memory serves me right, those who attended this first meeting included Stephenson, myself , Prof. Stoecker of the University of Illinois, and Lokmanhekim of GARD/GATX, and several others who were all interested in the application of computers for building thermal simulation. Most notable among them was James Anders of the US Post Office who was starting an ambitious program to renovate US post office facilities for which GARD/GATX was a subcontractor. The Task Group was divided into three subcommittees: those for the load calculation, system and equipment simulation, and for weather data. I was appointed to chair the load subcommittee and Prof. Stoecker was to head the system and component simulation subcommittee to develop the ASHRAE recommended algorithms (not the programs). The weather data subcommittee was to develop standard weather data tapes suitable for hourly energy calculations, and was headed by someone from the US Air Force Weather Record Center.

INTERNATIONAL SYMPOSIUM ON THE USE OF COMPUTERS FOR ENVIRONMENTAL ENGINEERING RELATED TO BUILDINGS

Recognizing the surging interest in the use of computers for building environmental system simulation, I organized in l971 the first International Symposium on the Use of Computers for Environmental Engineering Related to Buildings at the National Bureau of Standards. To my amazement, this symposium attracted over 400 participants throughout the word including a bus load of Japanese engineers involving some of you here. The paper included Mitalas’ pioneering paper on the z-transfer function method for the conduction transfer functions, Fromm’s cavity convection, Wakamatsu’s smoke migration, etc. At the conference banquet I asked Dr. Schumann of NOAA to talk about weather simulation by computer, and I was able to show a movie borrowed from Fromm of IBM of cavity convection represented by the stream functions, vorticities and isotherms of the air flow in a rectangular cavities for the low Rayleigh number before the flow became unstable. I explained to the audience that someday we would be able to simulate the turbulent convection in real rooms. The conference was so successful and was repeated in Paris (1974), Banff (1978), and in Tokyo (1983). I believe that the basic themes of these conference have been inherited by the IBPSA conferences that started later.

NBSLD

In addition to the response factors and weighting factor programs, Stephenson and Mitalas had been publishing many impressive papers in the late 60s and early 70s, all for the application of computers for building thermal design. One of them was the solar heat gain calculations for fenestration design. About the same time, Terry Sun published an elaborate shadow calculation routines for conventional window systems with side fins and overhangs. Fanger published his famous book on thermal comfort which showed the formulation of PMV (predicted mean vote). With the psychrometric routines that I had developed using the Goff/Gratch formulation of precise vapor pressure, and with the response factor programs, I was ready to extend my simulation program for the underground shelters to the above ground buildings by taking advantages of all of these routines. Instead of relying upon the room weighting factors, I studied Buchbergs paper (Cooling Load from Thermal Network Solution, ASHAE Standard 64:111, l958) for detailed heat balance calculation, which was centered around the radiative heat exchange network among room surfaces, and included the conduction heat gain, infiltration heat gain, solar heat gain, internal heat gain. With this method, I was able to determine the cooling load when the room air temperature was set at a control point, as well as to determine the room temperature when the cooling system is turned off or when the cooling system capacity is excessive or short of the cooling requirements. In other words, my detailed heat balance approach opened up a new possibility to couple the room heat gain/heat loss with the cooling/heating capacity of the HVAC systems through the heating/cooling coils. Since this was a heating and cooling load program imposed on the heating and cooling coils, and which was a product of the National Bureau of Standards, I named it as the NBSLD.

NBSLD ENERGY PROGRAM

The oil crises of l972 heightened the need for energy conservation to free the USA of foreign energy dependence. When a researcher at the Stanford Research Institute pointed out that the energy consumption by the building sector constituted almost one third of the total energy consumption of the USA, our activities at the Building Environment Division at the Center for Building Technology (CBT) began getting national attention. Traditionally, the activities on building research at NBS were somewhat neglected and was a low profile stepchild of the glamorous and internationally well-known research institution dealing with the basic science needed for metorology of basic properties of materials, elementary particles, time standards, electromagnetic waves, computer science, etc. NBS, at that time, also moved to the present Gaithersburg campus and acquired an Univac 1108 machine to replace the old IBM7094. Although NBSLD was originally designed for the cooling load analyses of a room for the design cooling day with the clear sky condition, it was modified for the annual energy calculation of a house with a single zone and simple HVAC system without sophisticated system and equipment simulation routines. The modification was accomplished by including a calendar routine, a weather tape reading routine, cloud cover modifiers for clear sky solar radiation using the Kimura/Stephenson model, and numerous other subroutines dealing with energy conservation options depending upon the seasons, including those for attic ventilation and natural cooling. The program was used often by many researchers who were suddenly in great numbers moving into the energy conservation areas from the nuclear and aerospace engineering fields, due to the shift in the government's research funding. The Energy Research and Development Administration (ERDA), an early version of DOE, was created to reorganize national laboratories to begin energy conservation research including several building energy programs. Many talented researchers started to apply computers for building energy analysis to study he effectiveness of various energy conservation strategies, and comparing the calculated energy consumption with the metered values. They contributed heavily to the advancement in building simulation technology in the USA. At the same time, the peaceful and rather slowly moving world enjoyed by the small number of building simulation researchers was gone for good.

DOE2 AND BLAST

I am sure that many of you in the audience may not be aware of the fact that the DOE2 program can be traced back to a sophisticated shadow calculation program of buildings that was devised by GARD/GATX engineers under the leadership of Metin Lokmanhekim. Using a ray tracing and "clipping" method, GARD/GATX engineers were able to calculate the complex shapes and the areas of shadows cast over the exterior surfaces of the building by adjacent buildings as well as by overhangs and side fins of its own. When Jim Anders of the US Post Office asked GARD/GATX to develop an energy simulation program for new post office buildings, it built an energy analysis program based on the draft report of the ASHRAE Task Group of Energy Requirements around this shadow program. The Post Office funded several organizations to conduct large scale validation programs. When Mr. Lokmanhekim joined the Lawrence Berkeley Laboratory to direct its energy simulation program under ERDA, the US Post Office energy analysis program went with him. The first version of the ERDA energy simulation program was called the CAL-ERDA, and it dutifully followed the conduction transfer functions and weighting factor based load calculation algorithms, with the independent and sophisticated quasi-steady state (explained in the next section) system and component simulation programs, as well as an economic analysis. These were large scale national activities involving many researchers. Many modifications and enhancements have been applied to CAL-ERDA evolving into the present DOE-2 program. By the same token, the BLAST program can trace its origins to NBSLD. It is based on the detailed heat balance method for room cooling load calculation coupled with a comprehensive part load performance simulation of the air handling systems and equipment which are extremely critical for energy analyses.

HVAC SYSTEM AND COMPONENT SIMULATION

It is a relatively straightforward matter, although it may not necessarily be easy, to determine the performance of air handling systems, compressors, coils, cooling towers, fans, etc. based on the first physical principles combined with some empirical data as long as each element performs perfectly and independently by following its prescribed set point. But it is another matter to simulate the interactions of these components among each other while responding to the changes in heating and cooling requirements of the building under changing operating conditions. Many system and component simulation programs were able to handle several innovative control schemes to improve its energy efficiency by changing the control set points. For example, a cooling and dehumidifying coil was assumed to satisfy the precise requirements of cooling and dehumidifying loads as determined by the load calculation by either regulating the inlet water temperature, water flow, or the air flow by some control scheme. The control scheme may be a simple "off and on" cycle or a sophisticated proportional control system. It was essentially assumed, with some exceptions such as HVACSIM^{+}, that the control systems were perfect and system and its component followed the changing cooling requirements without deviation from their set points. This I call a quasi-steady state model for the lack of a better term. In the real building, the actual room condition does not exactly match the set point, however. In the quasi-steady state model, it was impossible to determine the room condition that had drifted away from the set point. It was impossible to determine the room condition during the time when its heating and cooling systems were off or when the system or equipment was undersized. What happens when some of these set points are left uncontrolled, or at the "wild" condition? What was really happening in the realistic air-conditioning system is that the several off and on compressor cycles were taking place during the operation depending not only upon the room thermal mass but also upon the settings and the performance of thermostat, the simulation of which requires minute by minute or even smaller time increment simulation of interaction among the room thermostat, the cooling equipment in relation to the cooling requirement. Assume a simplest case in which the cooling system is turned off when the room temperature approaches its lower set point, and the system resumes the operation when the room warms up beyond the higher set point. The system and building interaction results in the room temperature fluctuating around these set points of the thermostat. The fluctuation amplitude and frequency of these off and on cycle depends upon the matching of the cooling system and the thermal inertia of the room, the width of the temperature control band, as well as the sensitivity of the thermostat. If the system capacity overmatches the cooling requirement and the room thermal mass is small, large and frequent off and on cycles take place. Thus the true simulation of the system and component simulation can not separate this interaction with the cooling load calculation. Yet, this type of small time step simulation may not be feasible for hour by hour energy calculations for large buildings having a complicated central air conditioning system.

GROUND CONTACT HEAT TRANSFER

The ground contact heat transfer, which is one of the major difficulties in analyzing the thermal performance of buildings having earth contact surfaces such as basement walls and floors. It requires sophisticated FEM or finite block algorithms to solve the diffusion equations for heat and water as well as the accurate values of earth properties, its thermal conductivity, thermal diffusivity, and temperature. Most of these parameters are strong functions of soil moisture contents. There are simulation methods to include the complex water migration under thermal gradient through the soil in the forms of vapor and capillary liquid into the ground heat transfer analysis, but not during my days. Because of my previous work involving underground survival shelters, I was increasingly involved in simulating the ground contact heat transfer problems, especially the slab on grade floors and for the underground heat distribution system. I was able to develop a steady state 2-D FEM program to determine the heat loss from an existing insulated two-pipe underground heat distribution system. It was almost immediately after the FEM method had been introduced. Crucial data for the analyses were the soil temperature and thermal conductivity around the pipes. I went around and measured these properties using the probe method, and found it to be very frustrating. These properties varied significantly from location to location, from time to time, from depth to depth, especially near the ground surface. In order to make an accurate simulation of the heat loss from the underground system, each element in the finite element program requires reasonably accurate temperature and thermal conductivity in the soil regime. Please remember that I had experienced similar difficulty in obtaining a good agreement between the measured and simulated underground fallout shelter temperature for the first 2 ~3 days of the test. This was mainly because of the inability to assign right initial temperature conditions for each of the finite difference grids that surrounded the shelter. The measured values were available only along the direction normal to the shelter walls, ceiling and floor at their geometric centers. If s 3-D FEM program is used instead the task to fill each element with the correct thermal properties will be formidable, even when such data are available. These data could then be applied to simultaneous 3D FEM programs for solving heat and mass diffusion equations simultaneously. I am sure by now that some of you have developed such simulation programs. But during my time, it was impractical to solve the ground heat transfer in an exact manner. I am dwelling upon this subject here more than necessary since this simple simulation problem addresses many fundamental problems involving building system simulation. It is stimulating, challenging, and rewarding to develop simulation programs capable of handling complex problems using advanced simulation techniques. Yet, advanced simulation techniques require more or better data than usually are available or those that deserve the sophisticated analysis (GIGO syndrome). Compromise and simplification are necessary depending upon the requirements imposed on the simulation task.

In 1963, for the thermal simulation of underground survival shelters, I was not sophisticated enough to be aware of these complex issues. I compiled all available data on measured ground temperature throughout the USA, and analyzed them in relation to the simple mathematical formula on semi-infinite and homogeneous media (single thermal diffusivity) that are exposed to periodic surface temperature variation. It was found that annual average ground temperature is almost identical to the annual average of the monthly normal air temperature. The annual average of the monthly normal air temperature is also very close to the deep ground temperature at around 30 ft below the ground surface and remained unchanged throughout the year. Later at an experimental site on the NBS Gaithersburg campus, I was able to measure the ground temperature at several selected depths down to 30 ft under different earth covers, bare, paved, paved and pained white, covered with short grass and covered with long grass. I found that the ground temperature near the surface, within one foot was strongly affected by the diurnal surface condition, and that even the monthly average temperature as deep as 10 ft was also affected by the type of ground covers, especially under paved surfaces. In this study, the soil core samples were taken to the laboratory for analyzing the types, density, and the water content. But the thermal conductivity was measured in-situ by a thermal probe method. I might add, at this moment, that the thermal conductivity measured by the probe method, if carefully done, should be more reliable than that measured in the laboratory (by either the hot plate methods or any other technique). Because it is impossible to reproduce the undisturbed earth condition in the laboratory. I thought that it would have been much easier to make the ground contact heat transfer analysis on the moon, where the number of variables would be much less. For most of the conventional calculations, I assumed that the ground was homogeneous and wanted to know only the approximate values of thermal conductivity, thermal diffusivity, and earth temperature. It was easy to force-fit the measured monthly average ground temperature data at several depths on a simulation model based on a semi-infinite and homogeneous domain equation, from which one could derive the thermal diffusivity. This thermal diffusivity may not be the true thermal diffusivity of the site, but it is the value consistent with the measured ground temperature as long as the assumption of semi-infinite and homogeneous heat conduction domain is accepted. I may call this thermal diffusivity the "pseudo thermal diffusivity." I found these pseudo thermal diffusivities varied around 0.025 ft^2/hr for the data reported by many earth temperature stations. By the same token, the measured in-situ thermal conductivity by the thermal probe technique is based on the line source theory, in which an infinitely fine line heat source is directly buried to a semi-infinite soil domain. The reality is however, the line heat source has a finite diameter as large as 1 inch and its contact with the soil is never perfect in the actual in-situ measurements. What I am really saying is that "is the precise knowledge of thermal properties as affected by moisture movement worth consideration for the 3D FEM modeling of ground contact heat transfer?" Perhaps not, at least for the annual energy simulation of most normal buildings. Yet, it may be of crucial importance for some specific applications such as for estimating heating/cooling requirements or thermal environment of non-insulated underground spaces, such as tunnels, mines, storage facilities, etc.

<u>AIR INFILTRATION:</u>

One area in building simulation which had defied accurate simulation for many years was air infiltration, since the air leakage mechanisms and flow path were very difficult to identify. Yet, air infiltration was a significant portion of thermal load for most residential buildings in those days. The only thing we had during the late '60s was the crack method and air-change method for heat loss calculations until an empirical relationship called the Achenbach and Coblentz equation or the Bahnfleth equation was published. By using the helium concentration measurement technique, Bahnfleth, et al (ASHAE Transactions, l957) were able to show a simple empirical formula for the air change per hour, from the data on a limited number of houses, such as $AC = a + bW + c\Delta t$. In other words, the air change (*AC*) by infiltration is proportional to the wind speed (*W*) and temperature differential (Δt) between the in- and outside of the building. The normalized values of constants *a*, *b*, and *c* were provided by Achenbach and Coblentz (ASHAE Transaction, 1963) based on their experiments as well as those of Bahnfleth. Helium was used as a tracer gas simply because of its high thermal conductivity. Coblentz devised an unique hot wire probe and measured its temperature change which is related to the concentration change of helium in the air. One problem was that a leaky building consumed a large amount of helium that used to be stored in a heavy pressure container, and the method was inconvenient for the large scale measurement of air infiltration. Later, the scientists at the Pennsylvania State University developed a method of using SF_6 based on its sensitive electron capture property. The electron capture measurement method can detect parts per billion quantity of SF6 in the air, thus small quantity of SF_6 is enough to measure the air leakage of large and leaky buildings. Using this SF method for many different types of buildings under many different conditions in combination with the so called "blower-door" technique to measure the air tightness of the building, the researchers at the Lawrence Berkeley Laboratory and NIST were able to develop a much more accurate and more comprehensive prediction method for building air leakage thus making a great contribution to building heat transfer and energy consumption simulation. Yet all of these modern simulation equations result in zero infiltration when the wind speed is zero and when there is no indoor and outdoor temperature difference, which is contrary to the findings of previous researchers such as Bahnfleth, Achenbach and Coblentz as well as several other researchers later.

I believed that the exact understanding of air infiltration required the consideration for the effect of the pulsating nature of atmospheric pressure and turbulence which could readily be observed by sensitive manometers. In other words, this pulsating effect may be the cause of the term "*a*" in the Achenbach and Coblentz equation mentioned above, which is as much as 0.19. A preliminary study of this pressure pulsation effect was first reported in a paper entitled "Dynamic Characteristics of Air Infiltration", (ASHRAE Transaction, Vol. 81, 1975) by Jim Hill and myself. This paper won the coveted 1976 Crosby Field Best Paper Award of ASHRAE. I also sponsored a PhD thesis by Dr. John Klote who studied this phenomenon in depth ("Pulsatile Infiltration" 1985 PhD Thesis at the George Washington University) in terms of differential pressure pulsation. I have a feeling that there is also an effect of the barometric pressure fluctuation in building air leakage, which can be left to future researchers.

FUTURE PROSPECTS

Perhaps it is presumptuous for me to talk about the future of computer simulation on building systems. Nevertheless, I would like to make the following observations, many of which I am sure have already been discussed among you thoroughly. The existing and sophisticated programs are probably good enough or even better than required (over-kill) for many practical situations. But there are many areas in which the existing simulation method may require further refinements in several different ways.

(1) More detailed and micro scale analysis in terms of handling the fast time domain problems or thermophysical details. Good examples are the ground contact heat and moisture transfer, the effect of atmospheric pressure fluctuation and turbulence on air infiltration, radiative energy absorption by moisture and CO_2 in the room air, radiative heat transfer through fibrous insulation in the walls and ceiling, the effect of room dust in radiative heat exchange, micro scale turbulence in room air circulation, better coupling among air, moisture and heat transfer, etc. to name a few.

(2) Extension of dynamic building energy simulation into the dynamic community-wide energy simulation, city-scale simulation, regional calculations involving the country to world scale simulation in conjunction with the energy and environmental planning of the community, city, state and the world.

(3) Improvements of coupling among different simulation models involving thermal, mechanical, acoustic, lighting, structural, material, economical, legal, biological, and social systems. I am sure that many existing programs already address these aspects, but I am not sure how extensive they are. I have no idea how the coupling can be made between thermal simulation and acoustic simulation. But I know the acoustic requirements of the building envelope must sometimes be affected by the natural ventilation requirements in naturally ventilated houses.

(4) What I would like to see most is that the concept of the PIHI (Predicted Indoor Habitability Index) that Jim

Hill and I once advocated in our l975 report (NBS BSS 71) be expanded or further developed. Our concept, at that time, was a simple algebraic formulation in which the energy performance, comfort performance, economic performance, are weighted (in accordance with specific application requirements) and summed up to arrive at an index for determining the building air conditioning need.

(5) Innovative application of new computer science technologies in terms of software as well as hardware, or in terms of the application of the advanced information technology such as the Internet to building simulation problems. These include the shortening of computer time by efficient programming, parallel programming, deconvolution of calculated data into transfer functions, use of artificial intelligence techniques or neural network methods, use of CAD/CAE and/or the Internet, etc.

CONCLUDING REMARKS

My association with building performance simulation started with graphical methods and ended at the time when desktop computers were beginning to be popular in the HVAC engineers' offices. I appreciate the understanding of some of the old timers in the audience that my memories of the building thermal simulation in the '50s through '70s may differ from what they believe really happened. This is especially true for the years and names of the personalities involved. My talk today was about what I remember about those good old days, when things were considerably less sophisticated, less complicated, and slower, but nevertheless very exciting. Again, I thank Prof. Nakahara for inviting me to tell you my reflection to this august body of advanced simulation specialists. I wish all of you a challenging and exciting tasks in this fast moving world of computer simulation.