Applying Building Simulation Tools to Optimize System Sizing and Operation Strategies

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ABSTRACT

Building operation strategies can greatly affect occupant comfort and energy use, especially in thermally massive buildings. Building simulation tools can provide the HVAC system designer with detailed information about the dynamic behavior of a building. With this information, the designer can then optimize the capacity and operating schedules of the HVAC system to take advantage of the thermal mass of the building. A design method is presented which is based on the use of an hour-by-hour building simulation program. The simulation tool is especially applied to determining optimal setback strategies. This design approach produces systems with smaller capacities which provide superior comfort with lower first costs and lower operating costs.

Key Words: Air Conditioning, Load Calculation, Energy Conservation, Sizing, Heating

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Building operation strategies can greatly affect occupant comfort and energy use, especially in thermally massive buildings. Building simulation tools can provide the HVAC system designer with detailed information about the dynamic behavior of a building. With this information, the designer can then optimize the capacity and operating schedules of the HVAC system to take advantage of the thermal mass of the building. A design method is presented which is based on the use of an hour-by-hour building simulation program. The simulation tool is especially applied to determining optimal setback strategies. This design approach produces systems with smaller capacities which provide superior comfort with lower first costs and lower operating costs.

INTRODUCTION

Hourly simulation programs provide the HVAC system designer with the capability to analyze the dynamic response of a building. With this information, the designer may optimize the building, system size, and operating strategies to minimize investment and operating costs while improving overall thermal comfort. Conventional simplified design procedures have two basic shortcomings:

- Frequently oversized equipment (sometimes as high as a factor of 2) due to the conservative assumptions required to insure an adequate design with a simplified procedure and to insure adequate capacity for recovery from setback conditions,
- Inability to model dynamic loads and the accompanying comfort conditions.

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For an optimal design, dynamic loads are especially important. Consider a heavyweight building during the heating season which has been in setback mode for an entire weekend. The time needed to heat up to the desired comfort conditions can be as long as two to three days. The air temperature may be raised quickly given enough heating capacity, but the mean radiant temperature will rise at a rate dependent on the following factors:

- the temperature difference
- the installed capacity of the heating and cooling source
- the mass of the building
- other internal or external loads.

The dynamic loads which are caused by set point changes are the dominant loads in many buildings. Changes in temperature levels require changes in energy input and put very uneven loads on the equipment. This can lead to high peak demands and low overall part-load ratios.

It follows then that one of the major design goals should be to have smooth load curves. A load curve with no peaks at all would be ideal -- small peaks are realistic. Furthermore, smooth changes in loads should also be the goal of the design. To fulfill all of these requirements, tools which model the thermal behavior of buildings as exactly as possible are necessary. These tools must model the dynamic loads and must lead to accurate results, especially under part-load conditions.

SIMULATION TOOLS

The use of simulation tools for design is not currently common practice. Simplified peak load methods (such as UAΔT for heating and the CLTD/CLF method for cooling) are typically used for design (sizing) calculations. These methods, by their nature, limit the range of conditions which can be analyzed for optimum sizing. Simulation tools have traditionally been used for energy analyses, that is, for the determination of annual energy consumption for a typical year. While this is a worthwhile use of these tools, they can also be used for design calculations if properly applied. The only differences between a peak load sizing calculation and an annual energy analysis are the assumptions which are made concerning the outside environment and the internal operation of the building -- the heat transfer principles are the same. A simulation which is valid for off-peak conditions will also be valid for peak conditions. The benefit of using a simulation tool is that complex peak conditions can be modeled which would not be possible with the traditional design methods. This requires, however, a flexible simulation tool which allows the user to manipulate the necessary inputs as needed for a proper design calculation.

In order to give the designer a complete picture of a building's thermal characteristics, a simulation tool must sufficiently model the dynamic effects of the building and mechanical systems. An hour-by-hour simulation program which uses a heat balance method is a minimum requirement in order to simulate dynamic effects. The program must be capable of dealing with varying space temperatures and must handle the transient thermal mass effects properly. In addition, the tool must account for all of the obvious environmental factors and internal loads. Finally, the tool must be available for a workstation and/or microcomputer environment in order for it to be feasible for day to day design use. The work which is presented here has been done using the Building Loads Analysis and System Thermodynamics (BLAST) software on a Unix workstation and on a 386-PC. This software uses conduction transfer functions (ASHRAE, 1989) and heat balances to model the building heat transfer. This fundamental approach gives the program the ability to simulate a wide range of conditions, including floating space temperatures. *Reviewers:*

Please advise whether mentioning this program by name is appropriate within the limits of the ASHRAE Commercialism guidelines. Thank you.

DESIGN METHODOLOGY

A method of design optimization is presented here which utilizes an hour-by hour simulation tool as the basic calculation procedure. This method has been repeatedly applied with much success and has proved its worth in practice. The discussion here will concentrate on the determination of the heating and cooling demands for each space in the building. There are also numerous system design considerations which will be briefly mentioned here.

The basic principle is to eliminate all load peaks as much as possible. The ideal goal is a system which operates at a constant load near the peak capacity of the equipment. This will minimize the peak energy demand and will minimize the amount of less efficient part-load operation. Naturally, this ideal goal will not be fully achieved, but for many applications, especially in high-mass buildings, the design can approach this goal. The design procedure involves several passes in which various scenarios are simulated. This method of iteration allows all influences to be included.

Appropriate Design Conditions

In order for the simulations to be useful for design, the appropriate design conditions, both external and internal, must be specified. For external conditions, a design weather year has been created using actual extreme weather conditions encountered in Germany. This design year includes a hot-sunny period for peak space sensible cooling loads, a hot-humid period for peak cooling coil loads, and an extreme cold period for peak heating loads. Each of these periods is approximately one week long with several days of approaching conditions and several days of extreme conditions. These extreme periods have been taken from actual weather data for different years and have been added to a typical German weather year to make a complete year. For most of the design process, only the extreme periods are considered even though the entire year is simulated. For internal conditions, the best estimates for occupancy, lighting, and other internal loads are used. For cases where exact values are unknown, a range of values can be simulated in order to determine the impact of the various internal loads. From these results, the designer can then choose what conditions will be used as the design basis.

Step 1: Optimize Building Envelope

The first step is to optimize the building envelope by performing simulations of the yearly energy consumption. A host of possibilities exists for building envelope changes which result in a reduction of energy consumption. These options should be explored first in order to reach a low energy consumption specific for the building. After optimizing all the measures such as insulation, design of the facade, shading devices, and other energy saving measures, the basic conditions for an economic operation of the building are established.

Step 2: Optimize Room Temperature Control

The next step is to optimize the control strategies in the individual rooms and sections. For this purpose one must establish the marginal conditions of thermal comfort for each space depending on its use. Office buildings are usually occupied from 8 a.m. until 5 or 6 p.m., and during this period the comfort conditions must be sufficient. The air temperature should be about 70°F (21°C) for heating and not exceed 79°F (26°C) for cooling. When heating, it is of vital importance that the mean radiant temperature is not lower than 65 to 66°F (18.5 to 19°C). When using setback operation, it is important to reheat the building in time. Simulations are performed for various setback strategies in order to determine the acceptable amount of setback in order to insure adequate comfort with minimal peak loads.

This is best illustrated by an example. Figure 1 shows the temperature and heating load profile of a section of a building with a heavyweight structure which is used as an office. The bottom graph represents the external temperature. Above it is the heating load for this section. The two upper graphs represent the mean air temperature and the mean radiant temperature in the space. The building was equipped with a control system which lowered the room temperature to 59°F (15°C) on weekends and by night. Subsequently, the mean radiant temperature dropped to approximately 57°F (14°C) at night. If the heating system was turned on on Monday at midnight, an air temperature of approximately 68°F (20°C) could be reached when office hours started. The mean radiant temperature, however, amounted only to 61°F (16°C). In the course of the day, the mean radiant temperature does not exceed 63.5°F (17.5°C). In the evening hours, the set-back program starts again so that only a small amount of energy is being supplied. The next day (Tuesday) it is noon before the mean radiant temperature reaches the value of 64°F (18°C) which is necessary for comfort. Only on the third day (Wednesday) is a comfortable condition maintained in the rooms for the entire occupied time. It is remarkable that during this time the external temperature by day did not drop below 5°F (-15°C). The heating load profile shows the peaks which are typical in the morning hours for this type of setback control. These comparatively high peak loads of approx. 1700 to 2000 BTU/hr (500 to 600 W) naturally have to be supplied by the systems and the central plant. This leads to a corresponding high demand for energy supply. Outside of the peak heating periods, especially on the weekend, significantly lower loads are required and the system is only partially loaded.

Different control strategies were tried in order to solve the problem of insufficient thermal comfort in the morning hours and after longer setback periods. Figure 2 shows the effect with no setback. The heating load graph is very well balanced and shows a generally constant quantity with the exception of office hours during the week. The temperature profiles of the room air and mean radiant temperature are also very well balanced. The temperature levels are within a range which can be considered to be sufficiently comfortable. It is especially striking that the heating power course shows no significant peaks. The result is that the systems and the central plant have to supply less peak load. Apart from that, the components are operated in a favorable working condition which results in improved efficiency.

Figures 3 and 4 show different heating load curves after a setback period during the night along with the corresponding temperatures. The graphs indicate that the thermal comfort when starting work in the morning can be guaranteed either by an excessive heating during a relatively short period of time or by preheating over a longer period of time. It can also be clearly seen that the required equipment capacity is a function of the preheating period. By an adequate synchronization of the equipment capacity and the preheating period it is possible to achieve a minimization of the peaks during the heating-up period. Since reductions in equipment size pay off in reduced initial investment costs, this is a very desirable goal.

This also applies to the case of the cooling load, though the approach is slightly different. In the case of the cooling load, the ranges of tolerance allowed for the admissible maximum air temperature are very important. In the case of computer rooms, for example, where the allowable deviation may be less than ±1.8°F (±1°C), there is almost no possibility for optimization. However, in offices, if a variation of temperature (e.g. from 70°F (21°C) in the morning to 79°F (26°C) in the afternoon) is allowable there are possibilities for optimization. These are represented in the figures 5 and 6.

In Figures 5 and 6, the first graph shows the thermal behavior in a room whose cooling system starts in the morning and operates during working hours with the corresponding loads. At night the systems do not operate. The second graph shows the same room with systems operating at night without active cooling. That is, unconditioned external air is used to cool the building mass during the night. The main point of this concept is to abduct the warmth accumulated in the building at a low cost. Of course this is only possible if the external temperature is correspondingly low during the night and morning hours. If this should not be the case, such as on very sultry and warm summer days, a nocturnal cooling of the building can be effected also by operating the chillers to provide active cooling. This is economical in two ways since the electrical rates are lower at night and the coefficient of performance of the chiller or cooling-tower will be much higher. This is shown with the third graph.

Step 3: Optimize Air Handling System and Plant Equipment

The air handling system design involves many tradeoffs which can be analyzed through a series of system simulations. Some of the design options which can be determined are:

- Selection of system type.
- Minimization of air flow volumes.
- Selection of air diffuser quality.
- Optimization of duct size versus fan power consumption.
- Optimization of deck temperature controls.
- Optimization of air flow rates versus deck temperatures.
- Optimum boiler and chiller sizes.

The air handling system optimization procedures will be discussed in more detail in a later paper.

EXAMPLES AND EXPERIENCES

Several examples are presented to illustrate the procedure and to illustrate the potential benefits of this method. Examples 1 (discussed above) and 2 illustrate how different setback and system control strategies can affect thermal comfort and equipment loads. Example 3 illustrates a retrofit project which has dramatically reduced the equipment size and energy consumption. Finally, a summary of experiences with five other projects is presented.

Example 2

This example is presented to illustrate the potential savings in energy consumption and investment cost. This example looks at two zones from a bank in Fuerth, FRG. These zones are offices as shown in Figure 7. This project was a retrofit project for which the following options were simulated:

- Baseline: Existing heavy masonry building with little or no insulation, occupied temperatures of 70°F (21°C) in winter and 68-82°F (20-28°C) in summer, setback temperatures of 59-63°F (15-17°C) in winter and no setback cooling in summer, multizone fan system.
- Option A: Add insulation and reduce supply air volumes and equipment sizes reduced accordingly.
- Option B: Same as option A plus winter setback raised to 66°F (19°C).
- Option C: Same as option B plus demand-controlled deck temperatures and equipment size reduce accordingly.

Figure 8 shows the annual consumption of boiler fuel and electricity for the two zones and the equipment serving them. Option A (insulation) provides the largest reduction in energy consumption, and in this case, the warmer setback temperature increases the overall energy consumption. However this produces significantly more comfortable conditions as shown by Figures 9 and 10. When the system controls are improved and the plant size is further reduced, the total energy consumption (boiler fuel plus electricity) for Option C is 102,000 BTU (30,000 kWh) vs. 160,000 BTU (46000 kWh) for Option A and 348,000 BTU (102,000 kWh) for the Baseline. This represents a savings of 71% from the Baseline and 36% from Option B. At the same time, the boiler/chiller size has been reduced by 70%/64% from the Baseline and 40%/33% from Option B (see Table 1).

Example 3

This example presents results from a four-story, 150,000 ft^2 (15,000 m^2) office building in Munich. The building contains a large computer center and is a lightweight construction with windows from floor to ceiling. This was another retrofit project where the following options were considered:

- Option A: Recalculate supply air volumes using a maximum room air temperature of 77°F (25°C) with a supply air temperature difference of 13°F (7°C). The lower supply air volumes reduced the fan power consumption and the temperature rise across the fan was reduced from 9°F (5°C) to 5°F (3°C).
- Option B: Install energy-efficient lighting, add shading devices, and reconfigure air outlets. Air volume flow rates were reduced to the point where adequate room air distribution became the limiting factor. Deck controls were changed to outside temperature controls.

Table 2 shows the changes in air volume flow rates and energy consumption for the two options. Option A was implemented at a cost of DM 350,000 and the energy savings last year alone was DM 405,000. Cost estimates for Option B are DM 1,500,000 with estimated annual energy savings of DM 330,000.

Additional Experiences

Table 3 summarizes results from six representative projects, five retrofits and one new construction. The consumption figures are actual values reported by the building owners. The reductions in equipment sizes and energy use vary significantly depending on the project. The most dramatic results can be seen in the Eschbom project where the heating capacity was reduced by 63%, the cooling capacity was reduced by 41%, the heating consumption was reduce by 40%, the electric consumption was reduced by 24%, and the peak electricity demand was reduced by 69%.

CONCLUSIONS

The dynamic loads which result from changing conditions in a building can greatly influence occupant comfort, required equipment sizes and overall energy use. A design method has been presented here which allows the designer to optimize the system control strategies in order to reduce peak loads as much as possible and to take full advantage of the thermal inertia of the building. The reduction in peaks improves thermal comfort and reduces the necessary equipment sizes. The rate of complaints in buildings with such optimized systems are very low

The equipment sizes for these systems are typically 30 to 50% smaller than for conventionally designed systems, although these reductions are very dependent upon the particular project. The smaller equipment operates for longer periods of time at higher part loads which improves the overall efficiency of the system. In addition, the building owners are pleased with the reduced investment costs for smaller equipment.

This approach is made possible through the use of sophisticated building simulation programs which are capable of modeling the dynamic response of the building. These tools provide the designer with information about the building that cannot be obtained with simpler calculation techniques.

REFERENCES

ASHRAE. 1989. *1989 ASHRAE Handbook -- Fundamentals*, Chapter 26, pp. 26.1-26.62, Atlanta: American Society of heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Table 1a. Summary of Options for Example 2 (IP Units)

Option	Occupied Temp °F		Unoccupied Temp °F		Supply Air ft^3/min		Equip. Sizes BTU/hr	
	Summer	Winter	Summer	Winter	Zone 1	Zone 2	Boiler	Chiller
Baseline	68-82	70	No Cool	59-63	996	318	170	75
A. Insulation	68-82	70	No Cool	59-63	763	254	85	41
B. Less Setback	68-82	70	No Cool	66	742	233	85	41
C. Deck Controls	68-82	70	No Cool	66	742	233	51	27

Table 1b. Summary of Options for Example 2 (SI Units)

Option	Occupied Temp °C		Unoccupied Temp °C		Supply Air m^3/s		Equipment Sizes kW	
	Summer	Winter	Summer	Winter	Zone 1	Zone 2	Boiler	Chiller
Baseline	20-28	21	No Cool	15-17	0.47	0.15	50	22
A. Insulation	20-28	21	No Cool	15-17	0.36	0.12	25	12
B. Less Setback	20-28	21	No Cool	19	0.35	0.11	25	12
C. Deck Controls	20-28	21	No Cool	19	0.35	0.11	15	8

Table 2a. Summary of Results for Example 3 (IP Units)

	Baseline	Option A	Base to A Reduction	Option B	Base to B Reduction
System 1 Supply Air	57,890	38,634	33%	27,982	52%
System 2 Supply Air	64,725	44,652	31%	31,047	52%
System 3 Supply Air	13,506	8930	34%	8930	34%
Total Heating Consumption	16,880	9475	44%	6838	59%
Peak Heating Demand	9950	7875	21%	5858	41%
Total Chilled Water Cons.	1989	1689	15%	1406	29%
Peak Chilled Water Demand	5173	4381	15%	3265	37%
Total Electric Consumption	16,430	12,550	24%	9680	41%
Peak Electric Demand	3617	3163	13%	2467	32%
Total Energy Costs (Est.)	1,280,000	951,000	26%	725,000	43%

Supply air volumes are in ft^3/min, peak demands are in 1000 BTU/hr, consumptions are in 1,000,000 BTU per year, costs are in DM.

Table 2b. Summary of Results for Example 3 (SI Units)

	Baseline	Option A	Base to A Reduction	Option B	Base to B Reduction
System 1 Supply Air	98,279	65,593	33%	47,508	52%
System 2 Supply Air	109,889	75,810	31%	52,711	52%
System 3 Supply Air	22,931	15,162	34%	15,161	34%
Total Heating Consumption	4947	2777	44%	2004	59%
Peak Heating Demand	2916	2308	21%	1717	41%
Total Chilled Water Cons.	583	495	15%	412	29%
Peak Chilled Water Demand	1516	1284	15%	957	37%
Total Electric Consumption	4815	3679	24%	2837	41%
Peak Electric Demand	1060	927	13%	723	32%
Total Energy Costs (Est.)	1,280,000	951,000	26%	725,000	43%

Supply air volumes are in m^3/h, peak demands are in kW, consumptions are in MWh per year, costs are in DM.

Table 3a. Overview of Selected Projects (IP Units)

Project:	Eschborn	Fürth 1	Stuttgart	Kassel	Minden
Retrofit/New Construction	Retrofit	Retrofit	New Constr.	Retrofit	Retrofit
Construction Weight		Heavy	Light	Heavy	Medium
Total Building Area	728,000	20,240	62,400	66,000	42,700
Cooled Area	487,300	6460	56,000	17,600	6700
Original Heating Capacity	65	60	None	38	37
New Heating Capacity	24	18	14	24	20
% Reduction	63%	69%		38%	46%
Original Cooling Capacity	59	None	None	24	36
New Cooling Capacity	34	28	3	21	23
% Reduction	41%			11%	36%
Original Heating Consumption	53	62	None	28	Unknown
New Heating Consumption	32	42	5	17	25
% Reduction	40%	32%		38%	
Original Electric Consumption	137	25	None	30	Unknown
New Electric Consumption	104	22	13	18	19
% Reduction	24%	12%		38%	
Original Peak Elect. Demand	64	Unknown	None	29	Unknown
New Peak Electric Demand	20	Unknown	6	14	9
% Reduction	69%			57%	

Capacities and demands are in BTU/hr-ft^2, consumptions are in 1000BTU/ft^2 per year, areas are in ft^2.
Heating capacities are normalized by total building area.
Cooling capacities are normalized by cooled building area.
Consumptions and demands are normalized by total building area.

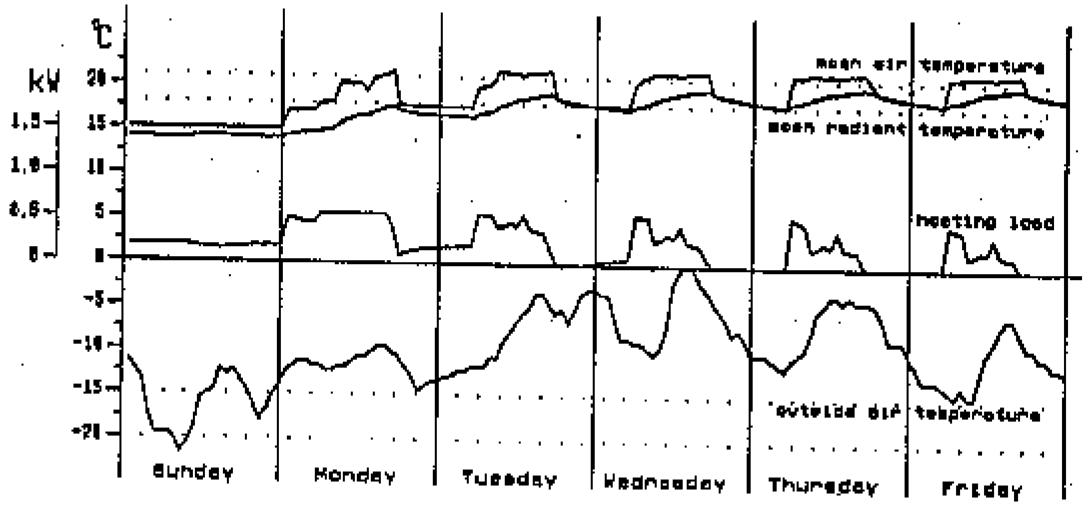
Table 3b. Overview of Selected Projects (SI Units)

Project:	Eschborn	Fürth 1	Stuttgart	Kassel	Minden
Retrofit/New Construction	Retrofit	Retrofit	New Constr.	Retrofit	Retrofit
Construction Weight		Heavy	Light	Heavy	Medium
Total Building Area	67,700	1881	5800	6132	3970
Cooled Area	45,285	600	5200	1637	625
Original Heating Capacity	206	188	None	121	117
New Heating Capacity	77	57	43	75	63
% Reduction	63%	69%		38%	46%
Original Cooling Capacity	185	None	None	76	112
New Cooling Capacity	108	87	9	67	72
% Reduction	41%			11%	36%
Original Heating Consumption	167	196	None	88	Unknown
New Heating Consumption	100	132	16	54	78
% Reduction	40%	32%		38%	
Original Electric Consumption	431	79	None	94	Unknown
New Electric Consumption	329	70	41	58	60
% Reduction	24%	12%		38%	
Original Peak Elect. Demand	202	Unknown	None	90	Unknown
New Peak Electric Demand	62	Unknown	18	43	28
% Reduction	69%			57%	

Capacities and demands are in W/m^2, consumptions are in kWh/m^2 per year, areas are in m^2.
Heating capacities are normalized by total building area.
Cooling capacities are normalized by cooled building area.
Consumptions and demands are normalized by total building area.

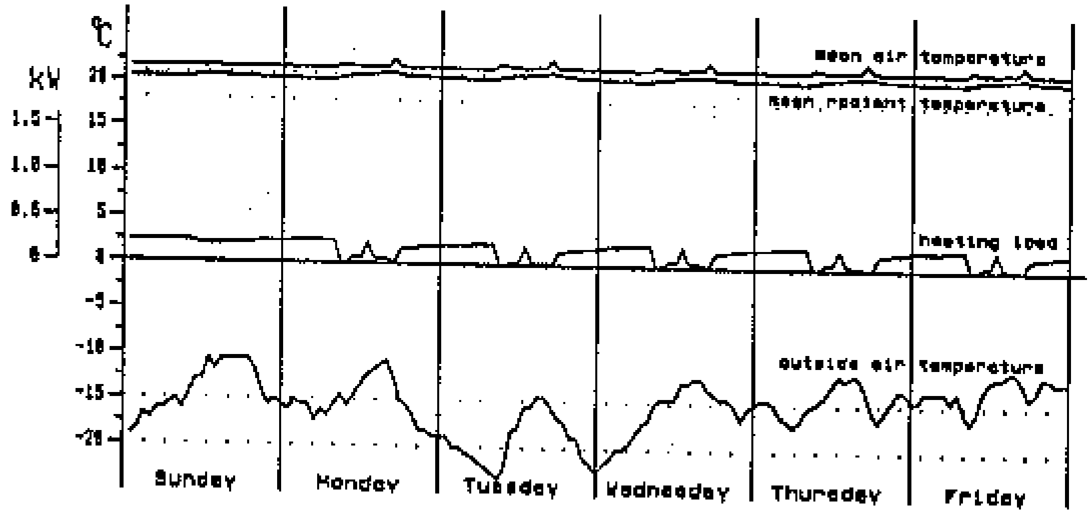
Temperature and Heating Loads

Figure 1 Setback Control



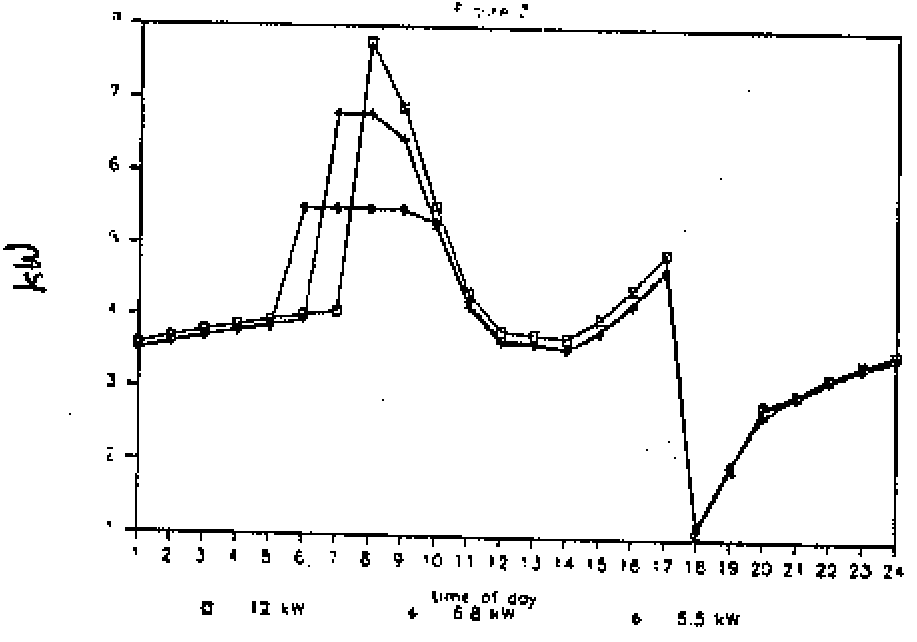
Temperature and Heating Loads

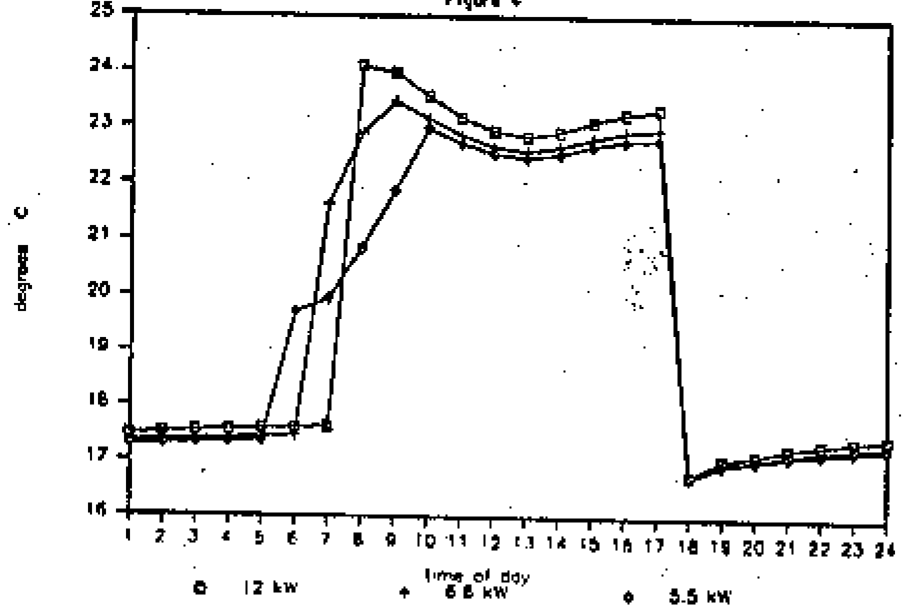
Figure 2 Constant Room Temperature



Heating Loads

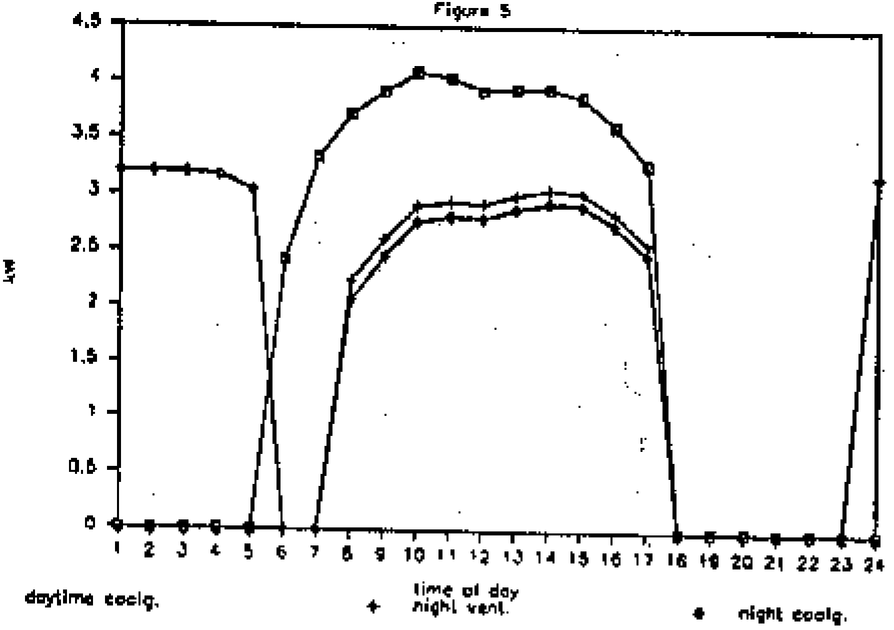
Figure 3





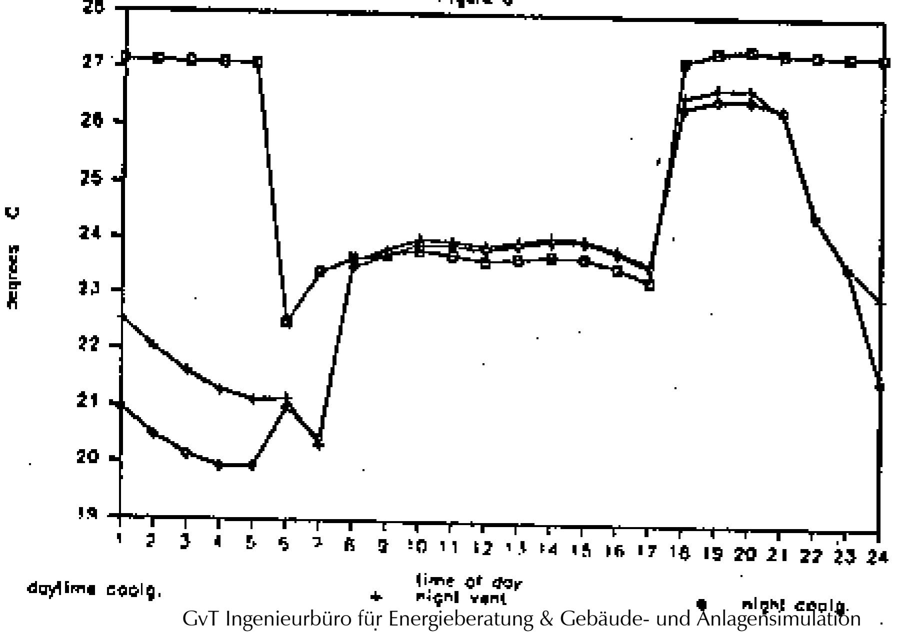
Room Air Temperatures

Figure 4



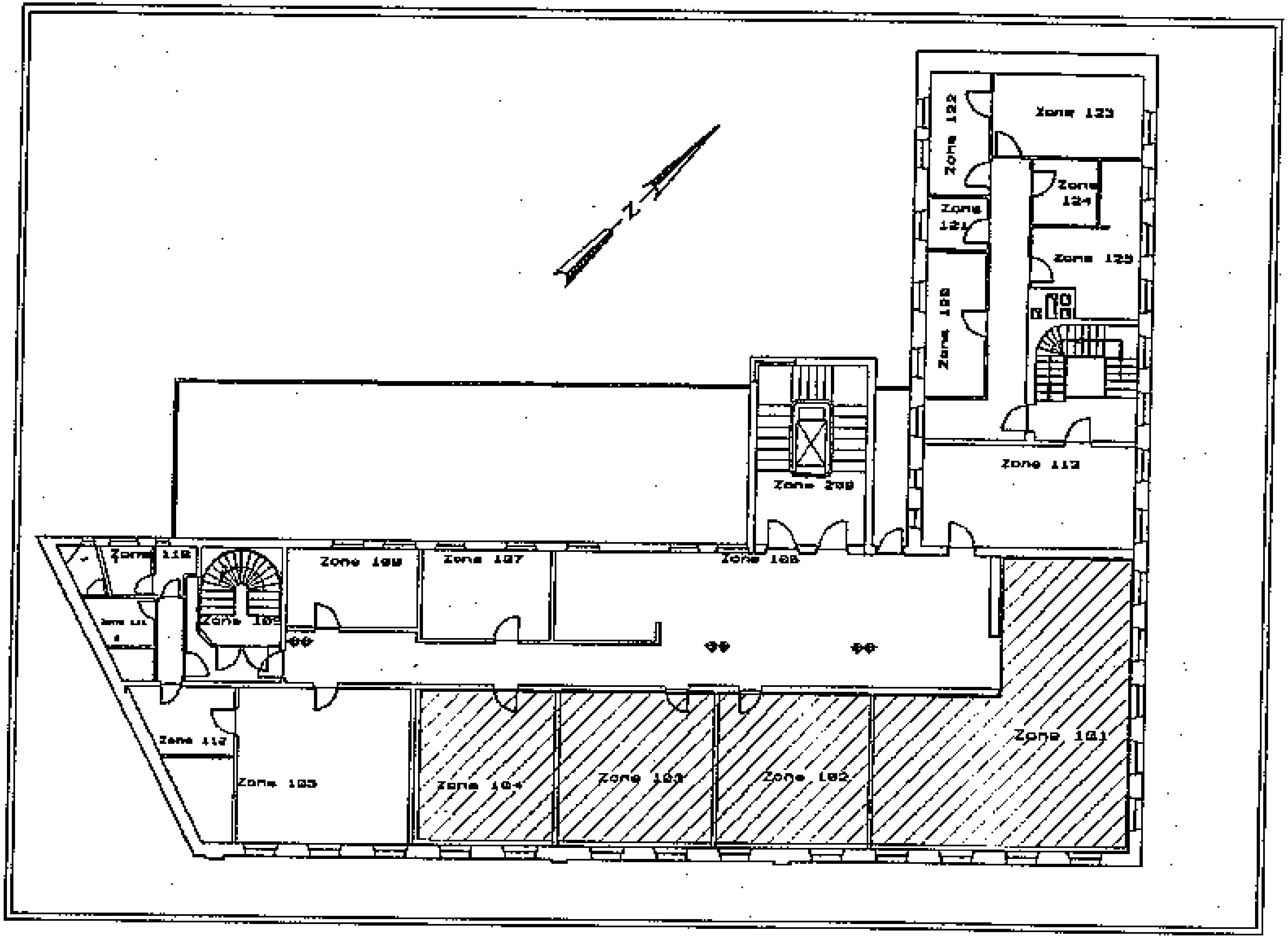
Cooling Loads

Figure 5



Room Air Temperatures

Figure 6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Zone 122
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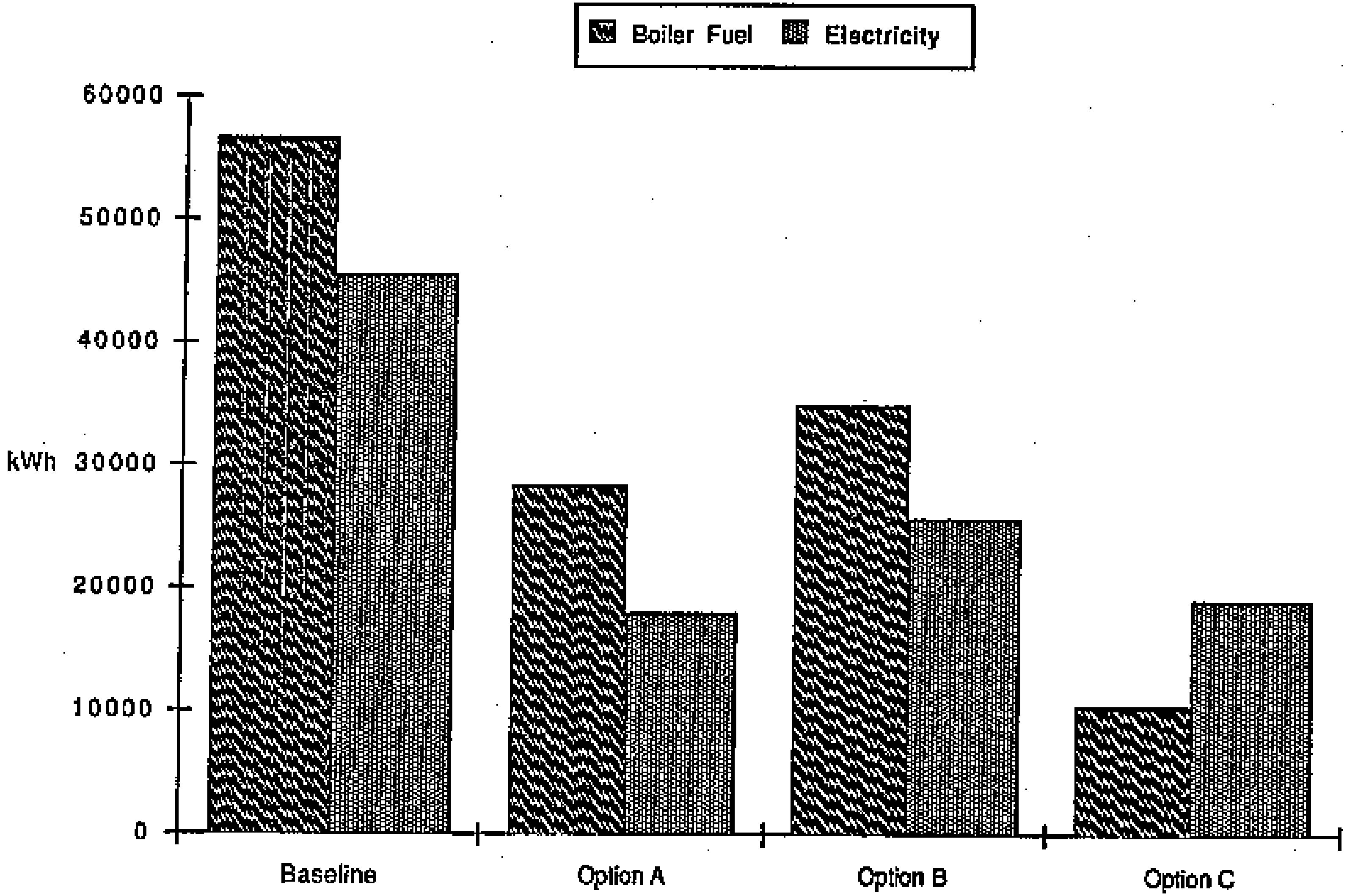
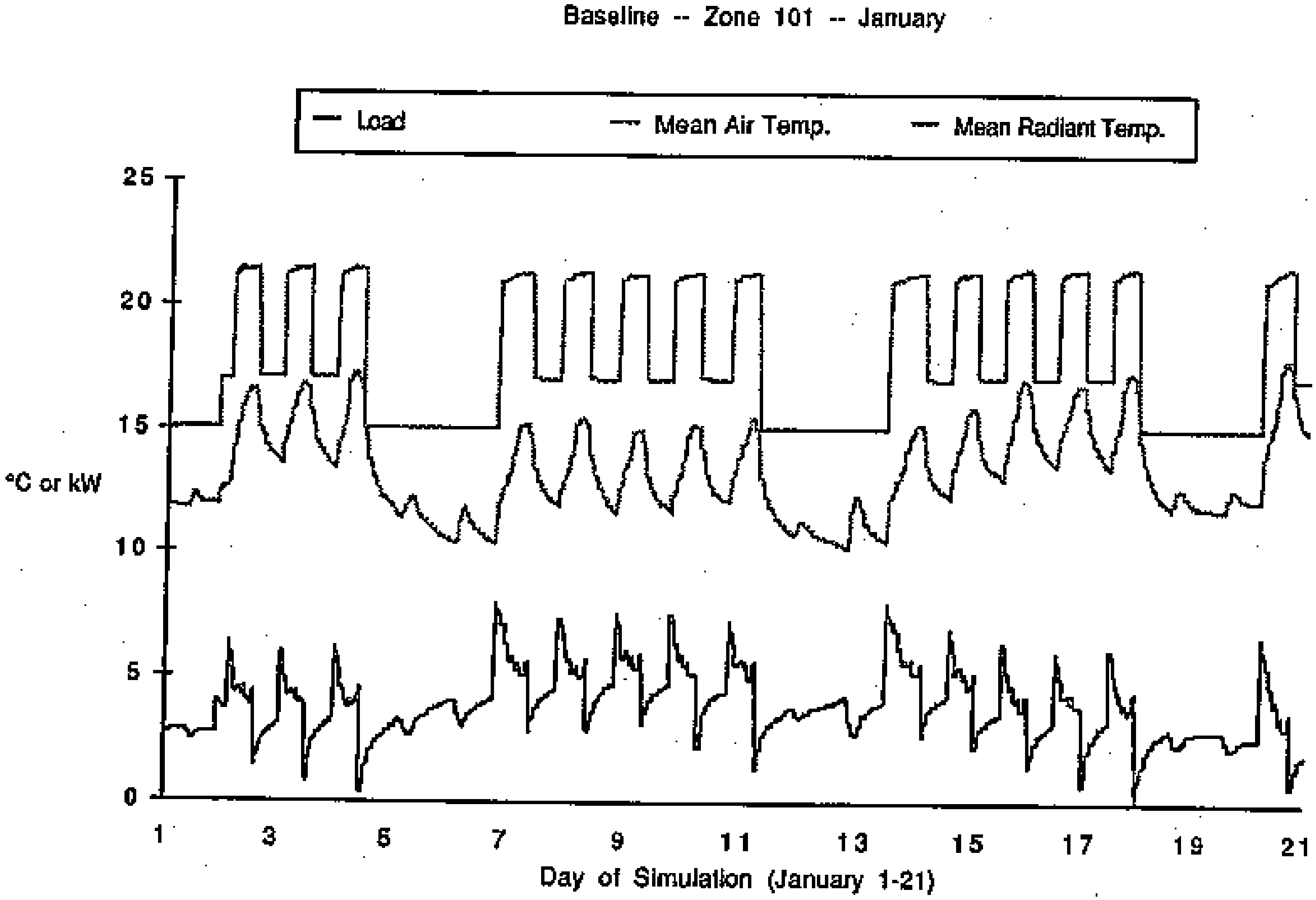
Figure 7

Figure 8


Boiler Fuel
Electricity
60000
50000
40000
kWh
30000
20000
10000
0
Baseline
Option A
Option B
Option C


Baseline -- Zone 101 -- January
Load
Mean Air Temp.
Mean Radiant Temp.
°C or kW
25
20
15
10
5
0
1
3
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7
9
11
13
15
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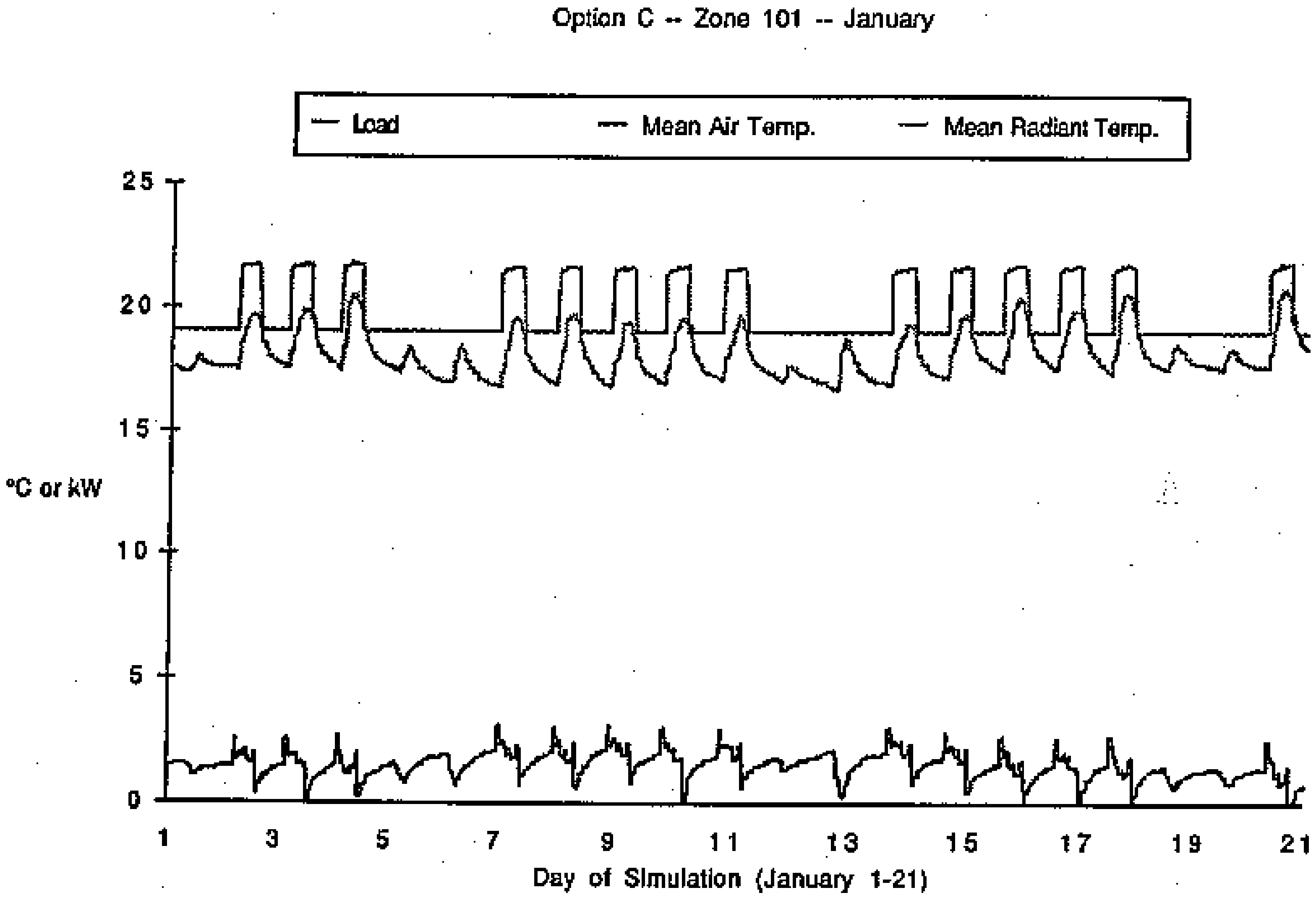
19
21
Day of Simulation (January 1-21)



Option C -- Zone 101 -- January