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COMFORT RANGE THERMAL STORAGE

by

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DISCLAIMER

1. INTRODUCTION

Residences and other space conditioned structures provide thermally acceptable conditions to occupants in a temperature range that may be expected to be a subinterval of a "Comfort Range." Definition of a Comfort Range is generally based on a number of factors, some of which are necessarily subjective.[1] We may, however, select the interval 65°F-75°F (18.33°C-23.89°C) as characteristic of the Comfort Range. Space conditioning and temperature control systems for typical structures are generally set to operate over some most desired subinterval (as defined by the user) of the Comfort Range. It is generally taken as a mark of "quality" for a space conditioning system to operate reliably over a fractionally small portion of the Comfort Range.

The heating and cooling systems that serve the conditioned space are generally designed to meet peak demand ("design") conditions. A (hot air) furnace or (hydronic) boiler that is sized to be adequate during the coldest winter day is generally operative over a small fraction of the time during a typical winter day. It is operative over a smaller fraction of the time during the heating season. For fully analogous reasons, space cooling equipment (compressor, etc.) is operative over a fractional period of the cooling season. The precise operating cycles, as prescribed by the space to be conditioned, affects the efficiencies of these two common devices. In fact, the seasonal operating costs of virtually any given space conditioning device has been shown[2] to depend markedly upon the seasonal space-conditioning operating strategy, as well as the design figures of merit of the device itself. Comfort Range Thermal Storage has been found to serve effectively in reducing seasonal operating costs. We have noted previously[2] that:

(1) Typical frame (single family) residences are characterized by relatively low thermal storage capacity, per unit area of floor space.

(2) Typical masonry (single family) residences are characterized by relatively high thermal storage capacity, per unit of floor space.

(3) The effective thermal storage capacity of a masonry building element can be substantially increased by the incorporation of a distribution of (comfort range) phase change transitions (a family of phase change materials) in the masonry. For certain distributions of phase change transition temperatures and physical scales of encapsulation, such Phase Change Masonry (PCM) can be made to physically behave as a super heat capacity material.

(4) Ordinary masonry or Phase Change Masonry (PCM) structures can be space conditioned in the Comfort Rnage at substantially

lower cost than an equally well insulated frame structure (same U value walls, ceiling, etc.) _if_ the masonry (or PCM) structure is insulated _exterior_ to its high mass structural elements (walls, slab, etc.).

(5) The conclusions of (4) above, have been shown[2] to follow from the facts that

(a) Taking 70°F to be the arbitrary zero enthalpy point of the comfort range, the one thermal storage reservoir (structure itself) can be employed for both positive and negative enthalpy storage.

(b) Negative enthalpy can be stored at the highest acceptable temperatures. Positive enthalpy can be stored at the lowest acceptable temperatures.

(c) Substantial thermal storage is achieved in a structure whose large internal surface area permits use of the structure as both heat exchanger and storage medium. The heat exchanger and thermal reservoir can be largely passive and charged/discharged by ordinary air handlers used for conventional air circulation and/or ventilation.

(d) Off-peak electric power can be effectively invoked in 24-hour space conditioning strategies.

(e) Cost-effective use of ambient (air and/or water) "temperatures of opportunity" may be invoked for space conditioning.

(f) The efficiencies of fossil fuel furnaces or boilers, as well as solar collectors and the COP's of heat pumps may all be optimized by the use of

  (i) thermal storage, in general

  (ii) comfort range thermal storage, in particular

This paper examines further the dynamic features of small buildings which are capable of substantial Comfort Range Thermal Storage and indicates some of the quantitative considerations in the effective coupling of the CRTS with existing or required space conditioning devices.

2. SPACE CONDITIONING DEVICE PERFORMANCE AND COMFORT RANGE THERMAL STORAGE

For fossil fuel fired boilers supplying hydronic heating to a single family residential structure (frame construction) seasonal burner "ON TIME" is a minor fraction of the total. Fractional "ON TIMES" of 0.20 are common (e.g., metropolitan New York area) and lead to seasonal efficiencies that may be only 70% to 80% of the usually cited steady state efficiency of the device. The degradation of efficiency has been cited in several studies.[2, 5] It results directly from enthalpy storage in the boiler being subjected to a variety of thermal loss mechanisms during the "off" portion of the cycle. Figure 1 (taken from Reference 2) typifies the relation between the normally observed cycle efficiency, η_c and the fractional ON TIME. The overall efficiency, $\bar{\eta}$, is given by

$$\bar{\eta} = \eta_c \, \eta_s$$

where η_s is the so called steady state efficiency.[2,6] It has been shown,[2] however, that correlations such as those of Figure 1 do not represent general truths, but derive directly and fortuitously from the present commonality of typical boiler cycles for devices which space heat a low mass structure. Quite generally, we may define the overall efficiency of a boiler by

$$\bar{\eta} = \frac{\int_0^{t_1} [\text{Net Enthalpy removal rate through boiler}] \, dt}{\int_0^{t_1} [\text{Chemical Enthalpy flow rate}] \, dt}$$

where the time limits are taken over very long times. For a boiler whose only losses are "stack losses," the denominator may be considered to be the sum of three terms:

$$\int_0^{t_1} [\text{Net Enthalpy removal rate through boiler}] \, dt$$

$$+ \int_0^{t_1} [\dot{\mathcal{L}}]_S \, dt + {}_0^{t_1} [\dot{\mathcal{L}}]_{NS} \, dt$$

where $[\dot{\mathcal{L}}]_S$ represents the constant stack loss rate during steady state operation and $[\dot{\mathcal{L}}]_{NS}$ is the variable stack loss rate during nonsteady state operation. If $(H_s - H_o)$ is the enthalpy (above ambient) stored in the device during steady state operation, it follows directly that

$$\int_o^{t_1} (\dot{\mathcal{L}})_{NS}\, dt \leq n\ (H_s - H_o)$$

where n = the number of cycles which occur during the period $t = t_1$. That is, the nonsteady stack losses per cycle can be no greater than (are generally smaller than) the enthalpy stored in the device at the termination of steady state operation.

As a practical matter, a residence having substantial comfort range thermal storage will <u>require</u> that the ON TIME per cycle be very long. This results in

$$\int_o^{t_1^*} [\dot{\mathcal{L}}]_S\, dt >> (H_s - H_o) \geq \int_o^{t_1^*} [\dot{\mathcal{L}}]_{NS}\, dt$$

where (t_1^*) is the characteristic time for a full cycle. Inasmuch as $\bar{\eta} \rightarrow \eta_s$ as

$$\frac{\int_o^{t_1} [\dot{\mathcal{L}}]_s\, dt}{\int_o^{t_1} [\dot{\mathcal{L}}]_{NS}\, dt} >> 1$$

it follows that very long characteristic boiler (or furnace) ON TIMES yields overall efficiencies that are very close to the steady state efficiency. Tests made at Brookhaven National Laboratory, employing absolute enthalpy flow rate measurements, confirm these conclusions.[7]

Relatively long ON TIMES are generally facilitated by space heating devices that are capable of low (or modulated) firing rates. On Long Island (New York) and elsewhere, it is generally found[2,3] that boilers (in the field) are overfired and that the reduction of the firing rate increases the steady state efficiency as well as the cycle efficiency. Experimental data illustrating the effect on a steel fire-tube boiler are shown in Figure 2.

Similarly, it is found that long ON TIMES for electric air conditioners leads to energy efficiency ratios that are close to the steady state value. For ON TIMES that are comparable to (or less than) the time necessary to achieve steady state operation of an electric air conditioner, considerably smaller energy efficiency ratios result. These consequences are illustrated in Figure 3 (Data of Reference 8). The physical bases for these effects are completely analogous to those presented for the case of a space heating device. In this case, nonsteady losses are sustained by a variety of air conditioner components. For very short ON TIMES, the thermal and pressure equilibration of the individual components can degrade its steady state pressure and temperature conditions by substantial amounts. Low instantaneous (and integrated) EER's result.

In general, the rates of enthalpy throughput of space conditioning devices and the characteristics of a structure's Comfort Range Thermal Storage will largely determine the characteristic length of ON TIME of a space conditioning device, once the space conditioning strategy (control philosophy) is determined. The interplay of these factors is considered next.

3. THERMAL RESPONSE CHARACTERISTICS OF COMFORT RANGE THERMAL STORAGE MATERIALS

Well insulated, single family frame dwellings provide thermal storage reservoirs through the structure's components interior to their insulation barriers. For a typical frame dwelling, this reservoir may consist largely of some 1000 to 3000 ft^2 of (3/8" to 1/2") plasterboard. Very meagre thermal storage indeed. For a masonry dwelling, insulated on its exterior, 8" masonry walls provide substantial thermal storage.[2] Materials that undergo phase transitions in the comfort range may be used to enhance the thermal storage characteristics of these commonly used building materials.[9,11] In the comfort range, the fatty acids have been identified as a family of compounds whose substantial heats of fusion make them promising thermal storage materials.

For illustrative purposes, one may consider the fatty acids to display heats of fusion that are about half that of water.

One method of enhancing the apparent specific heat capacity of masonry has been described earlier.[2] Consider that a family of phase change materials (fatty acids, perhaps) has been developed so that sharply defined phase transitions can be caused to occur at any temperature within the comfort range. Consider further that each pure material can be encapsulated and that a uniform mixture of some eleven varieties of capsules is then made. That is, the mixture contains (11 n) capsules where the contents of n capsules undergo a phase transition at each temperature, T_a, T_b, T_c, ...and where

$$T_a = T_1 + \frac{1}{22}(T_2 - T_1),$$

$$T_b = T_1 + \frac{3}{22}(T_2 - T_1),$$

$$T_c = T_1 + \frac{5}{22}(T_2 - T_1),$$

$$T_d = T_1 + \frac{7}{22}(T_2 - T_1),$$

$$\vdots$$

$$T_k = T_1 + \frac{21}{22}(T_2 - T_1)$$

Figure 4 shows the specific enthalpy vs. temperature characteristics of a mixture of such encapsulated (fatty acid-like) materials, as compared to a typical masonry material. The apparent heat capacity of the capsule mixture (mean slope of the staircase enthalpy function) is some 40 times that of ordinary masonry. As the number of distinct pure compounds employed in the mixture is increased, the height of each "step" is decreased, the number of steps increased, and the superb apparent heat capacity preserved. Further, if a composite wall element is constructed of such a mixture of capsules, comfort range heat transfer and storage measurements would indicate the wall element to have an apparent heat capacity of some 4.5 times that of water. It is clear that this experimental behavior of a mixture of capsules requires that the physical scale of an individual capsule be small, compared to the wall thickness, and that the number of phase transition temperatures employed, on the range $T_1 < T < T_2$, be large.

It may be unrealistic to consider a wall element that consists exclusively of such unmortared mixtures of capsules. However, one may (more realistically) consider a masonry wall which contains a mixture of such encapsulated phase change materials. We consider the case where the mass fraction of encapsulated phase change materials is only ten percent of that of the masonry binder. The character of a resulting wall element's enthalpy-temperature diagram is shown on Figure 5. In the comfort range ($T_1 < T < T_2$), the material has an apparent specific heat capacity of 1.0 cal/gm/^{o}C. Outside of the comfort range, but within the required operating range of the resultant structure, the specific heat capacity is of the order of 0.22 cal/gm/^{o}C.

To compare the three wall materials:

1/2" plasterboard

8" masonry

8" masonry with a phase change aggregate whose mass fraction is a tenth that of the binder

We consider the following heat transfer problem. Assume an initially isothermal wall element to be at 65^{o}F and to be "perfectly" insulated on one side. At time zero, impose a wall temperature of 75^{o}F on the uninsulated side of the wall element. Calculate the time-dependent thermal charging characteristics for each of the three wall elements.

One may use standard methods(12,13) to deduce the heat transfer results given in Table 2. The (1/2") plasterboard is over 93% thermally charged (saturated) in 5 minutes, having sustained a heat transfer rate (time averaged) of some 93Btu/ft^2/hr. That is, during a 5 minute period, a 1500 ft^2 wall area can accept the full enthalpy output of a (typical) 100,000 Btu boiler/furnace. However, due to the fact that the plasterboard is virtually saturated after 5 minutes, the <u>instantaneous</u> thermal charge rate, $\overline{\dot{q}''}$, is only about a fifth of the average over the first 5 minutes. Moreover, it is dropping quickly. Accordingly, a frame structure that is characterized by such a wall system(2,13) typically finds itself heated by a boiler-furnace that is "ON" for some 5 to 10 minutes and off for some longer period of time. Typical ON-OFF characteristics of boilers have been reported previously.(2) Figure 5, taken from Reference 2, illustrates the consistency of the intermittent operating character of a boiler/

furnace with the rapid thermal saturation characteristics of a typical frame structure.

Next, we consider the implications of the corresponding data for masonry structures and for PCM (m = 0.1) structures. From the results shown (Table 2) it is clear that a 100,000 Btu/hr. boiler/furnace would not saturate either a 1500 ft^2 masonry or PCM structure during several hours of continuous running (ON) time. Moreover, were lower-firing rate (or modulating) boilers or furnaces to be used,[(2)] running times (ON times) of a significant fraction of a day could be employed to charge these high mass heat capacity structures. The structures not only have substantial thermal storage capacity in the comfort range, but the physical characteristics (Tables 1 and 2) enable average heat transfer rates that are adequate for reasonable charging (and discharging) by presently operative space conditioning systems.

The use of a material having an enthalpy-temperature characteristic such as that shown in Figure 5 has other advantages as well. For a structure that has been allowed to "drift" out of the comfort range (e.g., during a weekend when it is unoccupied), restoration of comfort range temperatures requires no enthalpy investment in phase transition energies outside the range of interest. This is true for both cooling and heating season operation. Thus, for example, cooling season operation during a Friday (immediately prior to a substantial period of nonoccupancy of a structure) may usefully invoke the following strategy.

1. Permit the mean thermal condition of the structure to finish the operating period (Friday afternoon) in the neighborhood of T_2, the upper limit of the comfort range.
2. During the period of nonoccupancy, subject to exterior temperatures as high as T_{max}, the structure's mean thermal condition may drift upwards--perhaps approaching T_{max}.
3. In anticipation of reoccupancy of the structure, outside air (if suitably cool) may be used to cool down the structure below T_{max}. In any case, the low apparent (C_p) on the range $T_2 < T < T_{max}$ permits the restoration of the T_2 thermal condition without any investment in phase transition energies.

In the above "weekend" (or day-to-day) strategies, CRTS may permit very substantial cost savings through the use of "temperatures of opportunity" (outside air).[2] Nelson and Tobias[14] have shown how an Air Economizer (using outside air instead of an air conditioner's compressor) can be used to save "compressor time" for frame structures. Compressor time savings of 25%-35% are commonly predicted[14] for <u>frame structures</u> in major population areas of the country. It is clear that substantial CRTS permits even larger savings. In fact, we have noted[2] that during the in-between season (April, May, October, November in the Northeast) space heating and cooling can be carried out almost entirely without <u>either</u> air conditioner compressor time <u>or</u> boiler/furnace On Times. This is accomplished primarily through a control system that is designed to take advantage of outside temperatures of opportunity (either "high" or "low") which permit the thermal manipulation of a structure's CRTS. The strategy, useful for all seasons, involves the use of outside air to:

1. Keep the structure's CRTS in the neighborhood of $[(T_1+T_2)/2]$, during the in-between season.
2. Charge the structure's CRTS to as high a value of T as desirable, during the heating season.
3. Drive the structure's CRTS to as low a value of T as desirable, during the cooling season.

Solar heating design and operations are facilitated by the incorporation of substantial CRTS in a structure to be so heated. Recall, for example, the fact that the ideal efficiency of a conventional (air cooled or liquid cooled) solar collector is a maximum when the output temperature is as acceptably low as possible.[2] With comfort range thermal storage provided by masonry and/or PCM building elements, the high efficiency effluent of a solar collector can be employed to heat the structure directly. As illustrated by the results shown in Table 2, temperatures well below 100^{o}F can be used effectively (over a period of hours) to directly heat the structure which defines the conditioned space. CRTS thus permits high efficiency solar collector output, along with a thermal storage system that is useful during all seasons (heating and cooling) and that is largely paid for by the structural requirements imposed on any residential (or small commercial) building design.

It is significant to note that architectural windows may be used to admit large solar fluxes directly to the conditioned space. Such fluxes can be easily handled by the proposed high heat capacity structure. This is clearly not the case for an ordinary frame structure. Thus, for example, a 1500 ft^2 wall area of PCM could store more than 250,000 Btu in a 4-hour period (initial temperature of 65^{o}F) and still be only 20% charged (average temperature increase of some 2^{o}F, to 67^{o}F). The increase in enthalpy of this particular (1500 ft^2) wall system is 1.24 x 10^6 Btu, in going from 65^{o}F (initially) to 75^{o} (saturation). This is more than adequate storage for a 24-hr. period for any well insulated structure of 1500 ft^2 (metropolitan New York area).

Generally, there are two major objections to the extensive use of architectural windows for solar collection. One of these is concerned with the inability of the structure (frame, typically) to transfer and store the radiatively deposited enthalpy. The other relates to the commonly encountered high heat loss rates sustained by both single and double pane windows.[15] For a masonry (or PCM) structure, more than adequate CRTS is available, once adequate air circulation is provided. Further, results of recent investigations at the State University of New York (Stony Brook) and at Brookhaven National Laboratory indicate that large separation double pane windows can be made[16] which

(a) permit efficient transmission of solar radiation

(b) sustain conduction-convection-radiation heat loss rates (time integrated) which are very substantially smaller than those normally encountered.

With these two major objections now addressed, one can contemplate the major advantages that the architectural window--solar collector--CRTS system promises.

(a) <u>High efficiency</u>. Solar windows whose collection efficiencies are greater than 50% are easily available. This is true even though the new,[16] convection-radiation control windows (THERMOCELL) are expected to display collection efficiencies that are somewhat smaller than those found for ordinary double-pane windows.

(b) <u>Low cost</u>. The functionally simple system requires windows whose (per square foot) costs are about twice that of ordinary twin-pane glass windows.[16] The system is largely passive and involves no additional elements other than those (CRTS and appropriate air handling capacity) already required by other (previously noted) space conditioning requirements.

Accordingly, adequate CRTS in a space conditioned structure permits the optimum use of high efficiency space conditioning devices and strategies. For solar heating, this includes the use of remote collectors as well as collection via low heat loss architectural windows. For space heating and cooling, this includes fossil fuel fired boilers/furnaces, electrically driven space heating or cooling devices (e.g., heat pumps), space conditioning by selective use of "temperatures of opportunity" (ambient outside air), as well as the potential savings to be derived from the use of low cost off-peak electrical energy for 24-hour space conditioning.

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Table 1

Property Values of Wall Elements

Material	(lb/ft^3)	Spec.Heat Capacity $\left(\frac{Btu}{lb\ ^oF}\right)$	Thermal Conductivity $\left(\frac{Btu}{hr.ft.\ ^oF}\right)$	Thermal Diffu-sivity $\left(\frac{ft^2}{hr}\right)$	Thickness (ft.)
Plasterboard	100	0.20	0.42	0.021	0.0417
Masonry	140	0.21	0.50	0.017	0.6667
PCM(m = 0.1)	124	1.0	0.46	0.0037	0.6667

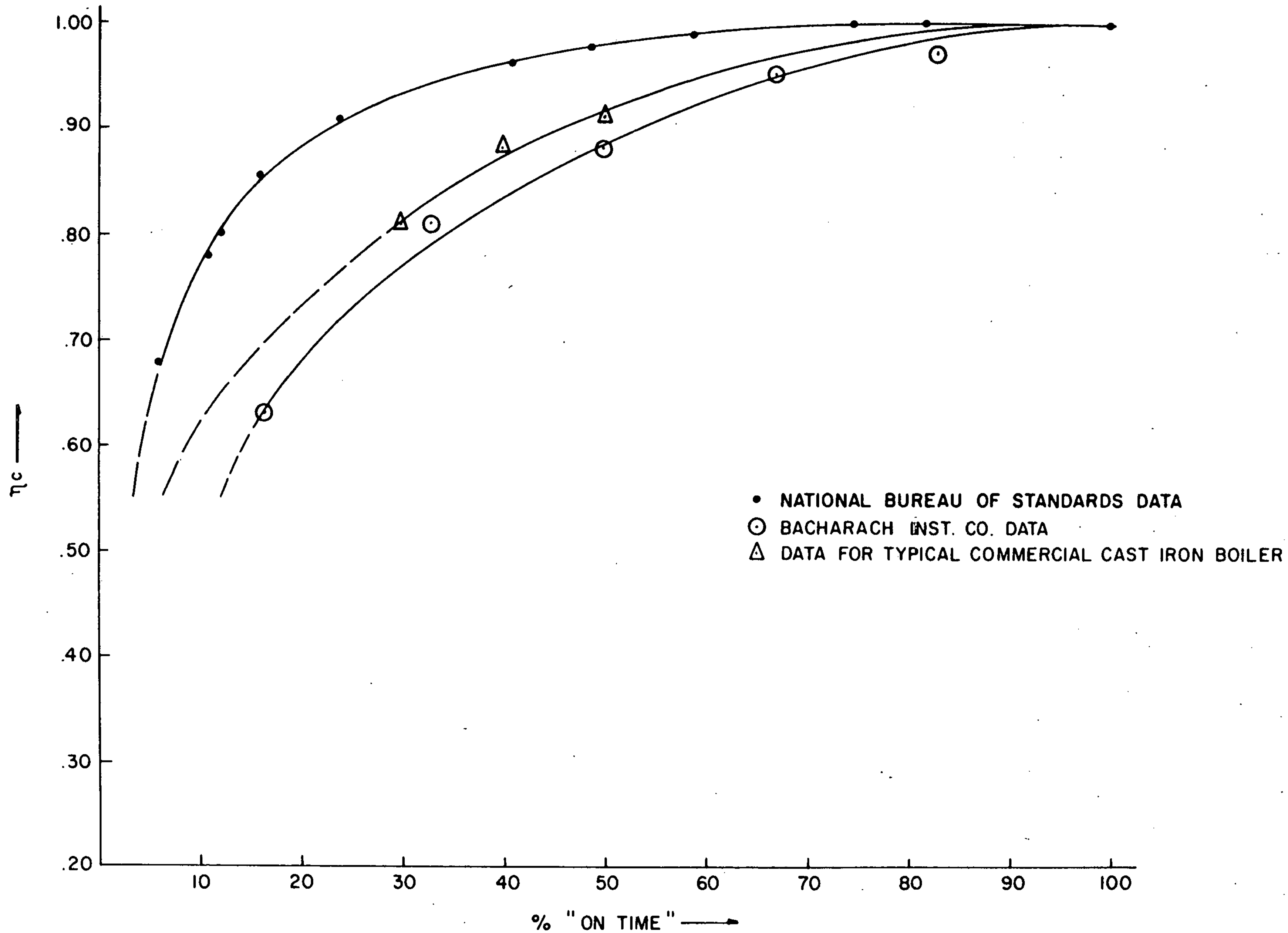
Table 2

Thermal Charging Characteristics for Three Different Wall Systems
The Wall is Insulated at $x = 0$ and Uninsulated at $x = \ell$. $T(x,0) = 65^{o}F$ for $0 \leq x < \ell$. $T(\ell,0) = 75^{o}F$.

	Elapsed Time (t) hr.	Fraction of Full Thermal Charge For Wall R --	Insul. Wall Temp. $T(0,t)$ ^{o}F	Instantaneous Charge Rate $\left[K\left(\frac{dT}{dx}\right)_{\ell}\right]$ Btu/ft^2/hr.	Time Averaged Charge Rate $\left[\bar{q}''\right]_0^t$ Btu/ft^2/hr.
Plasterboard (½ inch thick)	(1/12)	0.932	73.94	16.77	93.16
	(1/4)	0.999	74.99	0.116	33.32
Masonry (8 inches thick)	(1/12)	0.060	65.00	75.06	141.12
	(1/4)	0.110	65.00	43.35	86.24
	1	0.220	65.01	21.82	43.12
	2	0.311	65.20	15.32	30.48
	4	0.440	66.40	10.80	21.56
PCM ($m = 0.1$) (8 inches thick)	(1/12)	0.046	65.00	149.38	456.34
	(1/4)	0.053	65.00	83.28	175.26
	1	0.101	65.00	43.23	83.50
	2	0.143	65.00	30.46	59.11
	4	0.203	65.00	21.61	41.96

CAPTIONS

Figure 1	% "On Time" Cycle Efficiencies, η_c vs. "On Time" for Three Different Fossil-Fuel Systems
Figure 2	Steady State Efficiency vs. Oil (Air) Flow Rate (Steel Fire-Tube Boiler)
Figure 3	Effect of Cycling on Effective EER of a Given Air Conditioner
Figure 4	Fatty Acids vs. Concrete Comfort Range Composite Storage
Figure 5	Composite High "Cp" Material Enthalpy vs. Temperature
Figure 6	Cycle Characteristics of a Typical Oil-Fired Boiler



CYCLE EFFICIENCIES, η_c VS. "ON TIME"
FOR THREE DIFFERENT FOSSIL-FUEL SYSTEMS

Figure 1

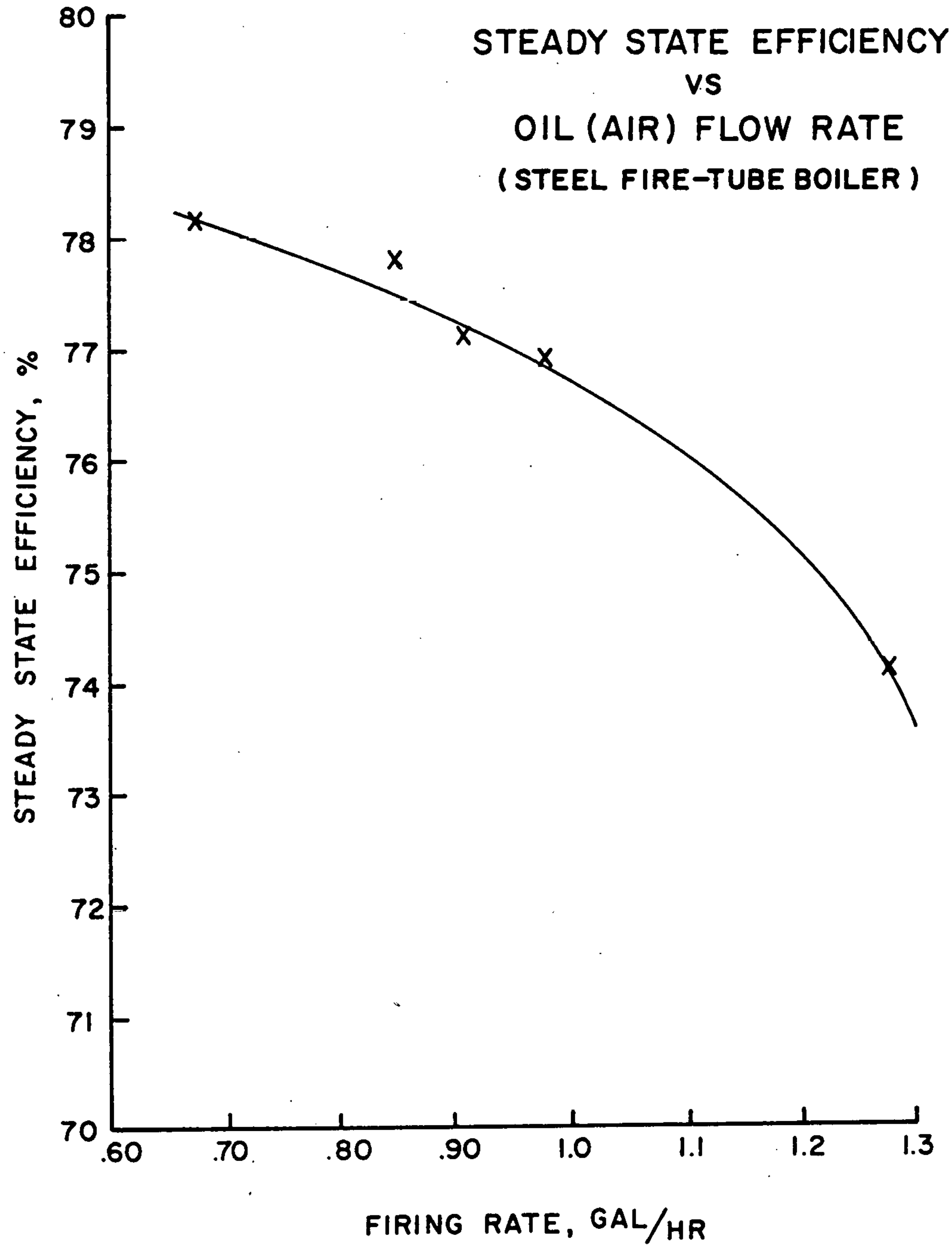
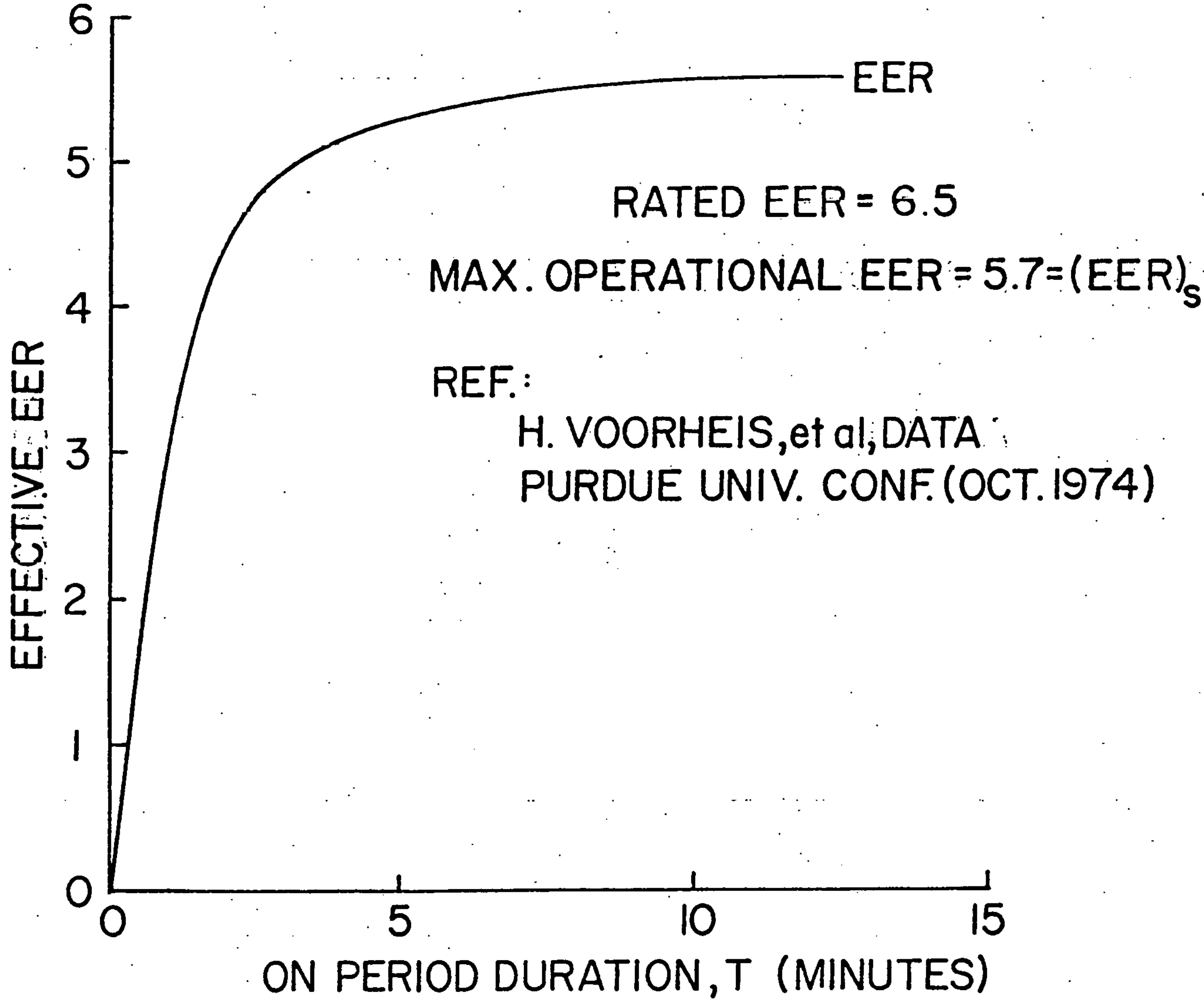

STEADY STATE EFFICIENCY
VS
OIL (AIR) FLOW RATE
(STEEL FIRE-TUBE BOILER)
STEADY STATE EFFICIENCY, %
80
79
78
77
76
75
74
73
72
71
70
.60
.70
.80
.90
1.0
1.1
1.2
1.3
FIRING RATE, GAL/HR

Figure 2



EFFECT OF CYCLING ON EFFECTIVE EER OF A GIVEN AIR CONDITIONER

Figure 3

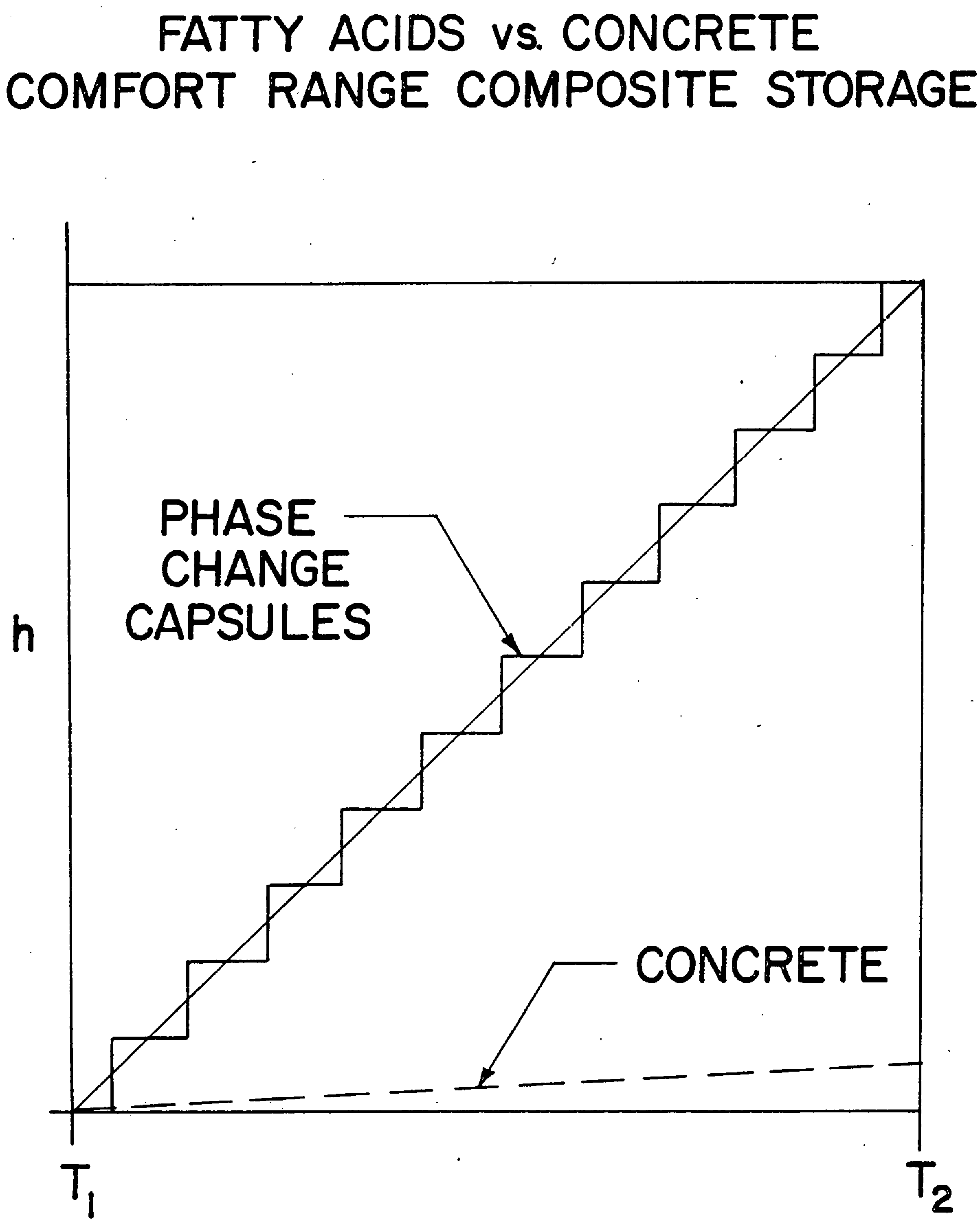

FATTY ACIDS vs. CONCRETE
COMFORT RANGE COMPOSITE STORAGE
PHASE CHANGE CAPSULES
h
CONCRETE
T1
T2

Figure 4

COMPOSITE HIGH "Cp" MATERIAL ENTHALPY vs. TEMPERATURE

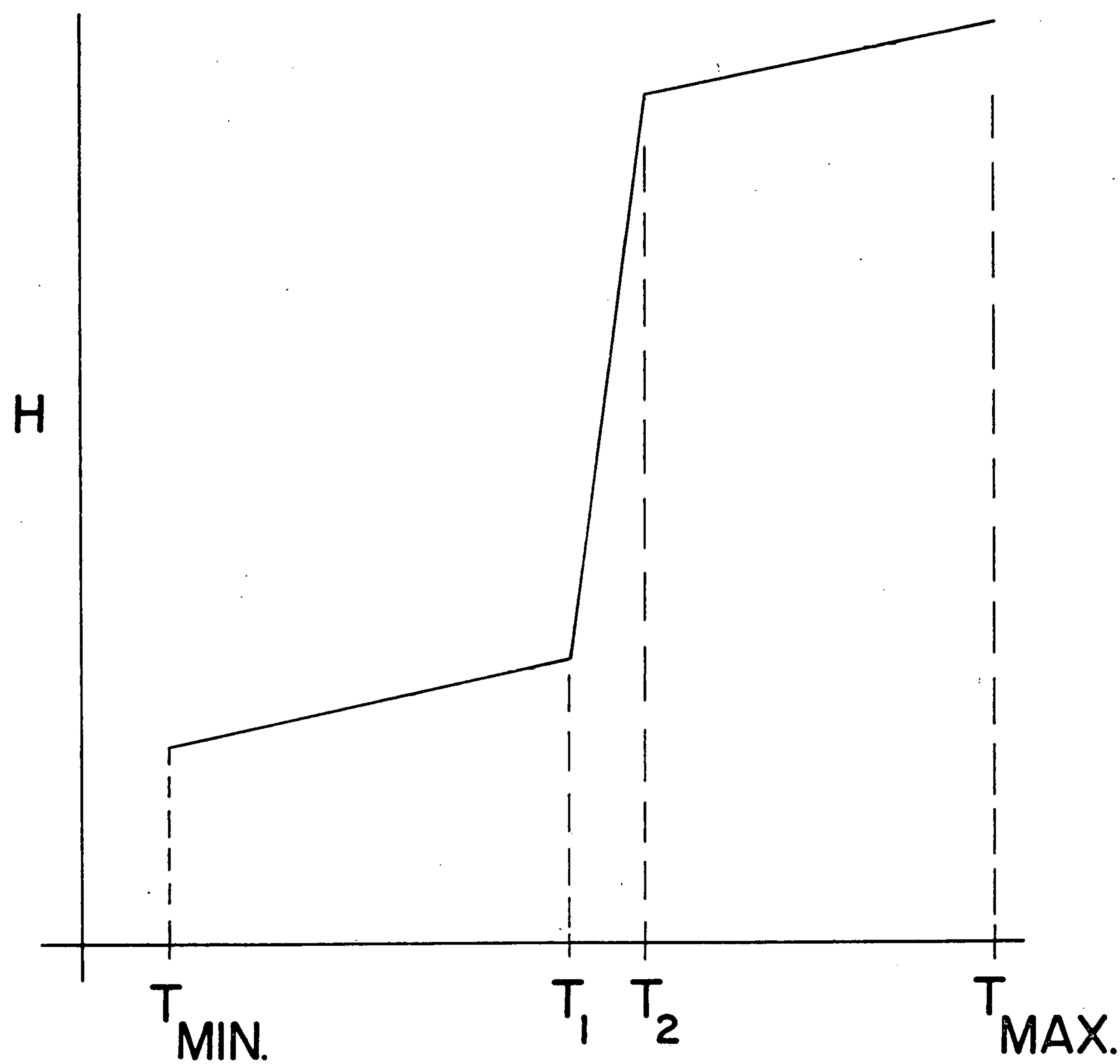


Figure 5

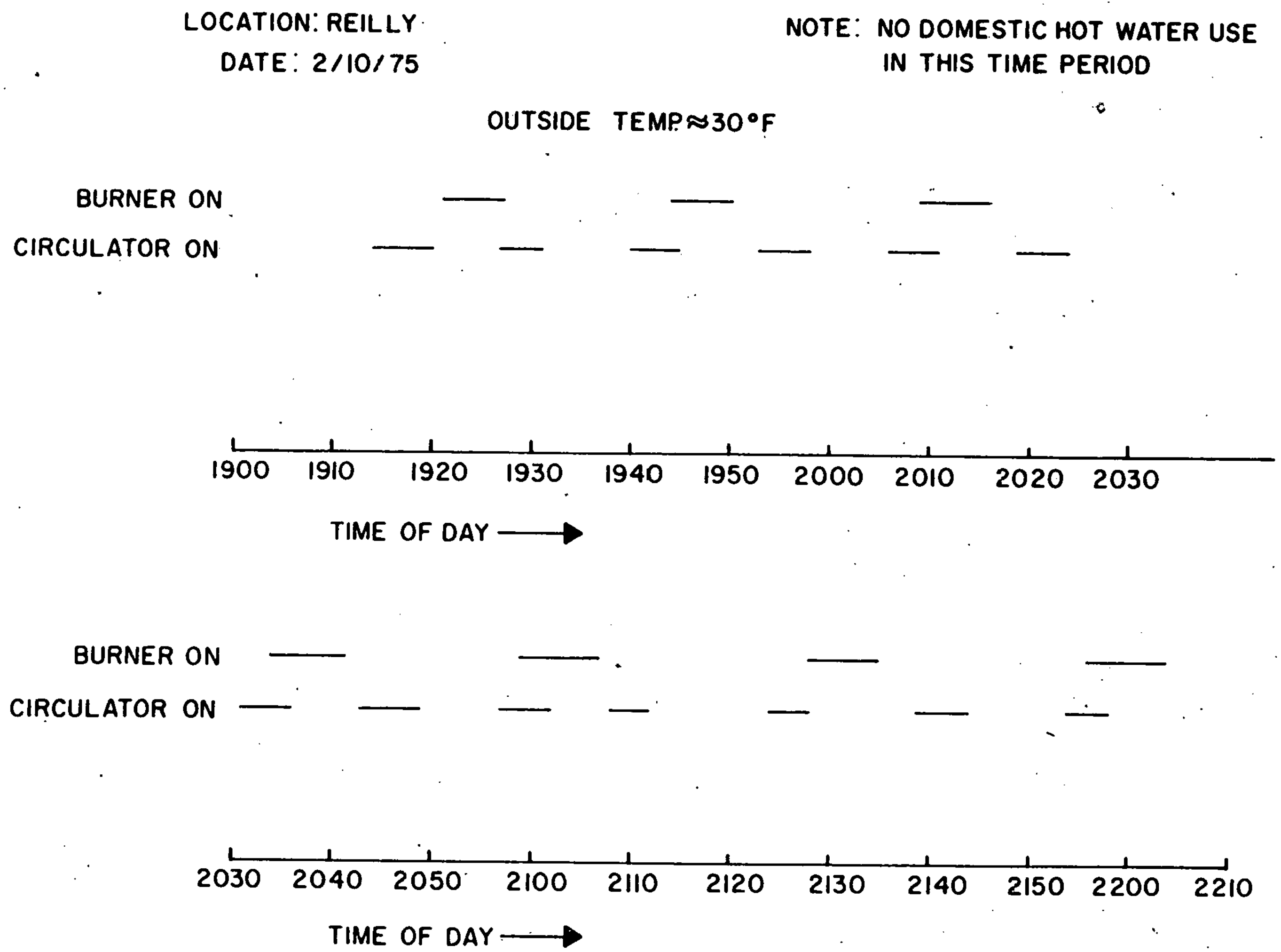


Figure 6

Cycle Characteristics of a Typical Oil-Fired Boiler