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A Gas-Fired Heat Pipe Zone Heater

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ABSTRACT

A gas-fired vented zone heater has recently been developed by the Altas Corporation for Colorado State University (CSU) under a Gas Research Institute (GRI) contract. The unit was developed for auxiliary heating applications in passive solar buildings. An early prototype was tested at Altas and operated as expected. The final model was shipped to CSU in December 1983 for testing in the REPEAT Facility at CSU.

A heat pipe extends through the wall to the outside of the building. It has a modest water charge which can freeze repeatedly with no damage, since the heat pipe is only partially filled. Firing efficiency at 4,000 Btu/h (1.17 kW thermal) is approximately 80%. The unit features a 3 foot by 3 foot radiator mounted inside the room to be heated, and is thermostatically controlled. Ignition is accomplished with an electronic sparker (pilot). The radiator typically operates at 150-180°F (65-82°C), and has been operated at between 2,000 and 5,000 Btu/h (0.6-1.47 kW). Results of testing the vented heat pipe zone heater at CSU are presented.

Also, a method for determining the optimal combination of zone heater, passive solar heating and energy conservation measures has been developed. Nomographs have been developed that may be used by a building designer to determine the optimal combination of zone heater size, passive solar system size, and energy conservation measures for given types of passive solar heating systems in selected locations. A representative nomograph is presented along with a design example.

INTRODUCTION

Spending on energy-efficient products and services amounted to approximately $9 billion in 1980, approximately $30 billion in 1983, and it has been estimated that approximately $50 billion per year will be spent in this area by 1990 (1). Residential energy conservation business activities have represented a significant portion of the spending on energy efficient products and services. Approximately $4.5 billion were spent in this area in 1982 and it has been estimated that the spending in the residential energy area will amount to approximately $30 billion per year by 1990. Zone heaters have represented a significant portion of the spending in this area.

There were rather dramatic sales of portable electric space heaters in the 1970's in the United States, with several million units being sold annually. Few, however, are being sold today. The reason is primarily due to the relatively high cost of electricity in most locations throughout the United States. Kerosene heaters have also experienced rather dramatic sales increases and decreases. For example, approximately 35,000 units were sold in 1974 and 3 to 4 million units per year were sold between 1981 and 1983 but sales of these units have also decreased. There are numerous disadvantages to kerosene heaters. These include the inconvenience of fuel handling (searching for fuel and filling the fuel tanks), the high cost of kerosene relative to that of natural gas, odors from fuel and combustion products inside the conditioned space, manual operation, dangerously hot surface temperatures, and ventilation requirements (1).

The topic of this paper is the use of gas-fired heat pipe zone heaters in very well insulated (superinsulated) buildings. Traditional type central heating plants are not appropriate for superinsulated buildings. In superinsulated buildings, the internal gains provide a significant amount of the energy required to maintain adequate comfort levels in the buildings. That is, the internal gains will raise the temperature inside the space to a value close to the desired value. Therefore, it may not be necessary to have a large, central heating facility. Instead, small zone heaters may be used to provide the additional energy required in order to maintain the inside temperature at the desired value. Electric resistance heaters are already available for this purpose. However, the costs for electricity are high compared with the costs for natural gas in many locations in the United States. Hence, the need exists for a gas-fired zone heater that may be used with superinsulated buildings. A zone heater of this type is described in this paper.

The gas-fired heat pipe zone heater described below represents a significant improvement over previous zone heaters in that combustion takes place outside the conditioned space, the zone heater uses natural gas or propane as a fuel, it has safe operating temperatures, no fumes or odors are inside the conditioned space, and it is fully automatically controlled.

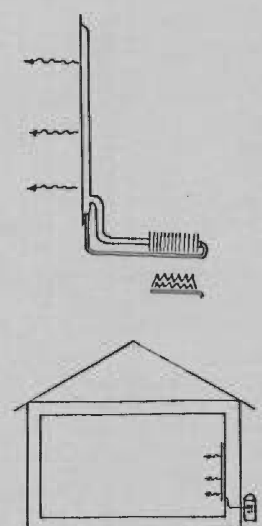
A description of the gas-fired heat pipe zone heater is given in the following section. This is followed by a description of a procedure for determining the optimal combination of zone heater, passive solar heating, and energy conservation measures for a building.

THE ZONE HEATER

The Altas Corporation developed a small, vented gas-fired space heater that was designed for heating only one room or section of a building. The firing rate was 2,000-5,000 Btu/h (approximately 0.5-1.5 kW thermal) and the firing efficiency was approximately 80%.. It consisted of a heat pipe device which penetrates the outside wall of a building, with a combustion chamber evaporator assembly unit outside of the building, and a condenser-radiator inside. The unit is thermostatically controlled and uses an electronic pilot. The condenser-radiator is a one meter by one meter square vertical copper plate which is mounted a few centimeters away from the inside surface of an outside wall of a building. Copper tubes were soldered to the plate at approximately 7 centimeter intervals and joined to a header at the bottom. The header is joined by a 1.91 centimeter (0.75 inch) diameter tube, referred to as the adiabatic tube, to the evaporator, which consists of a single tube with external fins. The insulated combustion chamber, the controls, the electronic pilot, and the flow control valves are in a box which is to be mounted on the outside of the building. The system is illustrated in Figure 1.

Figure 1

Pictorial Representation of Heat Pipe Zone Heater



The heat pipe behaves essentially as a thermal diode. When the burner is on, a large amount of heat will be transferred into the building at a very small temperature difference. When the burner is off there will be a large temperature difference (approximately 35°C) between the inside and the outside and yet there will be very little heat transfer out of the building. The heat pipe fluid used in the present device is water. A very small amount of water (approximately 50 ml) is used; hence the tubes outside the building are only partially filled, and the device can freeze without damage. However, if the water in the evaporator is frozen at start-up, it must first be thawed and then evaporated. This represents a transient loss in the system and this can be minimized by using a small charge of water and longer firing periods.

Several configurations are [illegible] The present configuration is designed for heating a single zone in a building. One could also design a device to heat two adjacent zones by placing the device in the wall dividing the two zones close to the point where the separating wall meets the outside wall of the building. The heat transfer to the zones could be by natural convection through registers placed in each side of the separating wall. One could also use standard hydronic heaters for the condenser. It is also conceivable that several units could be installed in separate zones of a building and each unit could be individually controlled. Numerous possibilities exist.

RESULTS OF ALTAS TESTING

A prototype of the zone heater was tested in the Altas laboratories and operated for several days in order to ensure proper operation. It was found to operate reliably through many on-off cycles. The heat pipe vapor pressure reached about 7 psia during steady state operation in the 65°F laboratory. Steady state conditions were reached after approximately 30 minutes. The flue gas temperature was 280°F with a CO_2 content of approximately 6%.

The prototype unit (which was essentially identical to the final unit) was also mounted on a wall with a 5 centimeter gap between the wall and the panel. The heat pipe vapor pressure, evaporator fin temperature, and panel surface temperature were monitored. The surface temperature was measured midway between riser groups, which corresponds to the coolest location. The system was then operated over a range of input firing rates. Results from these tests are shown in Table 1. The system efficiency was approximately 80%.

Table 1

HEAT PIPE ZONE HEATER BENCH TEST RESULTS

Firing Rate (Btu/hr)	Fin Temp. (°F)	Panel Temp. (°F)	Vapor Press. (psia)	Ambient Temp. (°F)
2025	155	136	4.0	77
2650	162	149	4.5	75
3300	176	162	6.0	78
4400	185	170	8.25	75

RESULTS OF CSU TESTS

Several tests of the Altas Zone Heater were performed between March 5 and May 4, 1984, in the "mystery room" of the REPEAT facility at CSU. The objective in performing these tests was to develop an engineering characterization of the zone heater. The characterization was to include:

- transient and steady state thermal efficiencies of the zone heater.
- relative contributions of radiation and convection to the steady state heat flux from the zone heater.
- a preliminary data base from which recommendations for refinements of the present design, as well as possible control schemes, may be made.

The tests consisted of 4 bench tests, 6 transient field tests, and a 3 day steady state field test. Optimization of the fuel-air ratio was performed during bench testing by recording temperature data on the condenser while varying the primary air supply in order to produce the largest average plate temperature. During the bench testing the radiation and convection heat flux contributions were determined and are shown in Figure 2.

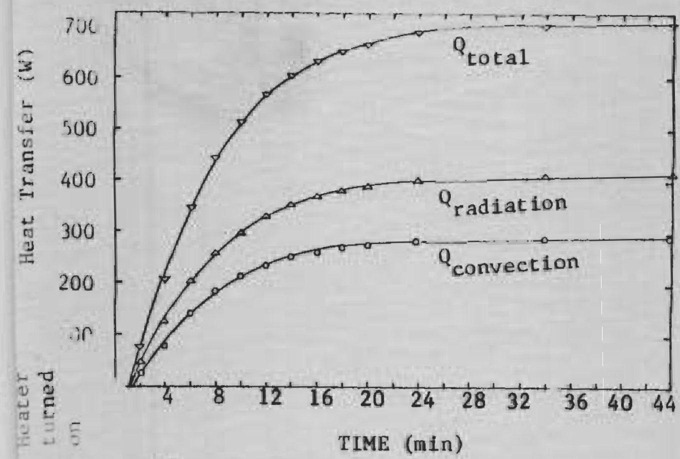


Figure 2 Heat Transfer vs Time for Heater Plate During Bench Test

All field testing of the zone heater was done in an environment which was relatively free from extraneous inputs. The "mystery room" of the REPEAT facility at the CSU Solar Village provided such an environment. The doors, walls, windows, and ceiling were insulated with 2 inches of styrofoam and then tightly sealed in order to minimize the thermal effects of outside temperature variations. Aluminum foil was placed on the outside of the windows to insulate the room from solar gains. The room was then instrumented such that the remaining thermal flux between the interior of the room and the outside environment was determined. The test arrangement is illustrated in Figure 3. Commercial grade bottled methane was used as fuel during the field tests.

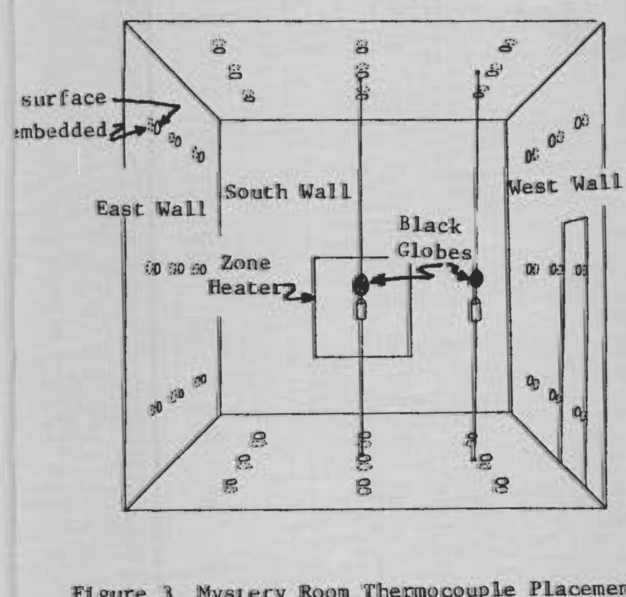


Figure 3 Mystery Room Thermocouple Placements

An average flow rate of 3.6 cubic feet per hour, at a pressure of 3 inches of water, was used during the tests. The condenser plate was divided equally into six vertical sections; each section was monitored separately using 25 equally spaced thermocouples.

The transient tests consisted of firing the burner and then recording temperature data at 2 minute intervals until the condenser plate temperature reached steady state conditions; this took approximately 30 minutes, comparable with the test conducted by Altas. The gas was then shut off while data collection continued until the plate temperature for the section had returned to its initial value. This process was then repeated for each section of the plate. The data collected during these tests were then used to determine thermocouple placements to be used during the steady state field test.

The steady state field test was performed for 72 hours. The zone heater was operated continuously during this time and temperature data were collected at 15 minute intervals. The following temperature measurements were made:

- wall, ceiling, and floor temperatures
- dry bulb air temperatures inside and outside the mystery room
- black globe temperatures inside the mystery room
- temperatures of the adiabatic pipe and the heater housing

These data were then used to determine the steady state efficiency of the zone heater, as well as the convective, radiative, and conductive heat fluxes from each surface during the steady state operation. The zone heater efficiency was found to be 81%. The system pressure was found to be about 30 kPa when the plate was at room temperature. The mass of air in the heat pipe was estimated to be 1.72 E-04 kg; it was found that this amount of air in the system tended to reduce the height to which the water could rise, which in turn resulted in a lower temperature for the top few centimeters of the condenser plate. A more complete system vacuum would eliminate this problem.

THE OPTIMAL COMBINATION OF ZONE HEATER, PASSIVE SOLAR, AND ENERGY CONSERVATION

The methodology for determining the optimal combination of passive solar heating, energy conservation, and the zone heater size has been presented previously (2). The method is based upon the work of Balcomb (3) and is briefly summarized as follows.

Consider a two zone building, in which one zone is maintained at some nominal temperature, say 60°F (15.6°C), whereas the other zone is to be maintained at certain time periods at a higher temperature, say 68°F (20°C). The zone heater provides the additional energy required to maintain the higher temperature in its zone. In addition, suppose that a passive solar heating system is to provide some portion of the baseline energy required and that energy conservation measures will be applied in order to decrease the overall energy requirements. The problem then is to determine the optimal amount of energy conservation, the size of the passive solar component, and the size of the zone heater. The optimal combination is based upon minimizing the life cycle cost, where the life cycle cost may be written as

$$LCC = \left[e + aA_P + \frac{b}{L_T} - c + dA_{ZH} + f\right]E_1$$

$$+ \left[Q_{AUX}\frac{C_{f_{AUX}}}{\eta_{AUX}} + Q_{ZH}\frac{C_{f_{ZH}}}{\eta_{ZH}}\right]E_4 \qquad (1)$$

where:

- e = the base cost for passive solar ($)
- a = the incremental cost for passive solar ($/ft^2)
- A_p = the projected collector area (ft^2)
- b = the incremental cost for energy conservation ($ · Btu/DD)
- L_T = the total building load coefficient (Btu/DD)
- c = the base cost for energy conservation ($)
- d = the incremental cost for the zone heater ($/ft^2)
- A_{ZH} = the zone heater area (ft^2)
- f = The base cost for the zone heater ($)
- E_1 = the present worth factor of capital equipment costs
- $C_{f_{AUX}}$ = the auxiliary fuel cost ($/Btu)
- $C_{f_{ZH}}$ = the zone heater fuel cost ($/Btu)
- Q_{ZH} = the energy consumed by the zone heater (Btu)
- E_4 = the present worth factor of the future fuel costs

Using an energy balance between the auxiliary heater and the heating requirements (for the lower base temperature), the energy provided by the auxiliary heater is obtained as

$$Q_{AUX} = (1 - SSF)L_T\, DD_{LB} \qquad (2)$$

where

- SSF = the solar savings fraction
- DD_{LB} = the degree days to the lower base.

The zone heater energy output may also be obtained using an energy balance:

$$Q_{ZH} = (L_1 + L_i)\,\Delta DD = L_1\,(1 + F)\,\Delta DD \qquad (3)$$

where

$$F = L_i/L_1$$

ΔDD = the difference between degree days to the higher and lower bases.

Using a heat transfer analysis the zone heater area required is determined:

$$A_{ZH} = Q_{ZH}/(24k) = L_1\,(1 + F)\,\Delta DD/(24k) \qquad (4)$$

where k represents the product of the zone heater heat transfer coefficient and the temperature differential between the zone heater and the zone 1 air temperature. That is,

$$k = h_{ZH}\,(T_{ZH} - T_1)\ . \qquad (5)$$

Two economic factors are introduced in Kirkpatrick and Winn (2):

$$h = \frac{C_{f_{AUX}}}{\eta_{AUX}}\,DD_{LB}\,\frac{E_4}{E_1} \qquad (6)$$

$$\tilde{h} = \frac{C_{f_{ZH}}}{\eta_{ZH}}\,\Delta DD\frac{E_4}{E_1} \qquad (7)$$

Substituting (2), (3), (4), (6), and (7) into (1) results in

$$LCC' = (\ e + aA_p + \frac{b}{L_t} - c$$

$$+ \frac{d\Delta T}{24k}\,(L_T - L_2)(1 + F) + f\ )$$

$$+ (\ (1 - SSF)\ L_T h + (L_T - L_2)\ \tilde{h}\ (1 + F)) \qquad (8)$$

where

$$LCC' = LCC/E_1 \qquad (9)$$

E_1 is the present worth factor of capital equipment costs. It accounts for interest, inflation, discount rate, taxes, and insurance.

Fuel costs for electricity and gas and estimated fuel inflation rates for each region are presented in Table 2. Values in this table were obtained from the 1983 Gas Research Institute Baseline Projection Data Book.

TABLE 2. GAS RESEARCH INSTITUTE ENERGY COSTS AND INFLATION RATES

Average Residential Gas Prices ($/MMBtu)
(1982 dollars)

Year	1982	1983	1984	1985	1990	1995	2000
New England	7.53	7.65	8.68	8.43	8.62	9.36	10.58
Middle Atlantic	5.84	5.93	6.25	6.36	6.87	7.68	8.86
South Atlantic	5.40	5.63	6.02	5.98	6.00	6.83	8.06
East North Central	4.54	4.64	4.73	4.94	6.00	6.80	7.98
West North Central	4.73	4.94	5.14	5.40	6.52	7.34	8.53
East South Central	4.60	4.69	4.85	5.08	5.53	6.47	7.70
West South Central	4.58	4.66	4.72	4.99	5.27	6.25	7.45
Mountain #1	4.52	4.41	4.41	4.59	5.29	6.29	7.67
Mountain #2	4.53	4.69	4.81	4.85	5.68	6.61	7.92
Pacific #1	6.84	6.41	6.29	6.46	8.05	8.75	9.94
Pacific #2	4.18	3.94	3.97	4.10	5.56	5.97	6.73

TABLE 2. (con't)

Gas Research Institute Fuel Inflation Estimates
Natural Gas

Years	1982-1990	1990-2000
New England	1.7	2.1
Middle Atlantic	2.1	2.6
South Atlantic	1.3	3.0
East North Central	3.5	2.9
West North Central	4.1	2.7
East South Central	2.3	3.4
West South Central	1.8	3.5
Mountain #1	2.0	3.8
Mountain #2	2.9	3.4
Pacific #1	2.1	2.1
Pacific #2	3.6	1.9

Average Residential Electricity Prices ($/MMBtu)
(1982 dollars)

Year	1982	1983	1984	1985	1990	1995	2000
New England	27.70	26.88	28.22	29.30	27.37	28.01	29.36
Middle Atlantic	25.66	25.23	25.92	25.83	25.36	25.61	26.25
South Atlantic	19.18	20.55	23.19	24.15	24.16	25.90	26.97
East North Central	18.80	19.84	21.12	21.61	22.23	21.98	22.49
West North Central	18.41	19.32	20.82	19.75	20.37	20.09	21.35
East South Central	15.35	16.44	17.81	18.47	18.53	19.75	20.69
West South Central	17.40	17.72	19.14	20.23	21.85	23.64	24.98
Mountain #1	14.18	14.33	16.02	16.88	16.42	15.27	16.47
Mountain #2	19.26	19.59	20.57	20.98	19.97	16.99	15.93
Pacific #1	8.25	8.97	9.99	10.33	11.69	12.19	14.71
Pacific #2	24.94	25.37	25.67	26.70	26.57	28.04	29.32

Gas Research Institute Fuel Inflation Estimates
Electricity

Years	1982-1990	1990-2000
New England	-0.2	0.7
Middle Atlantic	-0.1	0.3
South Atlantic	2.9	1.1
East North Central	2.1	0.1
West North Central	1.3	0.5
East South Central	2.4	1.1
West South Central	2.9	1.3
Mountain #1	1.9	0.0
Mountain #2	0.5	-2.2
Pacific #1	4.5	2.3
Pacific #2	0.8	1.0

The optimal building load coefficient, L_{T_o}, may be found by taking the partial derivatives of LCC' with respect to L_T and A_P. Setting the partial derivatives equal to zero to obtain the values corresponding to minimum life cycle costs yields equations (13) and (14).

$$L_{T_o} = (b/((1-SSF)h + a/LCR + (d\Delta T/24k + \tilde{h})(1+F)))^{0.5} \quad (10)$$

$$D = a/h \quad (11)$$

where D is the slope of the SSF versus 1/LCR curve at the optimum.

The conservation factor (CF) is used to determine the optimum passive solar and zone heater areas, insulation values for walls, ceiling, perimeter and windows, and infiltration strategies. The conservation factor has been defined by Balcomb (3) as:

$$CF = \left[24\left[\frac{1}{LCR} + \frac{1-SSF}{D}\right]\right]^{0.5} \quad (12)$$

The conservation factor may be expressed as

$$CF = \frac{1}{L_{T_o}}\sqrt{\frac{24b}{a}} \quad (13)$$

Substituting (6), (7), (10), and (11) into (13) provides:

$$CF = \left[24\left[\frac{1}{LCR} + \frac{1-SSF}{D} + \left[\frac{ADD}{DD_{LB}}\frac{R}{D} + \frac{d\Delta T}{24ka}\right](1 + F)\right]\right]^{0.5} \quad (14)$$

where

$$R = (C_f/\eta)_{ZH}/(C_f/\eta)_{AUX} \quad (15)$$

The optimal insulation values for walls, ceiling, perimeter and windows may be determined from

$$R_i = CF\sqrt{\frac{a}{r_i}} \quad (16)$$

The square root of the ratio of a and r_i must be determined for the building component in question. Multiplying this value by the conservation factor provides the optimal R-value. For perimeter insulation a conversion is used (4), and the optimal R-value equation becomes:

$$R_i = 2.04\ CF\sqrt{\frac{a}{r_p}} - 5 \quad (17)$$

Combining (4) and (13) yields

$$\frac{L_{T_o}}{L_{1_o}}\sqrt{\frac{a}{b}}\,A_{ZH} = \frac{1}{CF}\,\frac{ADD}{\sqrt{24}\,k}\,(1 + F). \quad (18)$$

This term may be multiplied by the value of $(L_1/L_T)\ \sqrt{b/a}$ to obtain the optimal zone heater area. The optimal passive solar area can be expressed as the optimal building load coefficient L_{T_o} divided by the load-to-collector ratio (LCR):

$$A_P = L_{T_o}/LCR \quad (19)$$

Rearranging (13) and substituting into (19) results in

$$A_P = \frac{1}{CF}\sqrt{\frac{24b}{a}}\,\frac{1}{LCR}. \quad (20)$$

which can be rearranged to give:

$$\sqrt{\frac{a}{b}}\,A_P = \frac{\sqrt{24}}{CF}\,\frac{1}{LCR} \quad (21)$$

The optimal infiltration rate can be obtained from (4):

$$ACH = \frac{7.5}{CF}\sqrt{\frac{\text{cost increase } \frac{1}{ACH} \text{ by } 1\ \$/ft^3}{a}} \qquad (22)$$

The above results may be used by a building designer to determine how many square feet of south-facing glazing should be installed for the given type of passive solar heating system, the R-value for walls and ceilings, and the size of the zone heater. The difficulty is that the calculations are tedious; however the tedium may be circumvented through the use of a simple graphical device (nomograph) as illustrated below. The nomograph allows the designer to determine the combination of passive solar features, zone heater size, and energy conservation level that result in a minimum cost to the consumer over the lifetime of the system. The nomograph synthesizes complex economic and thermal performance data into a form which can be used by a person without a technical background. Its use saves the designer from performing the complex, repetitive calculations required to obtain the optimal results. A representative nomograph for Ft. Collins, Colorado is presented in Figure 4. The use of the nomograph is described in the following section.

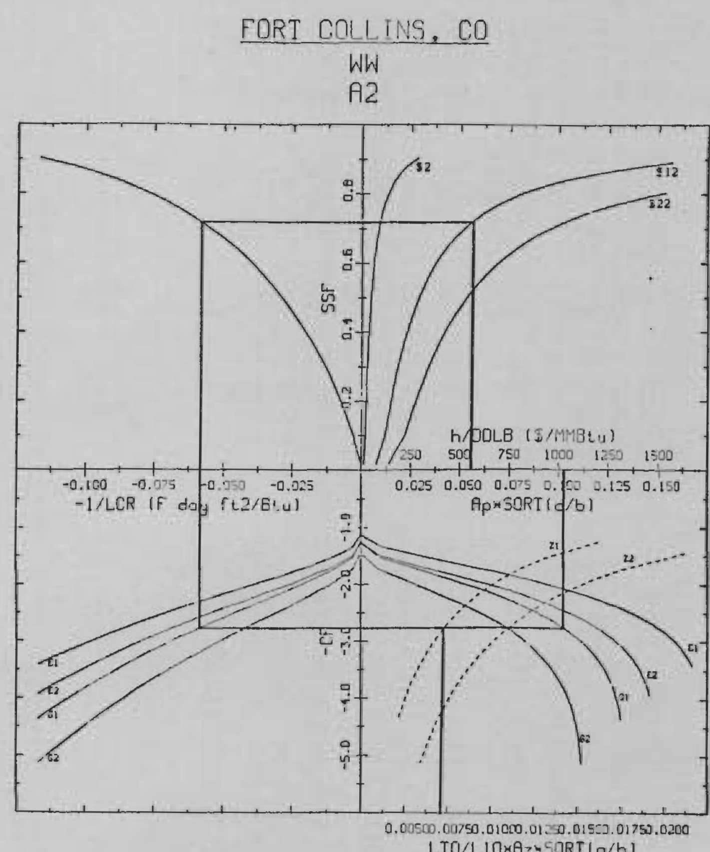


Figure 4 Nomograph for a Water Wall System in Ft. Collins, Colorado

EXAMPLE

Given a 14,400 cubic foot residence located in Fort Collins, Colorado, determine the optimum passive solar area for a water wall system, the zone heater area, and the energy conservation measures. The modified fuel levelizing factor (h/DD_{LB}) is 540 \$/MMBtu and the incremental cost for passive solar is 12 $\$/ft^2$ for system type WWA2 (4). Using the nomograph (Figure 4) the following data were extracted:

$$SSF = 0.72$$

$$CF = 2.75$$

$$\sqrt{\frac{a}{b}}A_P = 0.102$$

$$\frac{L_{T_o}}{L_{1_o}}\sqrt{\frac{a}{b}}A_{ZH} = 0.0071$$

Using $r_{windows} = 3.8\ \$/R\ ft^2$, $r_{walls} = 0.045\ \$/R\ ft^2$, $r_{ceiling} = 0.019\ \$/R\ ft^2$, $r_{perimeter} = 0.25\ \$/R\ ft$, and $r_{infiltration} = 0.031\ \$/\frac{1}{ACH}\ ft^3$ as the incremental costs for each energy conservation component of the house, the following optimum resistances were determined:

$$R_{window} = 5$$
$$R_{walls} = 45$$
$$R_{ceiling} = 69$$
$$R_{perimeter} = 23$$

The optimum infiltration is 1.39 ACH and b is 39.7×10^6. The optimum passive solar area and zone heater area are

$$A_P = 186\ ft^2$$

$$A_{ZH} = 1.5\ ft^2$$

SUMMARY

A gas-fired heat pipe zone heater for use in superinsulated buildings has been described. Results from bench tests and field tests have been presented. The efficiency of the zone heater has been determined to be approximately 80%. In addition, a method for determining the optimal size of zone heater to be used in a superinsulated passive solar building has been presented. A nomograph has been developed for designers to use in determining the optimal levels of insulation, the optimal size of zone heater, and the optimal size of the solar component in a passive solar building. An example of the use of the nomograph has been presented.

It should also be noted that the method presented in this paper may be applied to central heating systems only and to zone heating systems only. This may be done by setting the cost of the heating system proportional to the design heating load for the building and then following the same procedures described above in order to determine the optimal combination of energy conservation measures, passive solar heating, and heating from either a central heating system or zone heating system.

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