INTEGRATION OF THERMAL MASS HEAT STORAGE IN COMMERCIAL BUILDING DESIGN

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ABSTRACT

Operating performance of a large (39,744 ft^3; 3693.4 m^2) sand mass heat storage system is reviewed based on a one-year intensive monitoring project in a commercial building. The heat storage system has a gross heat storage capacity of 1,498,000 Btu/F (2.84 x 10^9 J/°C). The system is built into the foundation system of the building and is located within the building thermal envelope. The high internal heat storage capacity and high insulation standard of the building together account for a very long building time constant (1428 hours or 59 days) observed in a two-week coast-down test of the building. The heat storage system showed substantial benefit to building cooling requirements during the monitoring project.

The detail of design of the heat storage system as built is discussed. Consideration is given to the design of potential new construction using sand mass heat storage sized to maximum winter daily solar gain and heating requirements. The heat storage system as built is discussed. A cooling design criteria for new commercial buildings in which sand mass heat storage is sized to provide for sensible cooling requirements is described.

INTRODUCTION

Unusual public buildings incorporating a variety of energy-conserving building systems came into prominence in the 1970s in New York State as a response to the energy crisis. A large influence on the design strategy of these public buildings was provided by passive solar and superinsulated construction methods developed for home building. Major potential opportunities for energy conservation in public and commercial building design were recognized by a utility company in this building trend. A decision was made to intensively monitor and evaluate the performance of one particular building, the town hall of Volney, New York, since the building incorporates a number of the new building design features in one structure. These features include a superinsulated envelope; active and passive solar heating systems; and a large well-insulated sand mass heat storage system incorporated in the building's foundation. This paper details the performance results obtained from a year's monitoring of the building and outlines design criteria pertinent to the design of heat storage systems in new public and commercial construction.

METHODS

Volney Town Hall was continuously monitored using an on-site computer, data acquisition system, and sensing equipment for a period of one year. The site data acquisition system scanned 140 data points in 5-minute intervals and averaged the data for each sensor on an hourly basis. A data acquisition rate of 92% of the total annual data reported by the sensors was achieved by this method. Data analysis was performed on a central computer using algorithms specifically developed for the task.

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T-type thermocouples were placed throughout the building to determine variation in building temperatures. T-type thermocouples are well suited to the range of temperatures encountered in a building monitoring project; they have an accuracy over their full measured range of $\pm$1.8 F ($\pm$1 °C) with respect to a specific reference temperature and considerably greater accuracy $\pm$0.2 F ($\pm$0.1 °C) when used to measure the variation in temperature of a specific sensor. Other quantities, such as airflow rates in the air-handling system, were determined by site measurement with a portable vane-type anemometer. The device is accurate to $\pm$5% when used to measure velocities in excess of 200 Ft/min (1.016 M/s).

Figure 1 illustrates the thermocouple rake placed in the building's sand mass heat storage system. The building has a floor area of 10,000 ft^2 (929.3 m^2). The insulating system, exclusive of windows and doors, encapsulates the entire building including the sand mass heat storage system and is rated R40. A total of 245 ft^2 (22.8 m^2) of glazing are incorporated in the structure, placed strategically on the south, east, and west faces of the building. Figure 2 illustrates the placement of temperature sensors in the conditioned space within the building. Table 1 details the building heat storage capacity based on the quantities and properties of the materials incorporated in the building thermal envelope.

SIZE OF HEAT STORAGE IN RELATION TO MAXIMUM SOLAR GAIN

A total of 710 ft^2 (65.9 m^2) of south-facing solar air heating surface is installed at the Town Hall including (575 ft^2, 53.4 m^2) ofsouth-facing air collector and 135 ft^2 (12.5 m^2) of south facing window area. On a bright day in winter 1800 Btu (1899 Kj) of solar radiant energy passes through each square foot of collecting surface in the course of a day. Assuming a collection efficiency of 100%, the maximum solar energy gain available to the building through its south-facing air-heating devices is 1.28×10^6 Btu (1.35×10^6 Kj). Assuming good heat transfer to the sand mass (through the operation of the building air-handling system and heat transfer through the floor slab), a maximum temperature rise of 0.7 F (.4 °C) would be expected over the course of a bright day.

SAND MASS PERFORMANCE

Sand Mass Coasting Performance, Building Time Constant

Figure 3 illustrates building temperatures and solar data for the period February 23 to March 2, 1983. From February 23 to February 27 the building was intentionally allowed to coast without auxiliary gas heat (only the solar air collectors and air-handling system were enabled during the test) in order to observe the response of the building to solar and weather conditions. On February 25, 26, and 27 (days of maximum solar gain) air and slab temperature rises of no more than 1 F (0.5 °C) are evident during daytime hours in response to solar heating of the building. During this period building temperatures gradually dropped from 70F (21 °C) to 62 F (16 °C) with small daily temperature rises on the sunny days. On February 28 the auxiliary gas heat was restarted and the building was gradually (over a period of eight hours) brought back to the comfort range.

The very gradual temperature drop of the building during the coast-down test from a high of 70 F (21 °C) on February 23 to a low of 62 F (16 °C) on February 28 during a period when outside temperatures ranged from 20 F (-7 °C) to 50 F (10 °C) illustrates the heat storage of the building and sand mass. To better characterize the coast-down performance of the building and sand mass, a time constant may be calculated using procedures outlined in "A Two Parameter Model of Building Thermal Performance" (Lavine 1982). The model requires use of overnight temperature data to avoid the effects of solar gain during the daytime. Since the building has a lot of thermal capacitance, a sand mass temperature is needed to characterize the thermal performance of the building. The middle sensors in the group of main horizontal sand mass temperature sensors in the building sandmass are appropriate sensors to use for this purpose. When the data for the 96 inch main horizontal temperature is examined for the period of interest (February 23 to February 28, 1983) an average drop (D) of 0.21 F (.12 °C) for a 10-hour time period (A) is found. The average temperature difference between inside and outside of the building for the period is about 30 F (16.7 °C) (T). On this basis the building thermal time constant is given by:

$$\tau = \frac{(\Delta T)\ A}{D} = \frac{(30F)\ 10\ Hrs}{0.21F} = 1428 \text{ hours} = 59 \text{ days}$$

The building thermal time constant is a measure of the coasting ability of the building without auxiliary heat. The measure shows that in the case of Volney Town Hall, a period of 59 days of 35 F (2 °C) weather would be required for the building to coast from 70 F (21 °C) to 48 F (9 °C). The building time constant is very long in comparison to time constants for superinsulated houses with internal storage mass (100 to 200 hours). On the basis of Volney Town Hall's heat capacitance [(1,750,000 Btu/F; 3,323,500 Kj/°C)] and building time constant, the building heat loss character may be calculated. This calculation is shown below:

$$\text{Heat Loss Character} = \frac{HC}{\tau} = \frac{1{,}750{,}000 \text{ Btu/F}}{1428 \text{ Hours}} = 1226 \text{ Btu/h.F } (646.7 \text{ Watt/K})$$

The heat loss character can be checked against the monitored heat loss for the building. For example, using the building heat loss character of 1226 Btu/h.F (1646.7 Watt/K), the recorded average ambient temperature for November 1983 (38 F; 3°C), and the recorded average indoor temperature for November 1983 (65.8 F; 18.8 °C), the November 1983 heat loss may be calculated:

$$1226 \text{ Btu/h.F} * 720 \text{ Hours} * (65.8-38\text{F}) = 24.5 * 10^6 \text{ Btu}$$

This value is close to the monitored heat loss for November 1983 of 23.9 x 10^6 Btu (25.2 x 10^6 Kj; See Table 2). The above calculation is performed to increase confidence in the building time constant for Volney Town Hall since the time constant is very long in comparison to many familiar buildings. One of the reasons the Volney Town Hall time constant is this big is the very large thermal capacitance, which is about 29 times as large as the heat capacitance (60,000 Btu/F) incorporated in superinsulated houses with internal heat storage masses (Brown 1983). The time constant for Volney Town Hall (1428 hours) is about 10 times as great as the time constant for superinsulated houses with internal heat storage maasses, since the building time constant is large for a building with very large internal heat storage and low heat loss.

The high thermal capacitance of the building and high time constant help account for the building's behavior in cooling. With very little mechanical cooling, the building maintained average indoor temperatures of 72.5 F in July and August of 1983. Since very little mechanical cooling was utilized, the moderate interior space temperatures may be attributed to the presence of the sand mass capacitance in the building. This is an advantage of the large thermal mass in the building.

One disadvantage of the large thermal mass inside the building was also observed from the monitoring. It was difficult to supply heat to spaces distant from the mechanical rooms, as was shown by lower than average space air temperatures in these rooms detected by the sensors. This heating problem was traced to the location of long supply ducts in the sand mass causing excessive heat transfer from the duct in heating mode. The advantags and disadvantages of thermal mass inside the building need to be carefully weighed in the design of future buildings. One major question that arises in evaluating the Volney Town Hall sand mass is its size. Is the large heat capacitance incorporated in the Volney Town Hall really necessary or are there other ways to accomplish the heating and cooling task? The "Heat Storage Design Notes" section of this report outlines some of the potential alternatives.

Footing Heat Loss

Examination of the plans and pictures taken at the time of construction revealed that a gap in the insulation envelope exists at the base of the footings of the interior walls (see Figure 4).

The cross-sectional area of the footings is approximately 660 ft^2 (61 m^2) according to the building plans. The average earth temperature below the footings is 60 F and is fairly constant (as reported by the below-slab temperature sensor and indicated on monthly summary reports of the monitoring project). Temperatures in the sand mass vary between 65 F (21 °C) and 70 F (18 °C). The block footing walls are filled with cement with an R value of 0.08 per inch. Assuming 4 inches of cement (the thickness of the missing insulation materials) and a sand mass temperature of 65 F (18 °C), the footing heat loss is:

$$\frac{660 \times 5}{.32} = 10{,}312 \frac{\text{Btu}}{\text{hr.}} = 7.43 \times 10^6 \frac{\text{Btu}}{\text{Month}} \ (7.84 \times 10^6 \text{ Kj/month})$$

If the sand mass temperature is assumed to be 70 F, the footing heat loss is:

$$\frac{660 \times 10}{.32} = 20{,}625 \frac{\text{Btu}}{\text{hr.}} = 14.85 \times 10^6 \frac{\text{Btu}}{\text{Month}} \ (15.67 \times 10^6 \text{ Kj/month})$$

Software was programmed to use the temperature data from the below-sand mass temperature sensor and the remote sand mass sensor to calculate the footing heat loss on an hourly basis and sum the results on a monthly basis. The results reported as footing heat loss in Talbe 2 accountedfor 48 x 10^6 Btu or (51 x 10^6Kj) or 23% of the building heat loss during the heating season. This heat loss was unexpected in the initial monitoring phases of the monitoring and only discovered after careful checking of building plans and all initial energy results. The inclusion of the footing heat loss in the building heat loss table improves closure of energy gain and loss data on a monthly basis. The amount of footing heat loss (48 x 10^6 Btu; 50 x 10^6Kj) is about 45% of the gas heater output (113 x 10^6 Btu; 119 x 10^6 Kj) for the heating season. Therefore, the footing heat loss appears to be a fairly substantial and unanticipated heat loss in the Volney Town Hall.

HEAT STORAGE DESIGN NOTES

In the course of monitoring and analyzing the performance of Volney Town Hall, a number of alternatives to some of the building's design features were thought of as possibilities by the project staff. These alternatives are described below.

Building Heat Storage Sizing Based on Winter Solar Gain and Heating Requirements

The building heat storage could be downsized by a factor of five and still provide sufficient thermal inertia for the building to handle solar loads with a 5 F (3 °C) temperature swing. Such a downsized thermal storage would have a capacity of 1,750,000/5=350,000 Btu/F (185,000 Watt/K). This amount of heat storage could be provided by the existing building mass heat storage (252,000 Btu/ F; 133,000 Watt/K), plus additional heat storage (100,000 Btu/ F; 53,000 Watt/K). Four inches of wet sand located below the floor slab above the insulating zerotherm would be sufficient to provide this additional heat capacitance and also might serve as a good base for pouring a floor slab. Alternatively, an additional four inches of concrete in the floor slab would provide the desired additional heat capacitance. A reduced building heat capacitance would also reduce the time period required for the building to respond to auxiliary heating or cooling (Figure 5). If building thermal storage were downsized by a factor of five, the building time constant would be reduced proportionately from 59 days to 59/5 = 11.8 days. This time constant is adequate to allow for the use of heating equipment sized to average severe heating condition rather than the 97 1/2% design temperature normally used.

Building Heat Storage Sizing Bsed on Summer Cooling Requirements

The Volney Town Hall maintained space temperatures of 72.5 F (22.5 °C) in July and August with limited mechanical cooling (2 tons; 25,000 Kj/h) installed versus 20 tons (250,000 Kj/h) commonly specified for a 10,000 ft^2 (930 m^2) building. This result is attributable to the large heat capacitance in the building in combination with the high insulation standard of the building. The effectiveness of the building in cooling with limited mechanical cooling capacity suggest the possibility of significant downsizing of cooling equipment in new public and commercial construction in this northern climatic zone. A possible cooling design strategy for buildings including significant thermal mass is to size the thermal mass to handle the sensible cooling requirements of the building by averaging space temperatures on a weekly cycle. A nighttime ventilation strategy may be employed to assist cooling when nighttime temperatures are below interior building temperatures.

Mechanical cooling equipment may be sized to meet peak latent cooling loads introduced by moisture sources within the building, for example, a peak condition for a public building such as Volney Town Hall would be 150 people present for a town meeting on an August day. The mechanical cooling should handle the latent heat load from people and outside air requirements of this peak condition. Sensible load may be carried by the building thermal mass.

Interior Footings

A "thermal break" could be provided between the footings of interior walls and the interior walls themselves. This would eliminate the footing heat loss observed in the monitoring reducing the auxiliary heating requirement by about 48 x 10^6 Btu (51 x 10^6 Kj) per year from the present requirement of 112 x 10^6 Btu (118 x 10^6 Kj) per year. A "thermal break" might be provided by extending the zerotherm envelope across the interior footings. This method could work provided the interior footing were carefully constructed to have the same finished level as the graded earth on which the zerotherm was placed. The interior walls could then be constructed either directly above the zerotherm layer or above the finished floor slab so as to bear on the footings below. Alternatively, the floor slab mass storage system could be reinforced with steel reinforcing rods at locations below the interior block walls. In this case the footing for the block walls would be inside the thermal envelope and interconnected with the floor slab foundation of the building. Modified interior footing systems such as those proposed here would require careful design to account for weight of the block wall that would be carried by the system. A successful alternative design would provide about 48 x 10^6 Btu (51 x 10^6 Kj) additional savings in annual auxiliary heating requirement for buildings of this type.

Air Distribution

Air distribution from the air handler in the mechanical room to the conditioned space might be provided by an air distribution system whose airflow is essentially reversed from the existing air distribution system. In such a system air would be supplied through supply ductwork located in the space between the drop ceiling and the building envelope. Return ductwork could either be located in the floor slab mass storage system if space allowed or in the cavity between the drop ceiling and the building envelope (separated from the supply ductwork). A system in which air is supplied by ductwork passing through the space above the ceiling (rather than supply ductwork passing through the sand mass as in the present system) has the advantage that no heat is transferred to or from the mass storage in route to the space. Therefore, the space air temperatures in such a system will respond more quickly to thermostat settings in either the heating or cooling mode. Also, large temperature drops through the supply ducting should not be experienced in such a system with the attendant discomfort in rooms distant from the air-handling unit in the mechanical room.

CONCLUSION

A combination of a superinsulated envelope and a large building thermal capacitance was responsible for reducing Volney Town Hall's mechanical cooling and heating capacity by a factor of 4 in comparison to mechanical heating and cooling capacity of 20 tons (250,000 Kj/h) commonly specified for a 10,000 ft^2 (930 m^2) public or commercial building. A number of design alternatives for thermal mass design in new construction are presented. An optimum building thermal mass design may incorporate the features described.

However, further work is needed to determine the most economical size of building thermal mass in relation to building mechanical equipment requirements and building insulation standard.

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TABLE 1A (I-P Units)
Building Heat Storage Capacity

ITEM	AREA	WEIGHT	SPECIFIC HEAT	HEAT CAPACITY
SAND MASS	(ft^2)	(Lbm)	(Btu/Lbm/F)	(Btu/F)
Zone #1	7376	3,010,400	.37	1,113,000
Zone #2	2560	1,039,000	.37	385,000
Subtotal, Heat Capacity of Sand Mass				1,498,000
BUILDING MASS				
Floor Slab	9936	659,000	.22	150,000
Int. Block Walls	6600	396,000	.22	87,000
Gypsum Board	6800	14,000	.22	3,000
Furnishings	-	40,000	.03	12,000
Subtotal Heat Capacity of Building Mass				252,000
TOTAL, BUILDING HEAT STORAGE CAPACITY				1,750,000 Btu/F

TABLE 1B (SI Units)
Building Heat Storage Capacity

ITEM	AREA	WEIGHT	SPECIFIC HEAT	HEAT CAPACITY
SAND MASS	(m^2)	(kg)	(Kj/Kg/°C)	Kj/°C
Zone #1	685.4	1,365,000	1.549	2,113,700
Zone #2	237.9	4,712,800	1.549	731,200
Subtotal Heat Capacity of Sand Mass				2,844,900 Kj/°C
BUILDING MASS				
Floor Slab	923.4	315,300	.921	284,900
Int. Block Walls	613.3	179,600	.921	165,200
Gypsum Board	631.9	6,400	.921	5,700
Furnishings	-	18,100	1.256	22,800
Subtotal Heat Capacity of Building Mass				478,600 Kj/°C
TOTAL, BUILDING HEAT STORAGE CAPACITY				3,323,500 Kj/°C

TABLE 2A (I-P Units)

CUMULATIVE MONTHLY HEAT LOSS (All Values - Million Btu)

Month	Wall & Ceiling Heat Loss	Glazing Heat Loss	Heat Loss Due to Infiltration	Sand Mass Heat Loss	Footing Heat Loss	Total Heat Loss
February	8.17	4.07	11.14	1.74	5.60	30.71
March	6.80	3.44	8.58	1.95	8.40	29.17
April	5.36	2.88	6.14	1.84	7.18	23.40
May	2.57	1.65	3.16	1.32	7.04	15.73
June	-0.88	0.36	0.45	1.08	8.29	9.30
July	-1.13	0.09	0.05	0.94	7.78	7.74
August	-0.52	0.32	0.44	1.15	9.04	10.43
September	0.87	0.79	1.39	1.07	7.27	11.40
October	4.37	2.25	4.58	1.25	5.37	17.82
November	6.51	3.14	7.44	1.41	5.38	23.87
December	9.05	4.10	12.75	1.44	4.35	31.99
January	9.66	5.02	15.16	1.60	4.89	36.34
Annual Totals	50.83	28.11	71.28	16.79	80.59	247.90
Heating (Oct.-May) Totals	52.49	26.55	68.95	12.55	48.21	209.03
Heating (Oct.-May) Percent	25.11%	12.70%	32.99%	6.00%	23.06%	100.00%

TABLE 2B (SI Units)

CUMULATIVE MONTHLY HEAT LOSS (All Values - 10 E9 Joules)

Month	Wall & Ceiling Heat Loss	Glazing Heat Loss	Heat Loss Due to Infiltration	Sand Mass Heat Loss	Footing Heat Loss	Total Heat Loss
February	8.62	4.29	11.75	1.84	5.91	32.40
March	7.17	3.63	9.05	2.06	8.86	30.78
April	5.66	3.04	6.48	1.94	7.58	24.69
May	2.71	1.74	3.33	1.39	7.43	16.60
June	-0.93	0.38	0.47	1.14	8.75	9.81
July	-1.19	0.09	0.05	0.99	8.21	8.17
August	-0.55	0.34	0.46	1.21	9.54	11.00
September	0.92	0.83	1.47	1.13	7.67	12.03
October	4.61	2.37	4.83	1.32	5.67	18.80
November	6.87	3.31	7.85	1.49	5.68	25.18
December	9.55	4.33	13.45	1.52	4.59	33.75
January	10.19	5.30	15.99	1.69	5.16	38.34
		0.00	0.00	0.00	0.00	0.00
Annual Totals	53.63	29.66	75.20	17.71	85.03	261.55
Heating (Oct.-May) Totals	55.38	28.01	72.75	13.24	50.86	220.54
Heating (Oct.-May) Percent	25.11%	12.70%	32.99%	6.00%	23.06%	100.00%

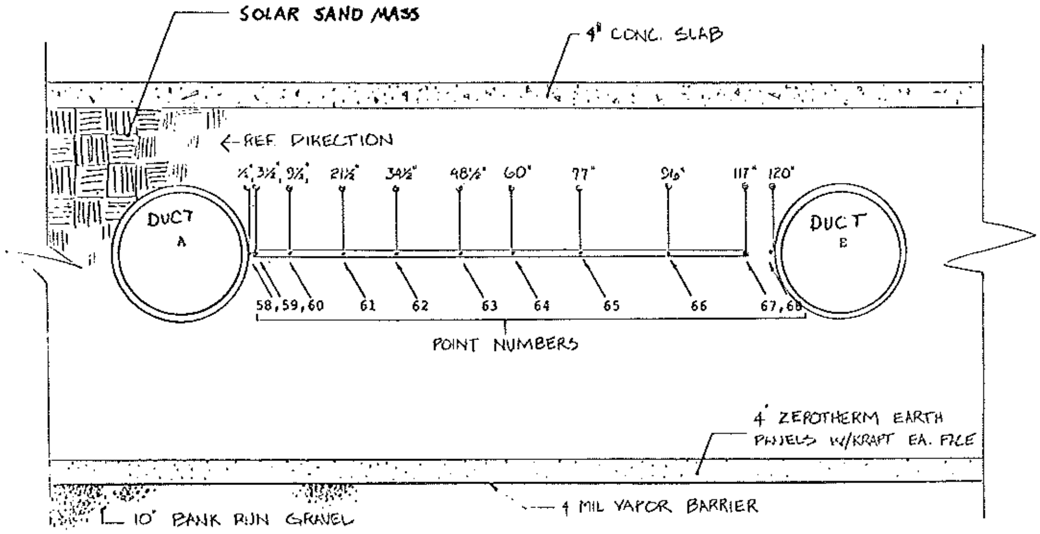

Figure 1. Sand mass temperature sensor placement

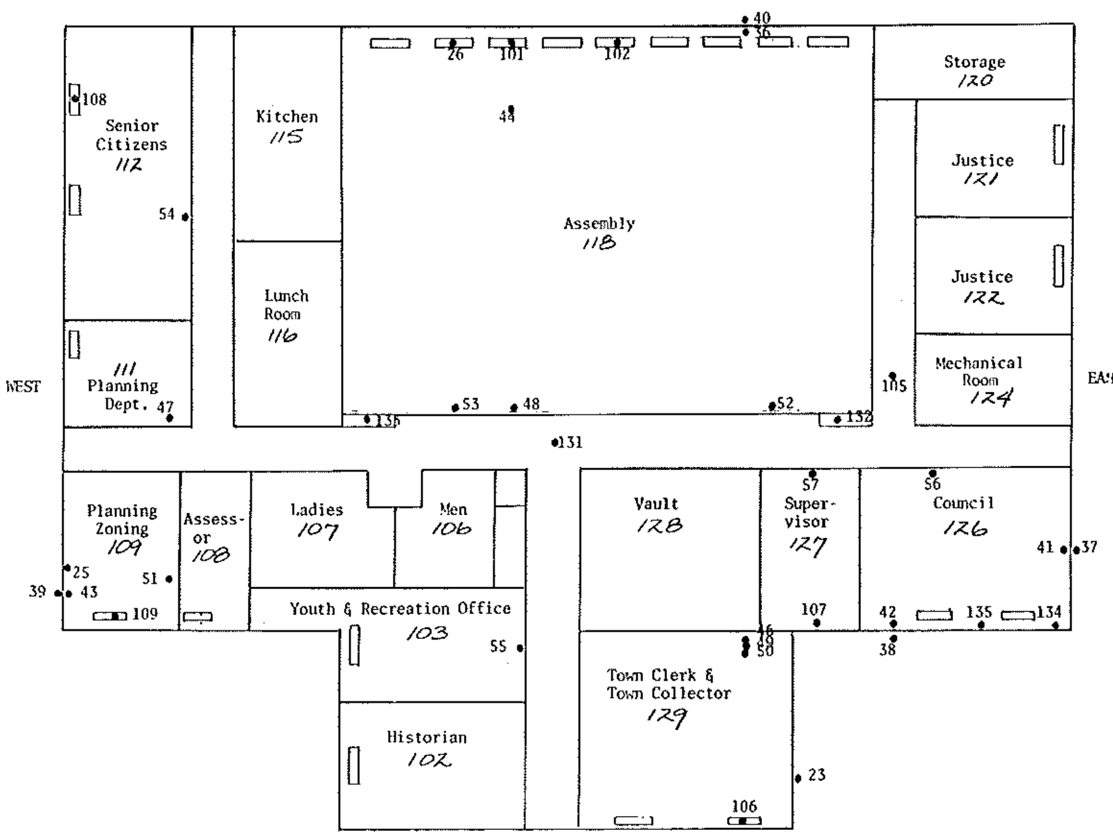

Figure 2. Volney town hall temperature sensor locations

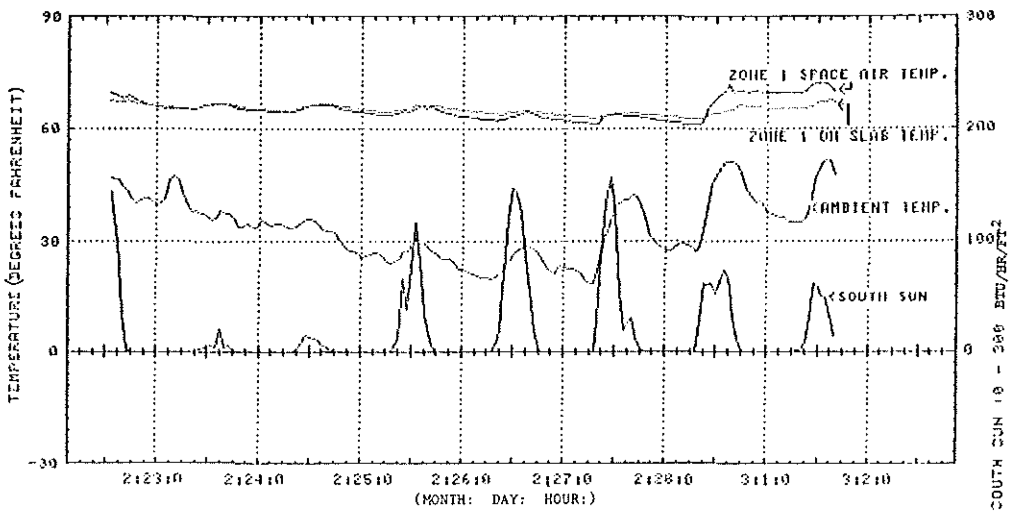

Figure 3. Solar and building temperatures, February 23 - March 2, 1984. (South sun = insolation measured through windows facing south)

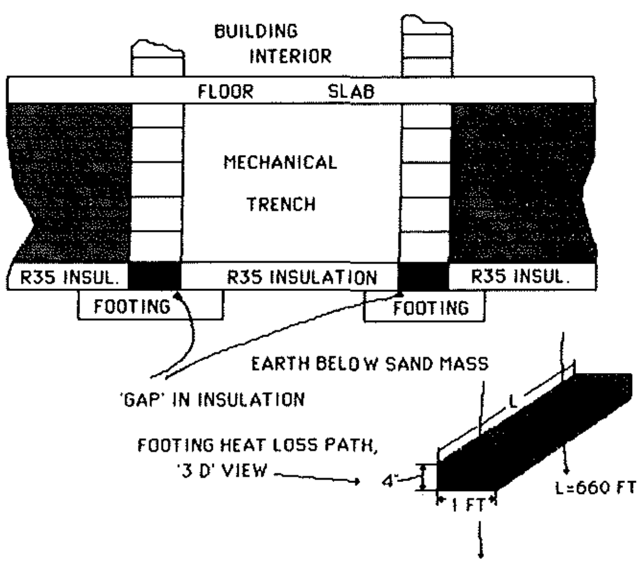

Figure 4. Insulation gap, sand mass footings

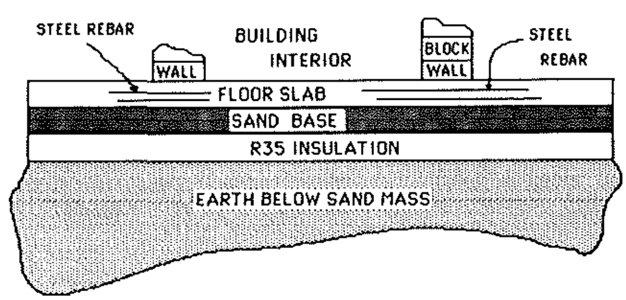

Figure 5. Alternate building storage mass design