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CONTROL SYSTEM ANALYSIS FOR OFF-PEAK AUXILIARY HEATING OF PASSIVE SOLAR SYSTEMS

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ABSTRACT

A computer simulation method is presented for the design of an electrical auxiliary energy system for passive solar heated structures. The system consists of electrical mats buried in the ground underneath the structure. Energy is stored in the ground during utility off-peak hours and released passively to the heated enclosure. An optimal control strategy is used to determine the system design parameters of depth of mat placement and minimum installed electrical heating capacity. The optimal control applies combinations of fixed duration energy pulses to the heater, which minimize the room temperature error-squared for each day, assuming advance knowledge of the day's weather. Various realizable control schemes are investigated in an attempt to find a system that approaches the performance of the optimal control system.

INTRODUCTION

The auxiliary energy for passive solar heated structures may be provided by storing energy in the ground underneath the structure during utility off-peak hours. This approach is attractive to contractors because of the relative ease with which electrical resistance mats may be placed on the ground during excavation for the foundation. The use of off peak storage released passively to the heated enclosure leads to significant control problems. Energy must be expended before it is needed to heat the structure due to the thermal lag of the storage medium. The success of this approach depends upon the development of a control system that regulates the room temperature sufficiently while using energy at a cost lower than that for a conventional electrical backup system.

A reasonably intelligent control system that can assume storage subject to the off-peak rate structure and anticipate the need for auxiliary energy will be necessary.

METHOD OF ANALYSIS

For the purpose of designing the auxiliary energy system, it is assumed that a good controller can be found to meet the system performance requirements. Generally, it has been found in this study that the design parameters are affected by the type of control used, that a simple conventional controller gives poor performance in terms of energy cost, and that the system performance is less sensitive to design parameters with an intelligent controller than with a very simple controller.

The analysis approach in this study is to use the best control that can be applied to the system. The best control is achieved with advance knowledge of the weather. For the purpose of this study, one day's advance knowledge is assumed. The off peak period is assumed to be between 10 p.m. and 8 a.m., during which time electricity would cost one half of the daytime cost. The ten-hour off-peak period is divided into five two-hour periods. To determine the best control, the differential equations that describe the system are solved as follows.

1. The equations are solved using actual weather data with no auxiliary energy used. This is called the unperturbed response.

2. The equations are solved using auxiliary power at a constant level applied over each of the five two hour periods during the off peak hours. These are the forced responses.

3. It is assumed that the system equations are linear, so the unperturbed response can be subtracted from each of the five forced responses to give that part of the system response due to each of the five energy pulses.

4. Again, due to the linearity of the system, the response difference due to any combination of the five individual responses

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differences can be found by addition of the individual responses, and the total system response can be found by adding the result to the unforced system response.

5. The combination of pulses that gives the minimum root-mean-square (RMS) room temperature error around 70°F over the entire day is the best control for that day.

Naturally, the number of pulses or time divisions over the off-peak period can be made arbitrarily large, but five pulses, giving 32 combinations, is used here. Ten pulses would give 1024 combinations, for example. However, although the method is well-suited to digital computer solution, computing time becomes prohibitive for ten pulses if very many days or parameter studies are to be examined.

The daily computations were repeated over a three-month period (December, January, and February) using weather data for the Los Alamos, New Mexico, winter of 1975. The effect of the design parameters of electrical mat placement depth and installed heating system capacity were studied with soil conductivity as a variable.

SYSTEM MODEL

The system model parameters are based on a passive solar heated home under construction in the La Veranda Subdivision in Santa Fe, New Mexico, in which the buried electrical backup heating system will be used. This project is a joint venture between the Public Service Company of New Mexico, the Los Alamos Scientific Laboratory, and Permatech, Inc., a Santa Fe builder, to demonstrate the use of an advanced, load managed electrical backup heating system in a passive solar heated residence. The house under study makes use primarily of a solar storage wall and considerable direct solar gain. The electrical mats are buried a prescribed depth beneath a four-inch concrete floor slab. The mats rest on undisturbed native soil (caliche), and are covered by a compacted fine-grained fill material.

The basic constants of the system are assumed to be

Total heat loss/load	567 Btu/hr.°F	(Int. Avg. Temp. Diff.)
Slab conductivity (k)	0.8 Btu/hr.ft.°F	
Solar wall (Trombe wall)	16 in. concrete, dul-glazed exterior, k = 1.0 Btu/hr.ft.°F	
Solar wall area / building load	Ratio = 1.0	
Solar wall int. heat transfer coefficient	1.0 Btu/hr.ft²°F	
Floor heat transfer coefficient	1.5 Btu/hr.ft²°F	
Constant soil diffusivity = conductivity / volumetric specific heat	0.03 ft²	

It is assumed that the soil is at a constant temperature of 50° five feet below the slab for the purpose of calculating downward losses. Rigid insulation limits heat loss at the periphery of the structure.

System Simulation with Perfect Control

Two standard cases were analyzed for comparison purposes. In each case, auxiliary energy is used directly in the heated enclosure at any time during the day to regulate the room temperature. In the first case, a "perfect" controller regulated the room temperature at 70°F at all times, and in the second case, a [illegible] around 70°F was used to simulate a [illegible] thermostat control. The estimated rate differential for off-peak electricity is one-half, so to compare the totally off-peak system, a rate-adjusted energy total is calculated as

$$E_{adj} = \frac{1}{2} E_{night} + E_{day} .$$

The 90 day heat energy balances for the standard cases given in Table I. The energy terms are

$E_{AUX,N}$	Auxiliary energy, night (off-peak);
$E_{AUX,D}$	Auxiliary energy, day;
E_{sd}	Direct solar energy;
E_{sw}	Solar wall energy input;
E_l	Total heat energy loss; and
E_{adj}	Rate adjusted auxiliary energy.

TABLE I
SIMULATED ENERGY BALANCE

	$E_{AUX,N}$	$E_{AUX,D}$	E_{sd}	E_{sw}	E_l	E_{adj}	[illegible]	[illegible]
Perfect 70°F control	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
70°F, [illegible] Deadband	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE II
SYSTEM DAILY SUMMARY WITH OPTIMAL CONTROL

DAY	AMBIENT TEMP (°F) AVG	HIGH	LOW	ROOM TEMP (°F) AVG	HIGH	LOW	70°F RMS ERROR	CONTROL SEQ	ENERGY kWHR
1	25.8	35.0	16.0	69.3	73.5	67.0	2.2	10000	20
2	28.6	40.0	18.4	69.2	73.0	66.7	2.3	10000	20
3	27.1	36.0	16.6	69.6	73.6	67.5	2.0	11000	40
4	28.0	38.0	18.1	69.6	73.9	67.4	2.3	10000	20
5	25.9	36.0	18.1	69.1	73.1	67.0	2.1	10000	20
6	30.6	42.0	23.0	69.2	73.1	67.4	2.0	10000	20
7	38.0	44.0	28.0	69.9	73.5	67.9	1.9	00000	0
8	28.1	38.0	17.2	69.5	70.6	68.1	0.9	11101	80
9	13.8	22.0	9.0	69.4	73.7	66.7	2.2	11100	60
10	16.2	30.0	3.0	69.1	74.2	66.4	2.6	11100	60
11	18.5	30.0	7.0	69.6	73.9	67.6	1.6	11111	100
12	17.2	31.0	4.3	69.5	74.1	67.4	2.3	11000	40
13	27.1	39.0	18.2	69.1	73.6	66.7	2.5	10000	20
14	26.3	41.0	17.0	68.6	71.1	66.4	2.1	11110	80

Energy terms are in kWhr. The other terms are:

F_{OP} Fraction of auxiliary energy used off-peak, and

PS Percent solar.

Numerous simulation studies were made to determine the optimum placement depth of the electrical mats using the optimal control scheme.

A typical daily summary of the system simulation is given in Table II. This summary is for a two-week period taken from a three-month simulation. The control sequence column shows the two-hour time periods over the ten-hour off-peak period when the power is on. For example, 10000 represents power on from 10 p.m. to midnight, 00001 represents power on from 6 a.m. to 8 a.m., and so forth. The case shown in Table II uses the design parameters of 10 kW electrical capacity, 9-inch mat depth and assumptions of ground conductivity of 0.7 Btu/hr.ft.°F above the mats and the 0.5 Btu/hr.ft.°F below the mats.

The performance parameters that are used to determine the system design are seasonal RMS room temperature error, absolute minimum room temperature attained, total time spent below 65°F, total time spent above 75°F, and total electrical consumption.

The simulation studies indicate that, for this model, the performance parameters listed above become relatively insensitive to placement depth and soil conductivity at power density levels above 7.5 watts/ft². At power densities below this critical value, the performance of the system in terms of the listed parameters deteriorates sharply, except that less total energy is used. The house that is being built with this heating system has 1300 ft² of heated area, so this would indicate a design value of 9.75 kW of capacity. Actually, 10 kW was used, and this capacity is used in the remainder of the simulation examples.

Some typical results are summarized in Tables III and IV for different fill and base soil conductivities. The table headings are:

D Depth, inches

E_{ADJ} Rate-adjusted energy, kWhr

t < 65 Time below 65°F, hours

t > 75 Time above 75°F, hours

T_{min} Minimum room temperature, °F

TABLE III
SYSTEM PERFORMANCE SUMMARY

k_{fill} = .7, k_{ground} = .5, Btu/hr ft°F

D	E_{ADJ}	RMS	t < 65	t > 75	T_{min}
3	1600	2.16	9.5	0	64.2
6	1635	2.25	1.0	1.0	64.9
9	1710	2.27	0	0	65.3
12	1810	2.[illegible]	0	0	65.7
15	1900	[illegible]	0	0	65.1
18	2010	[illegible]	19.0	2.0	64.0

TABLE IV
SYSTEM PERFORMANCE SUMMARY

k_{fill} = .5, k_{ground} = .3, Btu/hr ft°F

D	E_{ADJ}	RMS	t < 65	t > 75	T_{min}
3	1300	2.16	3.5	3.0	64.6
6	1360	2.20	0	2.0	65.1
9	[illegible]	2.26	0	0	65.5
12	1460	2.26	0	3.0	65.6
15	1535	[illegible]	0	7.5	65.6
18	1625	2.55	0	14.0	65.7

It is assumed that the fill material will have a conductivity somewhat higher than that of the undisturbed soil below the mats.

The general findings from the studies are:

1. The seasonal RMS temperature error increases with depth, but over the range of conductivities examined, exhibits a broad region of insensitivity to both depth and minimum RMS error for depths between 6 and 15 inches. Generally, for depths in excess of 12 inches, the RMS error increases rapidly with increasing depth.

2. A depth of at least 6 inches is required to obtain acceptable minimum temperatures (over 65°F). The minimum temperature also drops off rapidly for depths in excess of 12 inches.

3. The time spent below 65°F exhibits a broad minimum (usually zero) for a depth between 6 and 12 inches.

4. Total energy consumption increases with depth. For higher base soil conductivities (above 0.6 Btu/hr.ft.°F) placement depth must be less than 12 inches for the system to use less rate-adjusted energy than is used in the standard case.

If all of the cases are considered, a depth of 9 inches appears to be the optimum value for a wide range of soil conductivities for the model assumed in this study; this depth has been chosen for the project.

CONTROL SYSTEM DESIGN

Work on the design of this system is incomplete. In order to design a control system, one must find a control algorithm that gives a system performance as close to the optimal system as possible. The optimal system performance can never be attained because knowledge of the next day's weather is not attainable. An important constraint on the design is that the control hardware must be kept simple and of low cost.

An analysis of two types of systems gives the results in Table V. The two ideal systems with heat added directly to the interior are also tabulated. The 70°F ± 1°F slab control system simply regulated the concrete slab temperature to 70°F during off-peak hours. The slab reset system moves the slab control setpoint as a function of ambient temperature according to the schedule $t_{slab} = 75.0 - 1.0\,t_{ambient}$ so that the slab setpoint is 75°F for 60°F ambient, and 70°F for 30°F ambient. The realizable schemes show poor performance compared to the optimal system, with considerable overheating. It is felt that some enhancement of the slab reset system can be realized by adding anticipation based on ambient temperature rates, and knowledge of the previous day's performance. Additional analysis in this area is continuing.

TABLE V
CONTROL SYSTEM COMPARISON

	E_{ADJ}	RMS	t_{air}	$t < 65$	$t > 75$
Perfect 70°F	1822	0.0	70.0	0.0	0.0
Perfect 70°F±2°F	1968	---	68.0	0.0	0.0
70°F±1°F Slab Control	1887	3.0	64.2	19.3	207.6
Slab Reset	1847	2.8	64.5	14.0	196.4
Optimal	1710	2.3	65.3	0.0	0.0

CONCLUSIONS

The design method leads to a system that will perform well with considerable insensitivity to system variables that may not be well known (soil conductivity). Very simple realizable controls do not approach optimal performance, but still show energy cost savings. Cost savings for the optimal control amount to 14%. For the slab reset control, savings are 6% when compared to the ideal room temperature control with deadband. The overall results of this study indicate that with a controller possessing a small amount of intelligence, multi-improved system performance can be attained. The control hardware that would be required to implement a variable setpoint controller (a simple microprocessor) could be used to implement a system which could anticipate energy needs based on previous performance history and the dynamics of ambient conditions without a significant increase in hardware complexity. Such a controller could also manage more complex off peak rate structures, than the one considered here and also accommodate peak load rate considerations.