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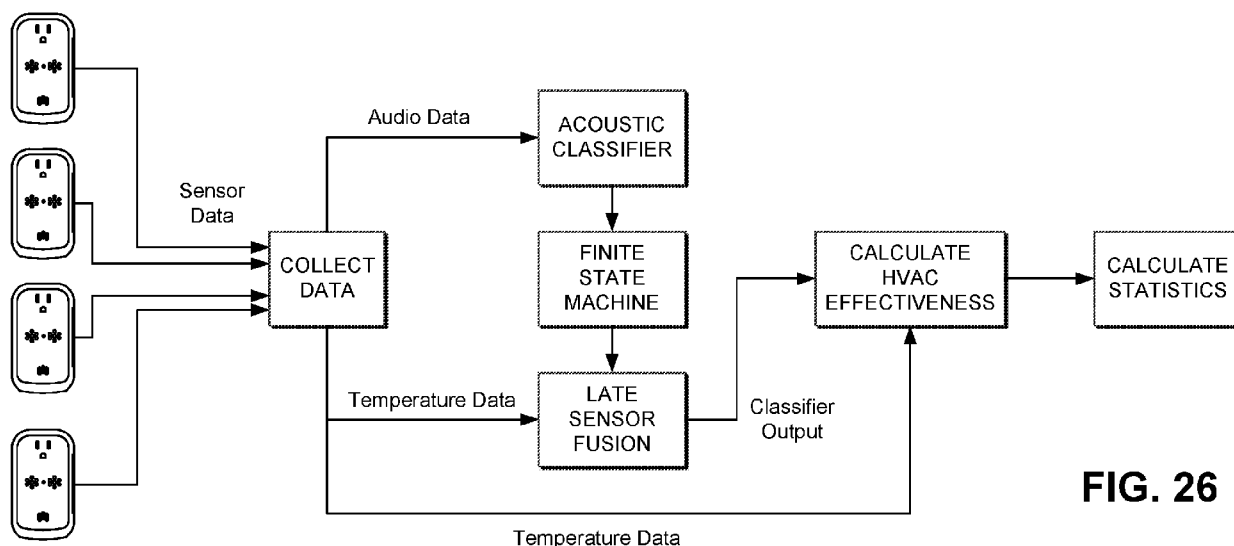


FIG. 26

(57) Abstract: A method according to some embodiments includes, for each of a plurality of cycles of an HVAC system, obtaining data representing a measured rate of indoor temperature change during the cycle and an outdoor temperature during the cycle. Some of the cycles are classified in one of a plurality of predetermined cycle categories. The classification is based at least in part on the associated measured rate and on the outdoor temperature. For at least one of the categories, a report is provided regarding statistics of the cycles in that category. The report may indicate an average time per temperature change (e.g. minutes per °C) for the cycles in that category. A change in the statistics over time may be detected and reported as an indication of HVAC and/or insulation problems.

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Apparatus and Method for Monitoring and Tracking of Heating, Cooling, and Heat Retention Effectiveness

CROSS REFERENCE

[0001] The present application is a non-provisional filing of, and claims benefit under 35 U.S.C. § 119(e) from, U.S. Provisional Patent Application No. 63/525,633, filed July 7, 2023, entitled "Apparatus and Method for HVAC Efficiency Monitoring and Tracking," which is incorporated herein by reference in its entirety. International patent application WO 2023147129, published August 3, 2023, entitled "Apparatus and Method for HVAC Efficiency Monitoring and Tracking," is also incorporated herein by reference in its entirety.

BACKGROUND

[0002] The HVAC (heating, ventilation, air conditioning) system is usually the most expensive appliance in the home. It can be critical to human comfort and health as well as the safety of the home itself (e.g., mold, excessive dryness). However, these systems are often not monitored at all and so maintenance typically is failure-driven. In other words, the system has to fail first – often on the coldest day in the winter or hottest day of the summer – before the maintenance crew is called to investigate and fix.

[0003] As a result, not only are the repairs more expensive and the disruptions to the home more numerous and extreme but there are complicating secondary factors as well. The HVAC failures for the whole area tend to cluster on the coldest day in the winter or hottest day of the summer. That can make it difficult to schedule a repair person to fix the unit and can also lead to parts shortages which delay the time to repair.

SUMMARY

[0004] A sensor node detects intervals during which an HVAC system is active (e.g. using sound and/or electrical transients). The node determines the time of the active interval (such as a heating period or a cooling period) and a change in temperature and/or another environmental parameter during the active interval. A histogram is generated in which a plurality of active intervals collected over a time period (e.g. over the course of a month or another time period) are binned based on the ratio of time to temperature change. An efficiency metric of the HVAC system is determined by fitting a predetermined curve type (e.g. "inverse gaussian") to the histogram. Changes to the efficiency metric may trigger alerts of a potential HVAC fault.

[0005] Example embodiments include an apparatus and a method for monitoring and reporting on HVAC performance. In an example method, an HVAC system is monitored to detect a plurality of sample intervals during which the HVAC system is active. The plurality of sample intervals may be, for example, a plurality of

heating intervals or a plurality of cooling intervals. An ambient temperature is monitored to determine a temperature change over each of the sample intervals. A sample value is determined for each of the sample intervals, each sample value representing a ratio or other metric between a duration of the interval and the change in temperature (or other environmental parameter) over the course of the respective period. Statistics of the sample values are evaluated and may be used to identify changes in HVAC performance. Use of statistical techniques may help to minimize the influence of factors that are not directly related to HVAC performance, such as different weather (outside temperature, wind, sunlight) and human activity (cooking, opening windows, etc.). Analogous methods performed for periods of HVAC inactivity may be used to detect changes in heat retention and/or heat exclusion performance.

[0006] Example embodiments provide an ability to discriminate between heating and cooling cycles. Differentiation between heating and cooling cycles may be made in some embodiments without direct communication with the HVAC system. Some embodiments operate to compare between different HVAC systems within one house. Some embodiments operate to compare HVAC systems among different houses. Some embodiments operate to normalize the HVAC slopes for heating/cooling in different rooms for a comparable value. Some embodiments operate to normalize the temperature retention slopes for heating/cooling in different rooms for a comparable value. Some embodiments operate to compare temperature retention among different rooms. Some embodiments operate to compare temperature retention among different houses. Some embodiments operate to plot temperature retention as a function of outdoor temperature. Some embodiments use the relation between temperature retention and outdoor temperature to compare over time to see changes in insulation. Some embodiments use the relation between temperature retention and outdoor temperature to compare between rooms. Some embodiments use the relation between temperature retention and outdoor temperature to compare between units of apartments/houses. Some embodiments operate to determine and/or plot HVAC effectiveness as a function of outdoor temperature.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] As illustrated in FIGs. 1A-1F, a device 100 includes a housing 108 having a rear surface 104. A set of power plug prongs 106 extends from the rear surface of the housing. Although the illustrated prongs are those compatible with standard North American outlets, other configurations may alternatively be used.

[0008] FIG. 2 is a graph providing a schematic example of a dirt loading curve for a filter.

[0009] FIG. 3 schematically illustrates a system in which heat Q flows between regions of different temperatures.

[0010] FIG. 4 is a graph schematically illustrating the performance of an example advanced multi-mode heat pump.

[0011] FIG. 5 provides example histograms of collections of sample values, which may be used as indicators of heating and/or cooling effectiveness.

[0012] FIG. 6 illustrates an example user interface providing a notification of a level of air filter cleanliness.

[0013] FIG. 7 is a histogram schematically representing the time divided by temperature change of HVAC cycles from a single sensor node, along with a curve fit to the histogram data.

[0014] FIGs. 8A-8B are histograms schematically representing data collected from two sensor nodes in the same home.

[0015] FIG. 9 illustrates an example user interface providing a report of collected data and results of data analysis.

[0016] FIG. 10 illustrates an example user interface providing statistical information on the detected operating cycles of an HVAC system.

[0017] FIGs. 11-13 illustrate examples of user interface elements providing different types of reports of heating effectiveness information.

[0018] FIGs. 14-16 illustrate examples of user interface elements providing different types of reports of cooling effectiveness information.

[0019] FIG. 17 illustrates an example of a user interface element in which temperature retention information is provided in some embodiments.

[0020] FIG. 18A illustrates an example of a user interface element in which temperature retention information is provided in some embodiments.

[0021] FIG. 18B illustrates a graphical display element used to display results in the example of FIG. 18A.

[0022] FIG. 19 illustrates a graphical display element used to display room-by-room temperature retention information in some embodiments.

[0023] FIG. 20 illustrates a graphical display element used to display temperature retention statistics in some embodiments.

[0024] FIGs. 21-22 illustrate graphical display elements used to display temperature swing information in some embodiments.

[0025] FIG. 23 schematically illustrates network topology used in some embodiments.

[0026] FIG. 24 is a schematic functional block diagram illustrating a sensor node used in some embodiments.

[0027] FIG. 25 is a schematic functional block diagram illustrating the functional architecture of a monitoring system according to some embodiments.

[0028] FIG. 26 is a schematic functional block diagram illustrating the functional architecture of a monitoring system according to some embodiments.

[0029] FIG. 27A is a graph illustrating a histogram of data collected in different rooms, each with a corresponding inverse Gaussian curve fit.

[0030] FIG. 27B is a graph illustrating the data of FIG. 27A, wherein the data from one of the rooms has been scaled.

[0031] FIG. 28 illustrates an example report of historical cooling performance according to some embodiments.

[0032] FIG. 29 illustrates an example report of historical heating performance according to some embodiments.

[0033] FIG. 30 illustrates examples of reports of heating and cooling performance according to some embodiments.

[0034] FIG. 31 illustrates an example of a report of insulation performance according to some embodiments.

[0035] FIG. 32 is a graph illustrating example temperature retention data and a corresponding slope according to some embodiments.

[0036] FIG. 33 is a graph illustrating the slope of the best fit line for the temperature retention rate (TRR) vs temperature as a function of thermal conductivity of the wall in simulated data.

[0037] FIG. 34 is a graph of air filter dirtiness percentage versus HVAC hours of operation that may be used in some embodiments.

DETAILED DESCRIPTION

[0038] As illustrated in FIGs. 1A-1F, a device 100 includes a housing 108 having a rear surface 104. A set of power plug prongs 106 extends from the rear surface of the housing. Although the illustrated prongs are those compatible with standard North American outlets, other configurations may alternatively be used.

[0039] The goal of example embodiment is to continually monitor the HVAC system's health and provide early warning of deterioration in performance and/or need for maintenance. This then augments the regular servicing visits with the ability to flag issues before a complete catastrophic breakdown.

Overview of an Example Embodiment.

[0040] In an example method, an HVAC system (e.g. of a residence) is monitored to detect a plurality of sample intervals during which the HVAC system is active. An ambient temperature is measured (e.g. by one or more sensor nodes disposed in the residence) to determine a change in temperature or other environmental parameter over each of the respective sample intervals. A sample value is determined for each of the sample intervals, each sample value representing a ratio between the duration of the interval and the temperature change over the course of the respective period. In some embodiments, the sample value may represent the duration divided by the temperature change. In other embodiments, the sample value may represent the temperature change divided by the duration. In further embodiments, the sample value may represent the slope of the change in temperature (or other environmental parameter) over time at or near the beginning of the interval.

[0041] In some embodiments, an environmental parameter other than temperature is used, following any of the techniques described herein. For example, a parameter representing humidity, comfort index, CO₂ level, or air quality may be tracked, and the effectiveness (or change in effectiveness) of an HVAC system may be monitored based on a collection of sample values, each sample value representing a rate of change in the relevant parameter during a respective active interval of the HVAC system. The value representing the rate of change may be, for example a slope of parameter change over unit time, or an inverse slope of time over unit parameter change.

[0042] In some embodiments, a change in HVAC performance may be detected based on a comparison between sample values collected in a first time period (e.g. a prior month or year) and sample values collected in a second time period (e.g. a current month or year). The comparison may be made based on statistical differences between the different collections of sample values. In some embodiments, data representing the changes to the HVAC performances is provided for display to a user.

[0043] For the purposes of the present disclosure, a system may be referred to as an HVAC system even if the system, for example, has only a cooling component or only a heating component, including systems such as PTAC, other portable air conditioners, and radiator systems.

[0044] Some embodiments include generating a histogram of the sample values and displaying the histogram to a user. Some embodiments include determining and displaying to a user at least one of the

following: a mode, a median, an average, an upper percentile (e.g. upper quintile), or lower percentile (e.g. lower quintile) of the sample values.

[0045] In some embodiments, the method includes, for each of a plurality of bins, each bin being associated with a range of sample values, determining a number of the sample values that fall within the associated range to generate histogram data; and fitting a curve to the histogram data. The curve may be an inverse Gaussian (or Wald distribution).

[0046] Some embodiments include detecting a change in HVAC performance by detecting a change between (i) at least one first parameter of a first curve fitted to a first histogram of sample values collected in a first time period and (ii) at least one second parameter of a second curve fitted to a second histogram of sample values collected in a second time period.

[0047] In some embodiments, the sample intervals during which the HVAC system is active comprise sample intervals during which the HVAC system is heating. In some embodiments, the sample intervals during which the HVAC system is active comprise sample intervals during which the HVAC system is cooling. In some embodiments, both heating and cooling sample intervals are collected, and they may be processed separately.

[0048] In some embodiments, each sample interval is a single “on” cycle extending from a time the HVAC system becomes active to a time it becomes inactive. In some embodiments, each sample interval is an interval of a predetermined duration.

[0049] The collection of data as described here regarding active periods of the HVAC system may be used for providing various assessments of HVAC effectiveness as described in greater detail below. In addition, some embodiments collect data regarding inactive periods of the HVAC system, which may be used in determining the heat retention (e.g. insulation) and/or heat exclusion (e.g. shading) performance of the residence.

[0050] In an example method, an HVAC system is monitored to detect a plurality of sample intervals during which the HVAC system is inactive. An ambient temperature is monitored to determine a temperature change over each of the first and second plurality of sample intervals. A sample value is determined for each of the sample intervals, each sample value representing a ratio between a duration of the interval and the temperature change over the course of the respective period. In some embodiments, the sample value may represent the duration divided by the temperature change. In other embodiments, the sample value may represent the temperature change divided by the duration. In some embodiments, the sample value may represent a rate of temperature change at a particular time period during the inactive interval, such as at or the start of the interval (e.g., shortly after the HVAC system has become inactive).

[0051] A change in heat retention or exclusion performance may be detected based on a comparison between sample values collected in a first time period and sample values collected in a second time period.

Such changes may be detected or characterized using statistical methods, including curve fitting, as summarized above (with respect to the “active” periods and as described in further detail below.

[0052] In some embodiments, a user is alerted to potential HVAC or heat retention issues in response to a determination that a value (such as mean, median, mode, or other value) derived from the sample values has changed by at least a threshold amount. The threshold may be, for example, a predetermined threshold, a user-defined threshold, or a contextually derived threshold.

[0053] Further described herein are embodiments in which sample values are processed for display using techniques that allow a user to readily identify changes or potential issues with HVAC or heat retention performance, for example showing comparisons of such processed data between different time periods, between different rooms (or different sensor nodes), or between dwellings that are expected to have comparable results.

[0054] In some embodiments, data presentation techniques are adjusted based on different levels of certainty regarding HVAC performance to provide users with useful information without conveying a misleading level of certainty.

[0055] In some embodiments, sample intervals in which the HVAC system is moving air (whether heating, cooling, or simply ventilating) are determined, and the total duration of such intervals is used to provide information as to an estimated remaining useful life of an HVAC filter. In some embodiments, the total duration of such intervals is used to provide information as to an estimated time to service or estimated time to failure of the HVAC system.

[0056] Some embodiments operate to determine temperature changes and intervals during which the HVAC system is heating, cooling, or ventilating without any direct communication with any component of the HVAC system itself. For example, one or more sensor nodes may be provided in a dwelling. In some embodiments, such nodes may be installed by plugging them into a household electrical socket. Each sensor node may include a temperature sensor, such as a thermocouple or other type of thermometer, for determining temperature changes. In some embodiments, each sensor node further includes a microphone, and the determination of times during which the HVAC system is heating, cooling, or ventilating is based at least in part on audio data collected using the microphone of one or more sensor nodes.

HVAC Air Filter “Dirtiness” Metric Based on Operational Time.

[0057] Some embodiments include the implementation of a remote monitoring system to measure HVAC air filter dirtiness over time based just on operational time. The input from the hub device or for this method may be the times when the HVAC system (or fan) is running.

[0058] In some embodiments, calculation is made of how dirty the air filter is by using the HVAC Operational Time. This may be implemented separately and distinctly from the methods of estimating HVAC Air Filter Dirtiness using, for example, trend analysis on HVAC Run Rate or direct classification of the acoustic signature of air ventilation sounds.

[0059] The following terms are used in the present disclosure:

Term	Description
HVAC Operation Time	The length of time the HVAC air handler has been on since the air filter was last changed
Dust Holding Capacity	The amount of dust retained by the air filter at the point when the air pressure drop across the filter hits the Terminal Pressure Drop value.
Terminal Pressure Drop	The pressure drop across the air filter reached when the air filter has reached the end of its life. This also defines the Dust Holding Capacity of the filter.
Initial Pressure Drop	The pressure drop across a clean air filter.

[0060] The air filter gradually picks up dust as air flows through it. Typically, HVAC air filters may be depth loading filters that capture particles throughout the depth of the media. Such filters may have a loading profile approximated by an exponential curve. ("Air Filtration: Predicting and Improving Indoor Air Quality and Energy Performance", Ph.D. Thesis by James Montgomery, University of British Columbia, 2015, Section 6.1, p. 102) An example of a dirt loading curve for a hydraulic case is given in FIG. 2.

[0061] Note the curve is substantially exponential with the differential pressure staying nearly flat until roughly 30 grams of accumulated dust. The dust holding capacity is reached for this example at around 50 grams of accumulated dust. So there is very little or no change in differential pressure for the first 60% of its life. A recommendation may be made that the air filter should be changed when the differential pressure is double its initial value. That more or less happens at around 40 grams for this particular case. If we use that limit, then the air filter is pretty flat for the first 60% of its life (the same percentage noted by the source of this example dirt loading curve).

[0062] The presentation "Delivering Sustainability Promise to HVAC Air Filtration" by Dr. Christine Sun and Dan Woodman of Freudenberg Filtration Technologies, L.P., 2009 NAFA Annual Convention, Toronto, Canada, describes the exponential curve fit for various air filter types. The form is $\Delta P = a \cdot e^{bx}$, where x is the accumulated grams of dust. For a panel as used in some embodiments, parameters used may be $a = 36.21$ and $b = 0.0027$.

[0063] Example embodiments may use one or more of the following assumptions:

- Assume a linear rate of dust accumulation on the filter as a function of HVAC Operational Time. This makes sense since the dust is distributed in the air and more dust will therefore be collected when there is air flow than when there is not. Assuming a constant average level of dust in the air and a constant average air flow throughout the life of the filter is reasonable. This is a slow metric operating over months and so short-term variations from the average in either dust concentration or air flow are not especially relevant.
- Assume that the filter is a panel type that matches the exponential curve fit given above.
- Assume that the recommended air filter change period of 3 months corresponds to the typical recommended operational time of 3 times per hour for 15-20 minutes at a time on average. Assume that the air filter manufacturers have designed their marketing around average run times across the country. While the general guidelines are that the operational time should be 2-3 times per hour for 15-20 minutes at a time, this over-estimates the total number. The following may be more accurate estimates:
 - An average air conditioner runtime per day may be estimated as 8.9 hours. An average furnace operating time in the winter may be about 5.8 hours per day. Some embodiments use an estimate of 8.9 hours/day (534 minutes/day) all the time when estimating air filter life.
 - This translates to 90 days * (534 minutes/day) = 48,060 minutes of operational time before filter needs to be changed. A conservative estimate here may be 3 months, not 4 months for the base and also assuming the HVAC operational time that the filter manufacturers used was on the shorter end of normal.
- It may be assumed that the differential air pressure at the end of 3 months is double the initial differential air pressure. Using the equation, that means $a \cdot e^{bx} / a = e^{bx} = 2$. Since we know b , we can compute $x = \ln(2)/b$. Substituting the actual value of b in, we get $x = \ln(2)/.0027 = 256.72$. This is the assumed total amount of accumulated dust in the air filter at the end of 48,050 minutes of operation.

[0064] Some example methods embodiments may operate as follows:

- Calculate current x as $x_{\text{current}} = ((\text{HVAC Operational Time in minutes})/(48060)) * 256.72$.
- Calculate dirtiness percentage as dirtiness = $(e^{(.0027 * x_{\text{current}})} - 1) * 100\%$.

[0065] Note that in the above formula, dirtiness can exceed 100% if the homeowner continues operating the HVAC beyond the point where we've estimated the air filter should be changed. A user experience (UX) decision may determine whether to show that or to clamp it at 100%.

[0066] In some embodiments, x_{current} may be adjusted upward by a (multiplicative) factor if the homeowner has pets (more cats and dogs rather than fish) or a larger family. This reflects the fact that there will likely be more dust in the air to collect and the air filter then needs to be changed more frequently. The factor may be 1.5 if the homeowner has one cat or dog and 2 if they have more than one cat or dog. This information may be collected through a user interface.

[0067] In some embodiments, the estimate of dust buildup on the air filter may be adjusted based on humidity measurements.

Example Thermal Calculation Overview.

[0068] The change in energy in a thermal system is given by

$$\Delta U = Q$$

where U is the total energy of our system and Q is the heat flow (in and out). For example embodiments, we have ignored the work done on the system and the only change in energy is due to heat flow.

[0069] The heat flow is related to the change in temperature by

$$Q = C \Delta T$$

where C is the heat capacitance of the system. Having more things inside the house raises the heat capacitance. This is why an empty room is warms up faster than a furniture filled room.

[0070] There may be several sources of heat flow in our system. One source is conduction from outside of a room. Conductive heat flow is represented by the following, where there is a temperature gradient ∇T

$$q = \kappa \nabla T$$

where κ is the thermal conductivity and q is the heat flux.

[0071] For a wall of thickness d , and assuming two uniform temperature bodies (the room and the outside), we have a system as illustrated in FIG. 3, in which heat flow is illustrated schematically by the arrow Q . The equation of the thermal conductance is

$$dQ/dt = (\kappa A/d) (T_2 - T_1)$$

where A is the surface area between the two bodies, d is the thickness of the wall (represented schematically by region 300), κ is the thermal conductivity of the wall material.

[0072] For the case of heat sources Q (positive for heating and negative for cooling).

$$Q = C \Delta T,$$

[0073] If we have two rooms, each with heating sources

$$C \, dT_1/dt = (\kappa_1 A_1/d_1) (T_o - T_1) + (\kappa_{1-2} A_{1-2}/d_{1-2}) (T_2 - T_1) + dQ_{H1}/dt$$

$$dT_1/dt = k_1 (T_o - T_1) + k_{1-2} (T_2 - T_1) + q_1$$

$$C \, dT_2/dt = k_2 (T_o - T_2) + k_{1-2} (T_1 - T_2) + dQ_{H2}/dt$$

$$dT_2/dt = k_2 (T_o - T_2) + k_{1-2} (T_1 - T_2) + q_2$$

Here, we have 5 variables, k_1 , k_2 , k_{1-2} , dQ_{H1}/dt , and dQ_{H2}/dt .

HVAC Efficiency, Effective Outdoor Temperature.

[0074] In some embodiments, various thermal model elements are combined to get a single effective outdoor temperature.

[0075] There are many factors that influence the temperature of the interior, such as the outside temperature, but also other aspects, such as the ground temperature influencing the basement. In some embodiments, to simplify the analysis, the various outdoor temperatures may be combined into a single effective temperature T_{eff} , and the heat conductance through various different components of a dwelling may be combined into a single effective heat conductance, k_{eff} .

HVAC Effectiveness/Efficiency Method for User Interface.

[0076] Some embodiments provide a detailed HVAC monitoring method that is based on a number of factors so that to provide useful insights into HVAC operation.

[0077] Example embodiments may operate to calculate one or more of the following parameters. Such parameters may be delivered to a user for display.

Vsymbol	Parameter	Description
T-HVAC-Run _{daily}	HVAC Daily Run Time	The total time during a day that the HVAC system ran (whether for heating or cooling).
T-Heat-Ave _{week}	Average Heating Run Time Over Week	The average (median) time the HVAC system ran over the past week to raise the internal temperature by 1 degree C .
Heat-Effect	Heating Effectiveness	Ranging from 0% (broken) to 100% (as good as ever seen in this install), this is an estimate of current heating efficiency including normalization for outside temperature.

T-Cool-Ave _{week}	Average Cooling Run Time Over Week	The average (median) time the HVAC system ran over the past week to reduce the internal temperature by 1 degree C .
Cool-Effect	Cooling Effectiveness	Ranging from 0% (broken) to 100% (as good as ever seen in this install), this is an estimate of current cooling efficiency including normalization for the difference between inside and outside temperature.
T-Temp-Retention _{week}	Average Temperature Retention Time Over Week	The average (median) time it took for inside temperature to move closer to outside temperature by 1 degree C .
Temp-Retention	Temperature Retention Effectiveness	Ranging from 0% (no thermal resistance to outside at all) to 100% (as good as ever seen in this install), this is an estimate of how well the room/house retains temperature. The initial version does not normalize for the effects of wind or sun.

[0078] The performance of some HVAC equipment varies with the outdoor and sometimes indoor temperatures. The relevant details are below.

[0079] In general, the maximum energy efficiency ratio (EER) decreases as the temperature differential between the inside and outside air temperature increases. For an air conditioner, at lower outdoor temperatures, more of the cooling is performed with greater efficiency by the heat exchanger. At higher outdoor temperatures, more of the cooling is performed with less efficiency by the compressor.

[0080] As for heating systems, some heating systems put out the same amount of heat regardless of the outdoor temperature, but this is not true for air source heat pumps. FIG. 4 schematically illustrates the performance of an example advanced multi-mode heat pump. The heat output within each mode (illustrated with solid lines) decreases with outdoor temperature. The appropriate mode is selected in an attempt to compensate for the heat lost from the home (illustrated with a dashed line), with the outdoor temperature triggering the change between modes. The vertical arrows represent transitions between modes as the outdoor temperature falls. While most heat pumps are significantly simpler than this one, the main point remains – the heat output decreases with outdoor temperature. Heat pumps may include a mode transition to electrical “emergency” heat when the temperature gets to a low temperature (generally around 30-40 degrees F. Example embodiments may operate on the assumption that measured HVAC efficiency for heating will depend on the outside air temperature.

[0081] Example embodiments may use one or more of the following parameters.

Symbol	Parameter	Description
HRR _c	HVAC Run Rate for Cooling	The rate at which the HVAC system is cooling the indoor temperature of the room the sensor node is in. Units are °C/sec

HRR_h	HVAC Run Rate for Heating	The rate at which the HVAC system is heating the indoor temperature of the room the sensor is in. Units are °C/sec
k_{co}	Thermal Retention Factor	When multiplied by the difference between inside and outside temperature, this gives the rate at which the room/house is getting closer to the outside temperature. Parameter units are sec^{-1}
cb	Cooling Bin	Bin index for HVAC Run Rate history when cooling
$HRR_c[cb].count$	Cooling Bin Count	Number of readings for a given cooling bin index
$HRR_{c-ref}[cb]$	Reference HVAC Run Rate for Cooling	The reference value for the HVAC Run Rate for cooling for this cooling bin index. It should represent the best value seen for this system and cooling bin.
hb	Heating Bin	Bin index for HVAC Run Rate history when heating
$HRR_h[cb].count$	Heating Bin Count	Number of readings for a given heating bin index
$HRR_{h-ref}[hb]$	Reference HVAC Run Rate for Heating	The reference value for the HVAC Run Rate for heating for this heating bin index. It should represent the best value seen for this system and heating bin.
$HRR_c[cb].P50$	Median Cooling HVAC Run Rate	Median HVAC Run Rate for a given cooling bin index
$HRR_c[cb].P90$	P90 Cooling HVAC Run Rate	90 th Percentile HVAC Run Rate for a given cooling bin index (Avoid max so that outlier measurements are suppressed)
$HRR_c[cb].P10$	P10 Cooling Run Rate	10 th Percentile HVAC Run Rate for a given cooling bin index (Avoid max so that outlier measurements are suppressed)
$HE_c[cb]$	HVAC Effectiveness during cooling for cooling bin index cb	The HVAC Effectiveness for a given cooling bin index from 0% to 100%.
$HE_{c-week}[cb]$	$HE_c[cb]$ values restricted to the current week	The HVAC Effectiveness values for a given cooling bin index for this week
$HRR_h[hb].P50$	Median Heating HVAC Run Rate	Median HVAC Run Rate for a given heating bin index
$HRR_h[hb].P90$	P90 Heating HVAC Run Rate	90 th Percentile HVAC Run Rate for a given heating bin index (Avoid max so that outlier measurements are suppressed)
$HRR_h[hb].P10$	P10 Heating Run Rate	10 th Percentile HVAC Run Rate for a given heating bin index (Avoid max so that outlier measurements are suppressed)
$HE_h[hb]$	HVAC Effectiveness during heating for heating bin index hb	The HVAC Effectiveness for a given heating bin index from 0% to 100%.
$HE_{h-week}[hb]$	$HE_h[hb]$ values restricted to the current week	The HVAC Effectiveness values for a given heating bin index for this week
TRL	Temperature Retention List of k_{co} values	The list of k_{co} values with implicit ability to be indexed by the time the underlying measurement was made (i.e., the time the k_{co} value was estimated)

TRL _{week}	TRL values restricted to the current week	The list of k _{co} values for the current week.
TRL.P10	P10 Temperature Retention value	10 th percentile value for the associated Temperature Retention List TRL
TR _{ref}	Reference Temperature Retention value	The reference k _{co} value which should represent the best value seen for this sensor node.
TRE	Temperature Retention Effectiveness	Ranging from 0% (no thermal resistance to outside at all) to 100% (as good as ever seen in this install), this is an estimate of how well the room/house retains temperature. Some embodiments do not normalize for the effects of wind or sun.
T _i	Internal temperature of room sensor node is in	Internal temperature in degrees C for room sensor node is in
T _e	Exterior (outside) temperature	Outside temperature in degrees C for house where system is installed
MIN_BIN_COUNT	Minimum number of entries in bin required to do statistics	Minimum number of entries in bin required to do statistics; should be at least 3
PLOT_TIME_BASE	Minimum time value on x-axis for HVAC Effectiveness plots	Minimum time value on x-axis for HVAC Effectiveness plots; should be no lower than 0 and typically is 1
PLOT_TIME_RES	Resolution of time values on x-axis for HVAC Effectiveness plots	Resolution of time values on x-axis for HVAC Effectiveness plots; typically 0.1 minutes
MAX_PLOT_TIME	Maximum time value on x-axis for HVAC Effectiveness plots	Maximum time value on x-axis for HVAC Effectiveness plots; typically 20 minutes
PLOT_MIN_COUNT	Minimum number of entries in bin required to do statistics for Auxiliary Plots	Minimum number of entries in bin required to do statistics for Auxiliary Plots; should be at least 3

[0082] A simplified thermal model for the home that may be used in some embodiments is given as follows. This example model ignores other factors like sunlight, wind and room to room heat transfer within the house.

- When the HVAC is off, $dT_i/dt = -k_{co} * (T_i - T_e)$
- When the HVAC is on, $dT_i/dt = -k_{co} * (T_i - T_e) + dT_{hvac}/dt$

[0083] Note the equation may be the same whether the HVAC is heating or cooling.

[0084] **Bin Readings.** In example embodiments, each HVAC Run Rate reading is binned in order to assess true HVAC system efficiency trends.

[0085] Cooling. On receipt of a new HRR_c for a given sensor node, do the following. In some embodiments, the sensor node will supply T_i and T_e for the calculations below. In some embodiments, these will be the values at the start of the cooling cycle.

- Compute the appropriate cooling bin index:

$$cb = \max((T_e - T_i)/2, 10)$$

- Add the HRR_c to the bin : $HRR_c[cb].append(HRR_c)$

[0086] Heating. On receipt of a new HRR_h for a given sensor node, do the following. In some embodiments, the sensor node will supply T_e for the calculations below. In some embodiments, these will be the values at the start of the heating cycle.

- Compute the appropriate heating bin index:

$$hb = \min((\max(T_e, -18) - (-18))/2, 20)$$

- Add the HRR_h to the bin : $HRR_h[hb].append(HRR_h)$

[0087] Cooling or heating. On receipt of a new k_{co} for a given sensor node, add it to the list:
 $TRL.append(k_{co})$.

[0088] Compute un-normalized parameters. In some embodiments, the time-based parameters UX seeks ($T_Cool-Ave_{week}$, $T_Heat-Ave_{week}$, $T_Temp-Retention_{week}$) are all referenced to a 1 degree C change. The HRR and $T_Temp-Retention$ values on which this is based have units which may be inverted to yield the desired values. For example, if the HRR run rate is .25 degrees C per second, the T_Cool reading UX seeks is (1 degrees C)/(.25 degrees C per second) or 4 seconds.

$T_Cool-Ave_{week} = 1. / \text{median}(HRR_{c-week}[cb] \text{ for all } cb \text{ where } (HRR_{c-week}[cb].count > MIN_BIN_COUNT))$

$T_Heat-Ave_{week} = 1./ \text{median}(HRR_{h-week}[hb] \text{ for all } hb \text{ where } (HRR_{h-week}[hb].count > MIN_BIN_COUNT))$

$T_Temp-Retention_{week} = 1./ \text{median}(\text{abs}((k_{co} \text{ for this past week}) * (T_i - T_e)))$

[0089] Determine Reference Values for Computing Normalized Parameters. Note that min rather than max is used in computing the reference HRR 's. That's because we desire to capture the peak operation and that will happen when the time to change the temperature by 1 degree C is the shortest.

$HRR_{c-ref}[cb] = \min (HRR_{c-week}[cb].P10, HRR_{c-ref}[cb])$ if $HRR_{c-week}[cb].count > MIN_BIN_COUNT$)

$HRR_{h-ref}[hb] = \min (HRR_{h-week}[hb].P10, HRR_{h-ref}[hb])$ if $HRR_{h-week}[hb].count > MIN_BIN_COUNT$)

[0090] When dealing with Temperature Retention, some embodiments evaluate the minimum value because the k_{co} term is multiplied by the difference between interior and exterior temperatures to yield the rate of change in degrees Celsius per unit time. Therefore the smaller k_{co} becomes, the better the Temperature Retention.

$$TR_{ref} = \min(TRL_{week}.P10, TR_{ref})$$

Other embodiments may alternatively use the maximum, mode, or some other measure in place of the minimum.

[0091] Compute normalized parameters. Normalized parameters may be determined as follows.

$HE_c[cb] = (\text{median}(HRR_c[cb]/HRR_{c-ref}[cb]) * 100\%)$ if $HRR_{c-ref}[cb]$ valid

Cool-Effect = median($HE_{c-week}[cb]$ for all cb where $(HE_{c-week}[cb].count > MIN_BIN_COUNT)$)

$HE_h[hb] = (\text{median}(HRR_h[hb]/HRR_{h-ref}[hb]) * 100\%)$ if $HRR_{h-ref}[hb]$ valid

Heat-Effect = median($HE_{h-week}[hb]$ for all hb where $(HE_{h-week}[hb].count > MIN_BIN_COUNT)$)

Temperature Retention Effectiveness = $TRE = (\text{median}(TRL_{week} / TR_{ref}) * 100\%)$ if TR_{ref} valid

[0092] Derive HVAC Effectiveness Plots. As an alternate visualization to the summary metrics computed above, some embodiments operate to graphically illustrate HVAC Effectiveness by plotting HRR_c and HRR_h for a recent period of time.

[0093] As noted above, in general HVAC performance varies with weather and not just its maintenance condition. That's why the calculations of HE_c and HE_h are normalized to bins that factor in weather conditions. This plot does not directly leverage bins and so will change with weather conditions. However, since we seek to minimize that effect, it may be desirable to pick an appropriate window of time. This is a design parameter that can be changed, but in some embodiments, it is to set it to 1 month, which is long enough to capture a broad collection of bins but short enough that seasonal variations can be seen.

[0094] The nominally 1 month period mentioned below may be a sliding window of time. This means that what we are plotting is the current day's results plus the prior 30 days. This is then a sliding month, not a calendar month.

[0095] There will be times when the HVAC system only heats (e.g., winter) or only cools (e.g., summer). In that event, only one of the two possible curves will be shown because there is no data for the other.

[0096] HVAC systems average just shy of 9 hours a day but generally 10-15 minutes at a time. This will vary for a particular house but suggests that the default x-axis range should be roughly 1 to 30 minutes to a resolution of .1 minute.

[0097] To calculate plot data, the following may be performed in some embodiments:

```
Define macro IN_RANGE(value, low, delta) = ((value >= low) && (value <
(low+delta)))
```

```
For I = 0 to ((MAX_PLOT_TIME-- PLOT_TIME_BASE)/PLOT_TIME_RES):
```

```
    HRRc-plot [i] = sum([1 for v in HRRc[:, :] if v in IN_RANGE(i*PLOT_TIME_RES +
PLOT_TIME_BASE, PLOT_TIME_RES)])
```

```
    HRRh-plot [i] = sum([1 for v in HRRh[:, :] if v in IN_RANGE(i*PLOT_TIME_RES +
PLOT_TIME_BASE, PLOT_TIME_RES)])
```

[0098] In the above calculation if there are HRR values greater than the last plot time, they will not be counted. If MAX_PLOT_TIME is set to allow this to happen, in some embodiments, all the values greater than the highest bin may be collected together into that bin.

[0099] **Calculating auxiliary plot data.** Calculation of auxiliary plot data may include defining a function such as PERCENT_FIND(x, p), where:

- x is the list of counts from index 0 at the low end and some finite number M at the high end so the array contains M+1 entries. Here x will be either HRR_{c-plot} and HRR_{h-plot}.
- p is the desired percentile which represents the cumulative percentage of counts from 0 up to the returned index is >= this percentage. To ease calculation, it is presumed in some embodiments that the returned index is fractional to allow for better handling of edge cases.

[0100] The method in Python-like pseudo-code may be implemented as follows.

```
desired_sum = p * sum(x) #if p = 50 and the sum of all the counts in the
array x is 120, desired_sum is 60 sine (50/100)*120 = 60
cum_sum = 0
```

```

for j = 0 to len(x):
    cum_sum += x[j]
    if cum_sum >= desired_sum
        break
if cum_sum < desired_sum:
    log.error()
else
    ''' x[j] moved cum_sum from below desired_sum to above it and so want to
    take back the fraction that is above desired_sum
    ret_index = j - (cum_sum - desired_sum)/x[j]

```

[0101] In some embodiments, statistics obtained from the main plot data are plotted. This may be performed as follows.

$$\text{HRR}_{c\text{-plot}} . \text{P90} = \text{PERCENT_FIND}(\text{HRR}_{c\text{-plot}} , 90)$$

$$\text{HRR}_{c\text{-plot}} . \text{P50} = \text{PERCENT_FIND}(\text{HRR}_{c\text{-plot}} , 50)$$

$$\text{HRR}_{c\text{-plot}} . \text{P10} = \text{PERCENT_FIND}(\text{HRR}_{c\text{-plot}} , 10)$$

[0102] Similarly the heating values may be computed as follows:

$$\text{HRR}_{h\text{-plot}} . \text{P90} = \text{PERCENT_FIND}(\text{HRR}_{h\text{-plot}} , 90)$$

$$\text{HRR}_{h\text{-plot}} . \text{P50} = \text{PERCENT_FIND}(\text{HRR}_{h\text{-plot}} , 50)$$

$$\text{HRR}_{h\text{-plot}} . \text{P10} = \text{PERCENT_FIND}(\text{HRR}_{h\text{-plot}} , 10)$$

[0103] For this option, the method may involve plotting these three values by day or week for the period chosen. Each single data point represents a calculation for the past window of time (here recommended to be 1 month long). So the plot shows how the statistics of the HVAC Effectiveness plots changes over time.

[0104] In some embodiments, statistics across bins are plotted.

[0105] The HRR's are normalized by bins and so shifts within a bin should correlate to changes in the system's operational efficiency. In some embodiments, the 90%, 50% (median) and 10% points may be plotted per bin against the temperature values the bins correspond to (e.g., the outside temperature is the x-axis for the heating case) for cooling and heating respectively. The formulas to calculate the relevant stats on HRR in some embodiments are given below.

$$\text{HRR-P90}_{c\text{-plot}}[;] = [\text{HRR}_c[\text{cb}].\text{P90} \text{ for all } \text{cb} \text{ where } \text{HRR}_c[\text{cb}].\text{count} \geq \text{PLOT_MIN_COUNT}]$$

$$\text{HRR-P50}_{c\text{-plot}}[;] = [\text{HRR}_c[\text{cb}].\text{P50} \text{ for all } \text{cb} \text{ where } \text{HRR}_c[\text{cb}].\text{count} \geq \text{PLOT_MIN_COUNT}]$$

$$\text{HRR-P10}_{c\text{-plot}}[;] = [\text{HRR}_c[\text{cb}].\text{P10} \text{ for all } \text{cb} \text{ where } \text{HRR}_c[\text{cb}].\text{count} \geq \text{PLOT_MIN_COUNT}]$$

$HRR-P90_{h-plot}[:, :] = [HRR_h[hb].P90 \text{ for all } hb \text{ where } HRR_h[hb].count \geq PLOT_MIN_COUNT]$

$HRR-P50_{h-plot}[:, :] = [HRR_h[hb].P50 \text{ for all } hb \text{ where } HRR_h[hb].count \geq PLOT_MIN_COUNT]$

$HRR-P10_{h-plot}[:, :] = [HRR_h[hb].P10 \text{ for all } hb \text{ where } HRR_h[hb].count \geq PLOT_MIN_COUNT]$

Distribution-Centric HVAC Efficiency Model.

[0106] Some embodiments provide for a simplified analytical model. Powerful insights can be had by, in this case, letting collections over longer periods of time average out the factors which may otherwise be considered.

[0107] Modeling HVAC and home thermal behavior in general is complicated. Example embodiments operate to determine relevant parameters via remote sensing using a collection of sensor nodes in the home (e.g. using audio data collected by sensor nodes for determining HVAC activity). Such embodiments provide useful and actionable insights for those who own and/or manage a home.

[0108] While the example is described here of an HVAC system cooling a house, the description also applies to cases where the HVAC system is heating the house, only the direction of temperature change is different.

[0109] In example embodiments, analysis is performed based on two types of observations, collected over a relatively long period of time:

- When the HVAC system is running, how long it takes to reduce the room temperature by 1° C. The symbol OnTime may represent this value.
- When the HVAC system is not running, how long it takes for the room temperature to rise by 1° C. The symbol OffTime may represent this value.

[0110] In some embodiments, for each HVAC “On” cycle for each sensor node of interest, a new OnTime is calculated. Similarly, for each HVAC “Off” cycle for each sensor node of interest, a new OffTime is calculated. Then, if one plots the distribution (e.g. a histogram) of OnTime values seen over a long period of time, the result may be a graph as shown in FIG. 5. The distribution of OffTime may be similar.

[0111] The distributions of OnTime and OffTime are valuable in and of themselves, as described below. In addition, example embodiments operate to compare the distributions of two time-periods with one another. For example, some embodiments compare the current year’s OnTime distribution with the prior year’s OnTime distribution, and if the HVAC system is degrading, the distribution may indicate a shift towards longer times. Some embodiments operate to detect such a shift and to alert a user to potential changes to the effectiveness

of the HVAC system. In particular, some of the peak (or mode), median, mean, lower quintile and upper quintile values may be greater than before. If those values are the same, that indicates the HVAC system is running at substantially the same efficiency level as before.

[0112] The situation with OffTime is similar. Example embodiments operate to compare the current year's OffTime distribution with the prior year's OffTime distribution and if the home's thermal retention is worse, the distribution may indicate a shift towards shorter times. Some embodiments operate to detect such a shift and to alert a user to potential changes to the effectiveness of the home's heat retention (e.g. insulation) or exclusion (e.g. shading). In particular, some of the peak, median, lower quintile and upper quintile values may be less than before. If those values are the same, that indicates the home's thermal retention is roughly the same as before.

[0113] Some embodiments operate to compare the OnTime distribution for one sensor node with another in the same house. A determination may be made that the one with longer times is not as well controlled. This could indicate that, due to duct design or vent position, the air flow is not as strong in the poorer performing room. It could mean that the thermal retention in that room is lower. That in turn could be due to poorer insulation, an open window or the like. Or it could mean another heat source is dragging down performance such as solar radiation. One example is if the poorer performing room has many windows and gets lots of sunlight.

[0114] Some embodiments operate to compare the OffTime distribution for one sensor node with another in the same house. A determination may be made that the node with shorter times has poorer insulation, which may be the result, for example of poor wall insulation or an open window.

[0115] In some embodiments, a comparison is performed of distributions from similar homes in the same geographic area. A determination may be made of how well a particular home/room is performing relative to neighboring homes. In some embodiments, a comparison is performed of distributions from different HVAC units in a single house or different HVAC units in different units of a multi-dwelling building such as an apartment building. Other comparisons may alternatively be made.

[0116] A comparison of two OnTime distributions is particularly useful when the distributions of correlated factors are roughly equivalent. For example, OnTime is heavily influenced by weather conditions. Comparing two distributions with different outdoor temperature patterns may lead to erroneous conclusions. Thus, if it is desired to compare the OnTime distributions for one sensor node in a house against one for another sensor node in the same house, it is desirable to use a period long enough to get a decent statistical average (e.g. a week or month). If it is desired to compare the current OnTime distribution against a prior time, it is desirable

for both time periods to have roughly the same distribution of weather conditions (and indoor thermostat settings). Since weather patterns can change a bit from year to year, in some embodiments, the periods of time are relatively long - say the last 12 months against the 12 months prior to that (the current year against last year).

[0117] In some embodiments, to compare two OffTime distributions, it is desirable to have information indicating that the distributions of correlated factors are roughly equivalent. In addition to weather, the main factors involved concern the layout and house orientation, the building materials, the number of windows and the like. The main result, therefore, is that the same general guidelines apply as detailed above for comparing OnTime distributions.

[0118] In some embodiments, a simplified thermal model is used to estimate the thermal retention and HVAC efficiency parameters. Analyzing those distributions separately with a binned approach as described herein allows for comparison of distributions across shorter periods of time.

HVAC Efficiency (Random Walk and Inverse Gaussian).

[0119] Some embodiments fit a histogram of HVAC Efficiency Ratios to a curve, such as an Inverse Gaussian curve. By fitting an Inverse Gaussian to the collected data, the resulting data may be presented in a more easily interpretable form for monitoring the performance of the system. For example, there is a closed form equation for both the mode and the mean of that curve. By using the fit distribution instead of the raw histogram bins, example embodiments are more robust to statistical variations and measurement noise. In example embodiments, the curve is fit to the data with a low number of variables, e.g. two variables for shape and one for height normalization, where the variables provide information regarding the HVAC efficiency.

[0120] When an HVAC system deteriorates or ages in performance, the peak of the fit distribution will generally shift to the right. Detecting this shift gives us a view into HVAC performance. Even comparing the distribution values (mean, mode, standard deviation) across units/homes can provide information the relative performance of the system, and changes in one or more such parameters (e.g. changes that exceed a threshold, which may be a predetermined threshold) may be used to indicate a loss of HVAC performance.

[0121] Some embodiments operate to scale the histogram values from one sensor node in the home to augment the histogram values from another sensor node in the home. For example, different sensor nodes may be placed in different-sized rooms, sensor nodes may have different distances from a vent, and there may be furniture or other obstacles between a vent (or radiator, etc.) and a sensor node. Such differences in room configurations may lead to differences in heating and cooling times. Despite these differences, data from different sensor nodes can be compared by re-scaling the data.

[0122] Example embodiments use artificial intelligence (AI) classifiers to determine when the HVAC is on and off. For example, audio data collected by sensor nodes may be converted into a spectrogram that in turn is provided to a convolutional neural network (CNN) trained to discriminate between HVAC active and inactive states. In some embodiments, additional information collected by additional sensors is used. Such additional sensors may be in the same sensor node. Such additional sensor information may include electrical transient signals detected at a power outlet, changes to temperature, humidity, or detected levels of different gases (e.g. CO, CO₂, or volatile organic compounds) that can be used as an alternative to or in addition to audio signals to provide greater levels of certainty as to the activity, inactivity, and type of activity (e.g. heating, cooling, or ventilating) of the HVAC system. Information from exterior sources may also be employed. For example, external temperature values may be determined (detected through an outdoor sensor or retrieved via online weather resources), with high outdoor temperatures increasing a prior probability of HVAC cooling activity and lower outdoor temperatures increasing a prior probability of HVAC heating activity. This information is used to help determine the efficiency of heating/cooling of the HVAC. In some embodiments, data is further collected from a thermostat. Such data may indicate whether the thermostat has requested activation of the HVAC system. Thermostat data may be used to augment a determination made using other sensor data (e.g. audio data) to determine whether the HVAC system is active. Furthermore, a potential failure state may be detected if the thermostat has requested activation of the HVAC system but other sensor data (e.g. audio data and/or temperature data) indicates that the HVAC system has not been activated.

[0123] In some embodiments, for each HVAC “on” cycle, the total duration and temperature change are measured. The value of time divided by temperature change is determined, where a higher value means that it is less efficient as it takes longer for the HVAC to change the temperature of the room by a set amount.

[0124] FIG. 7 illustrates a histogram showing the time divided by temperature change of HVAC cycles from a single sensor node. Investigations have shown that the overlay with an inverse Gaussian distribution fits the data well. The observation that such an overlay fits well for this histogram opens the door to some embodiments as disclosed herein.

[0125] The observation that the inverse Gaussian distribution (or “Wald distribution”) fits the histogram well indicates that the heating/cooling of the room is well modelled as heating/cooling from the HVAC plus environmental heating/cooling, where the environmental term is random and has a normal distribution. In general, the mean is proportional to the size of the room and the heat flow rate from the HVAC and is substantially independent of the environmental heating/cooling. The environmental heating/cooling only affects the variance of the distribution (width of the distribution).

[0126] In some embodiments, to determine HVAC efficiency, one sensor node is chosen for each HVAC/PTAC zone. The choice may be made through the input of a user, an installation professional, or it may be made automatically.

[0127] In some embodiments, the histogram could be fitted to the inverse gaussian distribution given by:

$$f(x) = \beta \sqrt{\frac{\lambda}{2\pi x^3}} e^{-\frac{\lambda(x-\mu)^2}{2\mu^2 x}} \quad \text{where}$$

mu = the mean of the distribution

lambda = (mean of the distribution)³ / (variance of the distribution)

beta = Fitted to match the height. This would vary depending on the data binning for the histogram.

[0128] In some embodiments, data is taken from multiple sensor nodes to describe the HVAC efficiency of the full house. As noted above, the mean of the distribution scales proportionally to the heat capacitance of the room. So a room of larger size would have a larger distribution mean than a smaller room. For example, a large living room would have a higher mean HVAC efficiency distribution than a bathroom.

[0129] FIGs. 8A-8B illustrate histograms of data collected from two sensor nodes in the same home. As seen in FIG. 8A, Sensor 1 has a lower distribution mean than Sensor 2. Multiplying each value of the time/degree Celsius for Sensor 2 by a factor gives the rescaled results of FIG. 8B. The rescaled distributions of the two curves in FIG. 8B match up quite closely. In some embodiments, rescaling is performed to combine data from different sensor nodes in a residence to provide additional analytical results. For example, rescaled histogram data from different sensor nodes can be pooled together into a single combined histogram, and changes to the statistics of the combined histogram may be used to detect potential HVAC issues.

[0130] In general, the change in temperature of a room due to a heat source is given by:

$$Q = C \Delta T$$

[0131] Q is the heat from a source, C is the heat capacitance, and ΔT is the change in temperature. With the heat capacitance remaining constant,

$$\frac{dQ}{dt} = C \frac{d\Delta T}{dt} \quad \text{. As}$$

$\Delta T(t) = T(t) - T(t = t_0)$, we therefore get:

$$\frac{dQ}{dt} = C \frac{dT}{dt}$$

We separate the heat terms as: $Q = Q_1 + Q_e$

[0132] Q_1 is the source from the system under test, such as the HVAC or PTAC, and Q_e is the heat flow from other environmental sources, such as the difference in temperature between the room and its surroundings, human presence, and other activities.

$$\frac{dT}{dt} = \frac{1}{C} \left(\frac{dQ_1}{dt} + \frac{dQ_e}{dt} \right) \text{ . Setting:}$$

$$q_1(t) = \frac{1}{C} \left(\frac{dQ_1}{dt} \right) \text{ and}$$

$$q_e(t) = \frac{1}{C} \left(\frac{dQ_e}{dt} \right)$$

[0133] In example embodiments, we can take q_1 as a constant in time as we assume the heat flow from an HVAC/PTAC system is constant in time. Note that q_1 is dependent on the velocity of air flow, temperature from the vent, the size of vent (due to the Q_1 term) as well as dependent on the room size (due to the C term).

$$T = q_1 t + \int dt q_e$$

We therefore get:

[0134] Note that the dQ_e/dt term, it is generally about 0 because we are typically in a steady state situation in the time scale of a HVAC cycle, resulting in the derivative of 0. For example, before the HVAC turns on, the temperature of the room is relatively stable over the approximately 10 minute time frame, which is the typical time scale of an HVAC cycle.

[0135] Thus we can describe the second term due to an environmental change as a random walk about 0.

$$\sigma W_t = \int dt q_e$$

[0136] The factor σ is a scaling factor and W_t is described by the Wiener process. The Wiener process is the continuous version of the random walk.

What is left is: $T(t) = q_1 t + \sigma W_t$

[0137] We are plotting the time it takes for the temperature to change by 1°C . This is equivalent to the “time of first passage problem,” where we are solving the probability distribution of a 1D Brownian motion particle described by:

$$X(t) = vt + \sigma W_t$$

[0138] As our equation for temperature is equivalent to the 1D Brownian motion equation, solutions to the 1D Brownian motion equation are also valid for our situation.

[0139] The probability distribution for the 1D Brownian motion to reach a distance α is given by:

$$f(t) = \frac{\alpha}{\sqrt{2\pi\sigma^2 t^3}} e^{-\frac{(\alpha-vt)^2}{2\sigma^2 t}}$$

[0140] We can rewrite this as:

$$f(x) = \sqrt{\frac{\lambda}{2\pi x^3}} e^{-\frac{\lambda(x-\mu)^2}{2\mu^2 x}}$$

where $\mu = \alpha/v$

and $\lambda = \alpha^2/\sigma^2$

[0141] This distribution is the Inverse Gaussian Distribution. The Inverse Gaussian Distribution has properties of:

Mean given by: $E[x] = \mu$

and variance given by: $Var[x] = \mu^3/\lambda$

[0142] Therefore lambda can be calculated by:

$$\lambda = E[x]^3/Var[x]$$

[0143] Note that the mean scales as

$$E[x] \propto C \left(\frac{dQ_1}{dt} \right)^{-1}$$

[0144] So the mean of the distribution is proportional to the heat capacitance of the room and inversely proportional to the rate of heat flow from the system under test.

Adjustment of Diagnostic Data for Reporting.

[0145] In some embodiments, methods are implemented to adjust some of the estimated values in order to optimize the quality of our diagnostic data shown to a user.

[0146] One element in some of the HVAC data calculations and visualizations analyzed below involves some inverses of derivatives ("ratios") of particular segments of the temperature time series capturing HVAC operational cycles. This group of parameters includes HER_{heat} , HER_{cool} , TRR_{heat} , and TRR_{cool} . Their units may all be minutes per °C, and in example embodiments they range in value from 0 to 60. Described herein are performance metrics for such parameters.

[0147] For the Air Filter Cleanliness method, some embodiments gauge the quality of the aggregate HVAC Operational Time estimates produced by an AI system over the course of the average day. A performance metric - the Operational Time Error Bound – is described in the table below.

Performance Metric	Definition
Ratio Error Bound	Based on an analysis of a collection of ratio-estimates computed on test examples, the Ratio Error Bound is defined such that 95% of the time, it is true that the (Estimated Ratio - Ratio Error Bound) < Actual Ratio < (Estimated Ratio + Ratio Error Bound). To be specific, when, for example, HER_{heat} is computed/estimated for a given segment in the temperature time-series, there is a 95% chance that the actual HER_{heat} value for lies within +/- Ratio Error Bound of the estimated HER_{heat} value. The Ratio Error Bound value might differ for each ratio type (e.g., HER_{heat}, HER_{cool}, TRR_{heat}, and TRR_{cool}). The method used to estimate these Ratios may indicate that the time-series segment is not suitable to produce an estimate.
Operational Time Error Bound	Based on an analysis of a collection of HVAC Operational Time estimates, the Operational Time Error Bound is defined such that 95% of the time, it is true that the (Estimated HVAC Operational Time - Operational Time Error Bound) < Actual HVAC Operational Time < (Estimated HVAC Operational Time + Operational Time Error Bound) when the period of time over which this estimate is made is at least a day (24 hours calendar time). The HVAC Operational Time refers to the operation of the HVAC Air Handler independent of whether any heating or cooling is occurring. This is because the air filter cleanliness is determined by air flow, not heating or cooling per se.

[0148] FIG. 9 illustrates an example report of collected data and results of data analysis, which may be displayed in a user interface in some embodiments. In the chart, the temperature reports may be direct readings and not inferences, in which case no adjustment is required. The gray vertical bands on the chart reflect the result of inferences by the system as to intervals during which the HVAC is running. Depending on the AI performance levels, adjustments may be implemented.

[0149] Some embodiments provide data such as that shown in FIG. 10. Such data may be displayed in a user interface.

[0150] In some embodiments, the following metrics may be applied to the HVAC On/Off determination along with associated timing. For this table, the focus is on the augmented state of when HVAC is either cooling or heating, rather than if the HVAC air handler is running without heating or cooling.

Statistic	UX Performance Objective	UX Adjustments Depending on AI Performance Levels
Average cycles/day	This should be within 10% of the actual number.	- If (Precision > 90%) AND (Recall > 90%), the statistic should stay as is. - If (Precision < 90%) OR (Recall < 90%), this statistic may be removed or recast. One example recast if (Precision > 70%) is this: "Average days this month with more than X cycles"; days would qualify if (classifier count of cycles > (X/Precision)).
Average runtime/cycle	This should be within 10% of the actual number.	- If (Precision > 90%) AND (IoU > 90%), the statistic should stay as is. - If (Precision < 90%) OR (IoU < 90%), this statistic should be removed or recast.
Total cycles	This should be within 10% of the actual number.	- If (Precision > 90%) AND (Recall > 90%), the statistic should stay as is. - If (Precision < 90%) OR (Recall < 90%), this statistic should be removed or recast. One example recast that is totally independent of classifier accuracy may be "Longest duration when temperature deviated outside the comfort zone limit".
Highest cycles/day	This should be within 10% of the actual number.	- If (Precision > 90%) AND (Recall > 90%), the statistic should stay as is. - If (Precision < 90%) OR (Recall < 90%), this statistic should be removed or recast. One possible recast if (Precision > 70%) is "Over X cycles seen today"; determined if (classifier count of cycles > (X/Precision)).
Days with no cycles	Included days should at most have 1 short cycle.	- If (Precision > 90%) AND (Recall > 90%), the statistic should stay as is as long as the typical number of cycles per day is approximately 10 or less. - If (Precision < 90%) OR (Recall < 90%) OR (typical number of cycles per day > 10), this statistic should be removed or recast.

[0151] In the above table, the measure "IoU" refers to "intersection over union," measuring the amount of overlap (intersection) between the predicted state from the classifier and the true state divided by the union of those two (for a particular state). Other measures of performance may alternatively or additionally be used.

[0152] In some embodiments, a user interface is provided as shown in FIG. 11.

[0153] The following metrics apply to HVAC On/Off determination along with associated timing. For this chart, the focus is on the augmented state of when HVAC is heating, rather than if the HVAC air handler is running without heating.

[0154] It may be desirable for the average HVAC Runtime for 1° heating to be within 10% of the right number. It may be desirable for the min and max HVAC Runtimes 1° heating to be protected against outliers. use of median and other percentile operations provides some built-in protection.

[0155] In some embodiments, the following are implemented:

- For normal operation of the chart, N_{HER} (the number of samples in the collection being analyzed for the displayed Heating Effectiveness) should be > 50 . This allows for the 5% level to accommodate at least 1 outlier on each end.
- If the Ratio Error Bound for $HER_{heat} < 10\%$, the chart should be used as is.
- If $10\% < \text{Ratio Error Bound for } HER_{heat} < 20\%$ across the range, consider two possible actions:
 - Remove the Min and Max displays on the chart and just leave the Average (Median) and/or
 - Check if Ratio Error Bound is better at one end of the range than the other. In that event, consider adjusting the region of operation so that the Ratio Error Bound is $< 10\%$.
- If the Ratio Error Bound for $HER_{heat} > 20\%$, suggest raising the required N_{HER} to a higher number (e.g., 200) before displaying the chart at all. Then only show the Average (Median) number. Assuming the estimation of HER_{heat} is unbiased and the error is symmetrically distributed, the Ratio Error Bound for the computed Average (Median) result should trend downward proportional to the $\sqrt{N_{HER}}$. Therefore, the resulting Ratio Error Bound when $N_{HER} = 200$ should be roughly half of what it is when $N_{HER} = 50$.

[0156] In some embodiments, heating effectiveness is displayed using a chart as shown in FIG. 12. The cycles that are analyzed to compute HER_{heat} ratios are, in general, a subset of the total detected HVAC cycles. In some embodiments, the method for computing the HER_{heat} ratios operates to reject that cycle as being unsuitable (too noisy or too weak) to compute the ratios. Therefore, in some embodiments, the following adjustments may be made to the interface:

- Change “Total runtime cycles” to “Total cycles analyzed”
- Change the vertical axis label to, e.g., “Number of cycles analyzed”.

[0157] In addition to the adjustments above, the following may be implemented in some embodiments:

- For normal operation of the chart, N_{HER} (the number of samples in the collection being analyzed for the displayed Heating Effectiveness) should be > 50 . This allows for the 5% level to accommodate at least 1 outlier on each end.

- If the Ratio Error Bound for $HER_{heat} < 10\%$, the chart should be used as is.
- If $10\% < \text{Ratio Error Bound for } HER_{heat} < 20\%$ across the range, further actions may be considered:
 - Shading the curve to illustrate error bounds around the main curve.
 - Check if Ratio Error Bound is better at one end of the range than the other. In that event, consider adjusting the x-axis of the chart so that the Ratio Error Bound is $< 10\%$ across the chart.
 - Adjusting the header/title text to make it clear that only the rough shape is accurate.
- If the Ratio Error Bound for $HER_{heat} > 20\%$, the required N_{HER} may be raised to a higher number (say, 200) before displaying the chart at all. In some embodiments, further actions may be used:
 - Do not display the extremes on either end - the bottom and top 5%
 - Shade the curve to illustrate the error bounds.
 - Make the tick marks very coarse or do not label them at all so as to convey only the shape of the distribution and not precise values.
 - If the Ratio Error Bound for $HER_{heat} > 30\%$, consider not showing the graph at all.

[0158] In some embodiments, a chart such as that of FIG. 13 is provided in a user interface. This screen plots the average (median) HER_{heat} over the period of interest.

[0159] In some embodiments, cooling effectiveness is provided in a user interface as illustrated in FIG. 14.

[0160] The following metrics apply to HVAC On/Off determination along with timing associated with that. This chart focuses on the augmented state of when HVAC is cooling, rather than when the HVAC air handler is running without cooling.

[0161] It is desirable for the average HVAC Runtime for 1° cooling to be within 10% of the right number. It is desirable the min and max HVAC Runtimes 1° heating to be protected against outliers. The use of median and other percentile operations provides some built-in protection. In some embodiments, the following are implemented:

- For normal operation of the chart, N_{HER} (the number of samples in the collection being analyzed for the displayed Cooling Effectiveness) should be > 50 . This allows for the 5% level to accommodate at least 1 outlier on each end.
- If the Ratio Error Bound for $HER_{cool} < 10\%$, the chart should be used as is.
- If $10\% < \text{Ratio Error Bound for } HER_{cool} < 20\%$ across the range, consider two possible actions:
 - Remove the Min and Max displays on the chart and just leave the Average (Median) and/or

- Check if Ratio Error Bound is better at one end of the range than the other. In that event, consider adjusting the region of operation so that the Ratio Error Bound is $< 10\%$.
- If the Ratio Error Bound for $HER_{cool} > 20\%$, suggest raising the required N_{HER} to a higher number (say, 200) before displaying the chart at all. Then only show the Average (Median) number. Assuming the estimation of HER_{cool} is unbiased and the error is symmetrically distributed, the Ratio Error Bound for the computed Average (Median) result should trend downward proportional to the $\sqrt{N_{HER}}$. Therefore, the resulting Ratio Error Bound when $N_{HER} = 200$ should be roughly half of what it is when $N_{HER} = 50$.

[0162] In some embodiments, cooling effectiveness information is provided in a user interface as shown in FIG. 15. The cycles that are analyzed to compute HER_{cool} ratios are, in general, a subset of the total detected HVAC cycles. The method for computing the HER_{cool} ratios may operate to reject that cycle as being unsuitable (too noisy or too weak) to compute the ratios. Therefore, the following adjustments to this UX screen may be implemented in some embodiments:

- Change “Total runtime cycles” to “Total cycles analyzed” or something to that effect.
- Change the vertical axis label to “Number of cycles analyzed”.

[0163] In addition to the adjustments above, the following set of adjustment guidelines may be implemented in some embodiments:

- For normal operation of the chart, N_{HER} (the number of samples in the collection being analyzed for the displayed Cooling Effectiveness) should be > 50 . This allows for the 5% level to accommodate at least 1 outlier on each end.
- If the Ratio Error Bound for $HER_{cool} < 10\%$, the chart may be used as is.
- If $10\% < \text{Ratio Error Bound for } HER_{cool} < 20\%$ across the range, consider three possible actions:
 - Shading the curve to illustrate error bounds around the main curve
 - Check if Ratio Error Bound is better at one end of the range than the other. In that event, consider adjusting the x-axis of the chart so that the Ratio Error Bound is $< 10\%$ across the chart.
 - Adjusting the header/title text to make it clear that only the rough shape is accurate.
- If the Ratio Error Bound for $HER_{cool} > 20\%$, suggest raising the required N_{HER} to a higher number (say, 200) before displaying the chart at all. Also, consider four possible additional actions:
 - Do not plot the extremes on either end - the bottom and top 5%

- Shade the curve to illustrate the error bounds.
- Make the tick marks very coarse or do not label them at all so as to convey the shape of the distribution and not precise values.
- If the Ratio Error Bound for $HER_{cool} > 30\%$, possibly refrain from showing the graph at all.

[0164] In some embodiments, cooling effectiveness trend data may be provided in a user interface using a chart such as that of FIG. 16. This screen plots the average (or the median in some embodiments) HER_{cool} over the period of interest.

[0165] In some embodiments, temperature retention data may be provided in a user interface using a chart such as that of FIG. 17.

[0166] The following metrics apply to HVAC “Off” determination along with timing associated with that. For this chart, the focus is on the augmented state of when HVAC is neither cooling nor heating. If the HVAC air handler is running without cooling or heating, that counts as HVAC “Off” in example embodiments.

[0167] For a given outdoor to indoor temperature difference and house configuration (apart from considering solar and wind effects), it is desirable for the average Temperature Retention Rate (TRR) (or time for 1° change) to be within 10% of the right number. It is desirable for the min TRR to be protected against outliers. The use of median and other percentile operations provides some built-in protection.

[0168] In some embodiments, the following may be implemented:

- For normal operation of the chart, N_{TRR} (the number of samples in the collection being analyzed for the displayed Temperature Retention) should be > 50 . This allows for the 5% level to accommodate at least 1 outlier on each end.
- If the Ratio Error Bound for TRR_{cool} (or TRR_{heat}) $< 10\%$, the chart should be used as is.
- If $10\% < \text{Ratio Error Bound for } TRR_{cool} \text{ (or } TRR_{heat}) < 20\%$ across the range, consider two possible actions:
 - Remove the Min displays on the chart and just leave the Average (Median) and/or
 - Check if Ratio Error Bound is better at one end of the range than the other. In that event, consider adjusting the region of operation so that the Ratio Error Bound is $< 10\%$.
- If the Ratio Error Bound for TRR_{cool} (or TRR_{heat}) $> 20\%$, suggest raising the desired N_{TRR} to a higher number (say, 200) before displaying the chart at all. Then only show the Average (Median) number. Assuming the estimation of TRR_{cool} is unbiased and the error is symmetrically distributed, the Ratio Error Bound for the computed Average (Median) result should trend downward proportional to the

$\sqrt{N_{\text{TRR}}}$. Therefore, the resulting Ratio Error Bound when $N_{\text{TRR}} = 200$ should be roughly half of what it is when $N_{\text{TRR}} = 50$.

[0169] In some embodiments, temperature retention information is provided in a user interface as shown in FIG. 18A. In some embodiments, the slope and offset of the mean/median/mode or other value may be compared between different time periods, different rooms, and/or different dwellings to compare temperature retention.

[0170] The cycles that are analyzed to compute TRR_{cool} and TRR_{heat} ratios are, in general, a subset of the total detected HVAC cycles. The algorithm computing the TRR_{cool} and TRR_{heat} ratios may operate to reject that cycle as being unsuitable (too noisy or too weak) to compute the ratios. The following adjustments to the user interface may be implemented:

- For normal operation of the chart, N_{TRR} (the number of samples in the collection being analyzed for a particular box-and-whiskers element) should be > 50 . This allows for the 5% level to accommodate at least 1 outlier on each end.
- If $15 < N_{\text{TRR}} < 50$, the whiskers portion of the display may be omitted for that element and just display the main box section for that slice of outdoor temperatures. If $N_{\text{TRR}} < 15$, leave the box blank. Note that this determination may be done separately for every potential box and whiskers element. Therefore it follows that some elements will be blank, some will just have the main box section and some will be full box-and-whiskers elements.
- If the Ratio Error Bound for TRR_{cool} (and TRR_{heat}) $< 10\%$, the chart may be used as is.
- If $10\% < \text{Ratio Error Bound for } \text{TRR}_{\text{cool}} \text{ (and } \text{TRR}_{\text{heat}}) < 20\%$ across the range, consider three possible actions:
 - Leave the whiskers off entirely and consider fuzzing/widening the line width of the bottom and top of the box section.
 - Check if Ratio Error Bound is better at one end of the time range than the other. In that event, consider adjusting the y-axis of the chart so that the Ratio Error Bound is $< 10\%$ across the chart.
 - Adjusting the header/title text to make it clear that only the rough shape is accurate.
- If the Ratio Error Bound for TRR_{cool} (and TRR_{heat}) $> 20\%$, suggest raising the required N_{TRR} to a higher number (say, 200) before displaying the box and whiskers element at all. Also, consider four possible additional actions:
 - Leave off the whiskers

- Fuzz or widen the bottom and top lines of the box element.
- If the Ratio Error Bound for TRR_{cool} (and TRR_{heat}) $> 30\%$, consider not showing the graph at all.

[0171] In some embodiments, room-by-room retention information is provided in a user interface as shown in FIG. 19. Since the N_{TRR} will vary by sensor node (since the quality of the estimate can vary based on different conditions of a room), it is possible that the user interface features described above will suggest showing data for some rooms and not others. Some embodiments operate to gray out the sensor node elements with too little data to be confident of the numbers. That way the chart would “show” all the rooms, but some would still be in “data gathering” or “measuring” phase.

[0172] In some embodiments, temperature retention statistical information is provided in a user interface as shown in FIG. 20. Information regarding the number of “best retention days” may be used to indicate the number of days (e.g. in the last twelve months) during which it took 60 minutes or more for a one degree change in temperature. Information regarding the “total below average retention days” may be used to indicate the number of days (e.g. in the last twelve months) on which retention was below the average year-to-date retention.

[0173] In some embodiments, temperature swing information is provided in a user interface as shown in FIG. 21. In some embodiments, temperature swing statistics are provided in a user interface as shown in FIG. 22.

[0174] In some embodiments, air filter cleanliness information is provided in a user interface as shown in FIG. 6. The interfaced reflects determination of the HVAC Operational Time. In this case, the relevant time is when the Air Handler runs whether or not heating or cooling is happening. The air filter collects more dirt when the air is flowing through it, and it does not matter if the system is actively heating or cooling the house.

[0175] It is desirable for the level of cleanliness reported to be within 20% of the actual state. Assuming the operational time model is correct, this means that the HVAC Operational Time should be within roughly 15% of the actual value. (Note that the nonlinear nature of the equation magnifies the impact of errors near the end of the filter’s anticipated life. Here we use 40000 minutes to determine the error bound.)

[0176] In some embodiments, the following are implemented:

- If HVAC Operational Time Error Bound $< (15\%$ of average daily HVAC Operational Time), no changes to the screen are suggested.

- If $(15\% \text{ of average daily HVAC Operational time}) < \text{HVAC Operational Time Error Bound} < (25\% \text{ of average daily HVAC Operational time})$, reduce the granularity of the display (e.g., reducing the number of “dots” in the air filter that indicate its dirtiness level).
- If $\text{HVAC Operational Time Error Bound} > (25\% \text{ of average daily HVAC Operational Time})$, consider two possible adjustments:
 - Adjust algorithm to weight calendar time more heavily than operational time in computing the level of dirtiness.
 - Remove the sub-heading item about changes week to week in amount of dirtiness that week.

Reporting HVAC Effectiveness.

[0177] Some embodiments provide information regarding HVAC effectiveness. In the following description, values used include HERheat[ci], HERcool[ci], TRRheat[ci], and TRRcool[ci] for each HVAC cycle ci. These values may be computed on a hub device based on data collected by one or more sensor node devices.

[0178] In the case of HER values, this is an inverse slope measurement on the temperature trend measured by a given sensor node during the portion of the HVAC cycle when the system is On (either heating or cooling). The units for HER may be minutes per degree Celsius, although other units may be used in other embodiments.

[0179] In the case of TRR values, this is an inverse slope measurement on the temperature trend measured by a given sensor node during the portion of the HVAC cycle when the system is Off (either heating or cooling). The units for TRR may be minutes per degree Celsius, although other units may be used in other embodiments.

[0180] This following describes the calculations used in presenting data regarding HVAC effectiveness in a user interface.

[0181] The methods detailed below for computing HVAC Effectiveness, Heating Effectiveness, Cooling Effectiveness, Temperature Retention and Temperature Swings all have an implicit perspective. Each sensor node offers a different observation point, a different perspective, on those parameters. This is perhaps easiest to understand with temperature swings that vary from room to room because, in part, the Temperature Retention varies room to room. But the system-level HVAC Effectiveness also varies room to room because, in part, the venting and air flow is different in each room. Some embodiments present to the user the median of all the calculated effectiveness ratings for the home. Some embodiments present to the user the worst calculated effectiveness ratings for the home.

[0182] Data used in determining HVAC effectiveness may be calculated using a method such as the following. The following steps may be repeated.

- On the completion of every HVAC On Cycle, an HVAC Effectiveness Rate (HER) is calculated and stored for either heating or cooling depending on which mode the HVAC is operating.
- On the completion of every HVAC Off Cycle the Thermal Retention Rate is calculated and stored for either heating or cooling depending on whether the outdoor temperature is greater than or less than the indoor temperature. In the case that an HVAC Off Cycle lasts for more than a threshold amount of time (e.g. two hours), the Thermal Retention Rate may also be calculated and stored. Note that in many of those cases, the TRR will be greater than 60.

[0183] The table below gives descriptions for a method for calculated HER's and TRR's using single point temperature values at the edges of an HVAC On or Off cycle respectively.

[0184] In some embodiments, a more refined estimation method of the HER's and TRR's may be performed. For example, the method may include taking the slope of a spline fit or using a smoothed derivative function, exponential decay function or something similar. A hub device may perform the calculation along with determining whether the cycle is heating or cooling and then send those results to a cloud service for processing.

[0185] In some embodiments, in cases for which HER's and/or TRR's are difficult to estimate/measure, the hub device may report such difficulty to the cloud service. The cloud service may ignore those data points in providing the user interface display.

[0186] In some embodiments, an initial determination is made of whether the HVAC is in an "on" state or an "off" state based on, for example, sounds detected (or not detected) by a sensor node, and a subsequent determination is made of whether the HVAC is heating or cooling (or merely circulating air) based on a change (or lack of change) in temperature detected by the sensor node during the "on" state. Example parameters used to present information are listed in the following table.

Symbol	Parameter	Description
cst	The "cycle start time" of the HVAC or Thermal event in question.	The time when the HVAC began an On or Off cycle.
cet	The "cycle end time" of the HVAC or Thermal event in question.	The time when the HVAC ended an On or Off cycle.
T_s	The starting indoor temperature when the cycle began (at cst).	The indoor temperature at time cst.

T_e	The ending indoor temperature when the cycle ended (at cet)	The indoor temperature at time cet.
ci	An internal index counter ("cycle index") that increments for every cycle that is stored in the database for processing later.	A basic cycle index to aid in algorithm description here. This particular variable is not explicitly required and other implementations are possible (such as a timestamp index).
HER_{heat}	The HVAC Effectiveness Rate in a heating cycle. Units are minutes/ $^{\circ}C$.	For the HVAC On heating cycle of interest, this is the time it took to raise the indoor temperature by $1^{\circ}C$. It is calculated as $(cet - cst)/abs(T_e - T_s)$. Units are minutes/ $^{\circ}C$.
$HER_{heat}[ci]$	The HER_{heat} for cycle ci.	The HER_{heat} for cycle ci.
HER_{cool}	The HVAC Effectiveness Rate in a cooling cycle. Units are minutes/ $^{\circ}C$.	For the HVAC On cooling cycle of interest, this is the time it took to lower the indoor temperature by $1^{\circ}C$. It is calculated as $(cet - cst)/abs(T_e - T_s)$. Units are minutes/ $^{\circ}C$.
$HER_{cool}[ci]$	The HER_{cool} for cycle ci.	The HER_{cool} for cycle ci.
TRR_{heat}	The Thermal Retention Rate when the HVAC is nominally in a heating mode. Units are minutes/ $^{\circ}C$.	For the HVAC Off heating cycle of interest, this is the time it took for the indoor temperature to fall by $1^{\circ}C$. It is calculated as $(cet - cst)/abs(T_e - T_s)$. Units are minutes/ $^{\circ}C$.
$TRR_{heat}[ci]$	The TRR_{heat} for cycle ci.	The TRR_{heat} for cycle ci.
TRR_{cool}	The Thermal Retention Rate when the HVAC is nominally in a cooling mode. Units are minutes/ $^{\circ}C$.	For the HVAC Off heating cycle of interest, this is the time it took for the indoor temperature to rise by $1^{\circ}C$. It is calculated as $(cet - cst)/abs(T_e - T_s)$. Units are minutes/ $^{\circ}C$.
$TRR_{cool}[ci]$	The TRR_{cool} for cycle ci.	The TRR_{cool} for cycle ci.
$P5(.)$	A percentile operator which selects the value which is greater than 5% of the list of candidate values.	A percentile operator which selects the value which is greater than 5% of the list of candidate values. This is used as a more robust form of the min or minimum operator.
$P95(.)$	A percentile operator which selects the value which is greater than 95% of the list of candidate values.	A percentile operator which selects the value which is greater than 95% of the list of candidate values. This is used as a more robust form of the max or maximum operator.

[0187] In some embodiments, heating effectiveness information is provided in a user interface as shown in FIG. 11. Elements used for this display are given in the following table.

Item	How to Calculate
Average (Median) HVAC Runtime for 1° Heating	$median(HER_{heat}[ci]$ for all ci in the 30 day interval of interest)
Minimum HVAC Runtime for 1° Heating	$P5(HER_{heat}[ci]$ for all ci in the 30 day interval of interest)
Maximum HVAC Runtime for 1° Heating	$P95(HER_{heat}[ci]$ for all ci in the 30 day interval of interest)

[0188] In some embodiments, heating effectiveness information is provided in a user interface as shown in FIG. 12. This is plot of the entire list of $HER_{heat}[ci]$ values for the time interval of interest (e.g., last 30 days). The statistic values shown were described above, except for the “Total runtime cycles” which is a count of the $HER_{heat}[ci]$ entries plotted.

[0189] In some embodiments, heating effectiveness information is provided in a user interface as shown in FIG. 13. This is a plot of the median($HER_{heat}[ci]$) for each month over the interval of interest (e.g., the last 12 months).

[0190] In some embodiments, cooling effectiveness information is provided in a user interface as shown in FIG. 14. Elements used for this display are given in the following table.

Item	How to Calculate
Average (Median) HVAC Runtime for 1° Cooling	median($HER_{cool}[ci]$ for all ci in the 30 day interval of interest)
Minimum HVAC Runtime for 1° Cooling	P5($HER_{cool}[ci]$ for all ci in the 30 day interval of interest)
Maximum HVAC Runtime for 1° Cooling	P95($HER_{cool}[ci]$ for all ci in the 30 day interval of interest)

[0191] In some embodiments, cooling effectiveness information is provided in a user interface as shown in FIG. 15. This is plot of the entire list of $HER_{cool}[ci]$ values for the time interval of interest (e.g., last 30 days). The statistic values shown were defined in the prior section except for the “Total runtime cycles” which is a count of the $HER_{cool}[ci]$ entries plotted.

[0192] In some embodiments, cooling effectiveness information is provided in a user interface as shown in FIG. 16. This is a plot of the median($HER_{cool}[ci]$) for each month over the interval of interest (e.g., the last 12 months). The gap in the plot is because during the winter months there were no HVAC cooling cycles.

[0193] In some embodiments, temperature retention information is provided in a user interface as shown in FIG. 17. Parameters used for this display are described in the following table.

Item	How to Calculate
Average (Median) time for 1° Change (when HVAC Off)	median($TRR_{cool}[ci]$, $TRR_{heat}[ci]$, for all ci in the 30 day interval of interest)
Minimum time for 1° Change (when HVAC Off)	P5($TRR_{cool}[ci]$, $TRR_{heat}[ci]$ for all ci in the 30 day interval of interest)

[0194] Note that there is no maximum time shown on the summary since it will often be off scale.

[0195] In some embodiments, temperature retention information is provided in a user interface as shown in FIG. 18A. This is plot of the box and whiskers processing of the entire list of $TRR_{cool}[ci]$ and $TRR_{heat}[ci]$ values for the time interval of interest (e.g., last 30 days). Note that for the plot, the calculations for heating and cooling are separated into the orange and blue lines respectively. Also note that they are plotted against the outside temperature applicable for each cycle of interest.

[0196] In this example there is a separate plot for Daytime and Nighttime. In the example figure above, the selection is indicated in the upper right as a Daytime plot. There are two reasons Daytime and Nighttime are shown in different plots. First, users tend to configure their home differently at nighttime by, for example, closing the blinds or drapes. This changes the thermal retention properties of the home. Second, sunlight can affect the apparent thermal retention during certain hours of the daytime but, of course, nighttime by definition has no sunlight.

[0197] In some embodiments, the sunrise and sunset times noted in weather data (which may be retrieved over a network) is used to separate Daytime and Nighttime for the calculations. Cases where the HVAC Off duration spans the boundary between Day and Night by less than 1 hour (or some other predefined duration) may be put in the category it was in longest. For example, if a given HVAC Off cycle spent 50% of its time or more in Daytime, put it in Daytime; otherwise put it in Nighttime. For cases, when the HVAC Off duration extend more than 1 hour in both categories, count it in both categories and count this for internal purposes.

[0198] The Box and Whiskers Figure Element of FIG. 18A may be understood as follows, with reference to FIG. 18B. FIG. 18B illustrates a graphical display element 1750 used to display results in some embodiments. In some embodiments, upper whisker 1752 illustrates 95th percentile value, upper box edge 1754 illustrates an upper quartile value, band 1756 illustrates a median value, lower box edge 1758 illustrates a lower quartile value, and lower whisker 1760 illustrates a 5th percentile value. Different percentile values may be used in different embodiments, and different graphical display elements may be used in different embodiments. The figure element values may be used as described in the following table. (The cooling case is described explicitly; the heating case follows the same process but uses the $TRR_{heat}[ci]$ values instead of the $TRR_{cool}[ci]$ values.)

Element	Formula	Comment
Lower Whisker	$P5(TRR_{cool}[ci])$ for all ci in the 30 day range of interest where the outdoor temperature is in range for this element)	The 5th percentile value is used here rather than minimum to screen out potential outliers.
Lower Quartile	$P25(TRR_{cool}[ci])$ for all ci in the 30 day range of interest where the outdoor temperature is in range for this element)	25% of the TRR values are less than this.
Median	$P50(TRR_{cool}[ci])$ for all ci in the 30 day range of interest where the outdoor temperature is in range for this element)	Median of the TRR values.
Upper Quartile	$P75(TRR_{cool}[ci])$ for all ci in the 30 day range of interest where the outdoor temperature is in range for this element)	75% of the TRR values are less than this.
Upper Whisker	$P95(TRR_{cool}[ci])$ for all ci in the 30 day range of interest where the outdoor temperature is in range for this element)	The 95th percentile value is used here rather than maximum to screen out potential outliers.

[0199] In the Temperature Retention plot of FIG. 18A, the lower values are nearer the bottom of the plot and the upper values are nearer the top. The temperature range for each Box and Whiskers computation is 2.5°. In some embodiments, even where calculations are performed using e.g. Celsius units, the display may be in Fahrenheit units to accommodate user preferences or local conventions.

[0200] In some embodiments, when an HVAC Off cycle crosses the boundary from one outdoor temperature range into another, it may be split for the purposes of this graph. The TRR may be calculated for each outdoor temperature range separately.

[0201] In some embodiments, room-by-room temperature retention information is provided in a user interface as shown in FIG. 19. What is shown for each sensor node in figure is the Average (Median) Temperature Retention time for that room for the period covered in the graph of FIG. 18A.

[0202] In some embodiments, temperature retention statistics are provided in a user interface as shown in FIG. 20. In some embodiments, the $TRR_{cool}[ci]$ and $TRR_{heat}[ci]$ are considered together, as one bundle when analyzing the stats. Losing 1 degree C in 10 minutes in the winter is bundled in with gaining 1 degree C in 10 minutes in the summer.

[0203] In some embodiments, temperature swing information is provided in a user interface as shown in FIG. 21. For the period shown, the following guidelines may be used:

- The minimum temperature shown for each day is the lowest indoor temperature detected by any sensor node in the house that day.

- The maximum temperature shown for each day is the highest indoor temperature detected by any sensor node in the house that day.
- Given the above, the full temperature swing of the house for each day goes from the lowest temperature measured by any sensor node in the house that day to the highest temperature measured by any sensor node in the house that day. The lowest and highest temperatures for a particular day may not be from the same sensor node.

[0204] In some embodiments, temperature swing information is provided in a user interface as shown in FIG. 22. In contrast with the summary Temperature Swing chart of FIG. 21, for the statistics here, each sensor node is considered separately. The “Biggest swing” entry is identifying the sensor node that experiences the greatest swing in temperature (e.g. from low to high) during the day.

Expansion of HVAC Monitoring Methods.

[0205] Described herein is an example method of modeling the system across multiple zones. While most smaller homes have just one HVAC system, it is relatively common for larger homes to have more than one HVAC system. Furthermore, some apartments use room-based PTACs (packaged terminal air conditioners) which effectively make them multi-zone residences. Example embodiments account for multi-zone operation.

[0206] In the development of a thermal model of the home there are multiple choices to be made regarding the structure and the type of model to be used. One approach is a physical model that is directly based on first principles from heat transfer. Such a model uses known thermal conductivity values that describe the building in which the sensor nodes are placed. Another approach is black-box model which utilizes the data to train a neural network to model the thermal properties of the house. A black-box model maybe accurate but it is difficult to interpret it to find the values of interest. A physical model requires information about the environment that may not be available, and thus using it would thus require many assumptions. Example embodiments use a hybrid approach which may be described as a grey-box model. A grey-box thermal model combines information about the system from physics with system identification methods to model the system accurately while preserving the meaning of the data. The details of an example model used in some embodiments are given below.

[0207] An example analysis uses an analogy between heat and charge to create an electric circuit that models the flow of heat with in a multizone building. In this model, each zone is modeled as a capacitor connected to ground. The flow of heat between zones is modeled as the flow of charge from one zone to another through a resistor. The flow of heat into the building due to energy from the sun and temperature

difference with the outdoors is modeled using a voltage source and a current source that are connected to the zones through resistors as well.

[0208] Node analysis gives the equation below for the temperature in a given zone:

$$\frac{dT_1}{dt} = \begin{cases} k_{n1}(T_n - T_1) + k_{(n-1)1}(T_{n-1} - T_1) + \dots + k_{21}(T_2 - T_1) & HVAC\ Off \\ k_{n1}(T_n - T_1) + k_{(n-1)1}(T_{n-1} - T_1) + \dots + k_{21}(T_2 - T_1) + \frac{dQ_1}{dt} & HVAC\ On \end{cases}$$

[0209] At any moment in time, the multizone building will be in one of four states given below. In each of these states we will perform calculations and store the results to be used in the other states. Since this the states some states depend on data from other states, full calculations may be performed after the building has gone through all states which should take at most a full day.

1. HVAC OFF, SUN OFF:
 1. During this state the System has no energy input and so the k values can be determined.
 2. This yields a system of n equations, one for each zone. To calculate the values of interest we solve the system of equations described above. During a period of time there will be many measurements and statistical methods can be used to aggregate the data.
2. HVAC ON, SUN OFF
 1. During this state the k values stored can be used to solve for the HVAC output for a given zone.
3. HVAC OFF, SUN ON
 1. During this state the k values stored can be used to solve for the Sun Input for a given zone.
4. HVAC ON, SUN ON
 1. During this state the HVAC Input into the system can be calculated using stored k values and stored sun input values.

[0210] The K Values will be the thermal will be the product of the thermal conductivity of the wall between two zones and 1/C, where C is the thermal capacitance of the zone.

[0211] In some embodiments, the following assumptions may be used:

- Sun Radiation Energy does not vary greatly over 15 min periods.
- K Values do not vary greatly during daytime

[0212] In some embodiments, Thermal Conductivity K values are found using previous data. Each sensor node may be treated as a zone. In some embodiments, no assumptions about the relationship of the zones to each other are made. The Outside Environment is treated as a zone.

[0213] Such embodiments generalize more easily rather than a hardcoded estimate of k values. Such embodiments update to reflect variations in thermal resistivity values due to weather conditions. Example

embodiments operate to provide useful information without requiring information on the relative locations of the sensor nodes. It may be assumed that all zones are adjacent, such that dT/dt for each zone in an n -zone home may be assumed to be the sum.

Thermal Model, First Order Approximation.

[0214] An example of thermodynamic method used to model the change in temperature over time as the HVAC system turns on and off is described here.

[0215] In some embodiments, it may be assumed that the only q source is from the HVAC system. Sources such as solar, human presence and other heating/cooling sources are absorbed into k . The single zone thermal model gives

$$dT/dt = k(t) (T_o - T_i) + q(t)$$

where T_i is the indoor temperature, T_o is the outdoor temperature, and q is the rate of heat added/removed by the HVAC system.

[0216] Performing a Taylor expansion,

$$T_i(t) = T_i(t = t_o) + T_i'(t - t_o) + \text{higher-order terms}$$

$$T_o(t) = T_o(t = t_o) + T_o'(t - t_o) + \text{higher-order terms}$$

Giving

$$dT(t)/dt = T' = k(T_o(t = t_o) + T_o'(t - t_o) - T_i(t = t_o) - T_i'(t - t_o)) + q(t) + \text{higher-order terms}$$

In the limit of $T_o'(t - t_o) \ll T_o(t = t_o)$ and $T_i'(t - t_o) \ll T_i(t = t_o)$, we can further approximate with:

$$T_i' = k(T_o(t = t_o) - T_i(t = t_o)) + q(t) + \text{higher-order terms}$$

With

$$T_i' = (T_i(t = t_1) - T_i(t = t_o)) / (t_1 - t_o)$$

[0217] The equation for T_o illustrates the time dependence. It may be used in some embodiments to get a more accurate measurement of the terms if needed. In some embodiments, the higher-order terms may be ignored.

[0218] With the HVAC system off,

$$k = (T_i(t = t_1) - T_i(t = t_o)) / [(t_1 - t_o) * (T_o(t = t_o) - T_i(t = t_o))]$$

where k is a function of time. The value k may be calculated for every x minutes.

[0219] For the following HVAC cycle, it may be assumed that k is constant for the HVAC cycle. Example embodiments take k as the peak of the distribution from the last cycle (If the cycles are very short, the average can be taken instead since a peak in a small sample size has less significance).

[0220] With the HVAC system on,

$$q = (T_i(t = t_1) - T_i(t = t_0)) / (t_1 - t_0) - k_{\text{peak from last cycle}} (T_o(t = t_0) - T_i(t = t_0))$$

[0221] The q is the rate of heat added/removed with the HVAC system. This can be calculated every x minutes to produce a distribution.

[0222] The distribution of k and q may be provided to a user, for example as a plot. The value q may be referred to as "Rate of heating/cooling" and k as "Rate of energy lost to environment."

Example System Hardware.

[0223] FIG. 23 schematically illustrates network topology used in some embodiments. One or more sensor nodes 3602a-c may be disposed in a residence, e.g. in different rooms. Each node may be plugged in to an electrical outlet. The sensor nodes are in wireless communication with a hub node 3604, e.g. using a WiFi connection or other local area network. The hub node 3604 may further have a connection to a wide-area network 3606 such as the internet through which a networked service 3608 running on one or more servers, such as a cloud service, may be accessed. Users may have personal devices such as a computer 3610 or mobile computing device 3612 that can also access the networked service 3608 over the network 3606. In some embodiments, the user interfaces described herein are displayed when the user accesses the networked service on their personal device. In some embodiments, the user's personal devices may be capable of communicating directly with the hub node 3604 and/or with the sensor nodes 3602a-c to view the user interfaces or to exchange other information. In some embodiments, the sensor nodes 3602a-c may be capable of communicating over the network 3606 without the intermediation of the hub node (e.g. through a router).

[0224] In example embodiments, as shown in FIG. 24, the sensor node includes a temperature sensor 418 in communication (e.g. over a bus or other internal connection) with a processor 2408. The temperature sensor is used in collecting the temperature measurements described herein. The sensor node may also include sensors that operate to assist in determining whether the HVAC system is in an "on" or an "off" state. For example, the sensor node may include a microphone 2402 that collects audio data that may be used in determining whether the HVAC system is in operation. In some embodiments, audio data is provided to the hub node to interpret the audio data of one or more sensor nodes to determine whether the HVAC system is in

operation. The sensor node may further include power monitoring circuitry 2424. Such circuitry may detect changes in power supply voltage that may be characteristic of the HVAC system being active or inactive, or changing states between active and inactive. The sensor node further includes a memory 2406, which may include a non-transitory memory. The memory may store collected data (e.g. temperature and audio data). The memory may further store instructions that are executable by the processor for causing the processor to perform any of the methods described herein. A network interface 2410 may be provided to allow for communication with hub devices, other sensor nodes, or other equipment.

[0225] The hub node likewise includes a memory, which may include a non-transitory memory, a processor, and one or more network interfaces for connection (e.g. a wireless connection) with the sensor nodes and with the internet (possibly through a router). The memory may store collected data (e.g. temperature and audio data) received from one or more sensor nodes. The memory may further store instructions that are executable by the processor for causing the processor to perform any of the methods described herein.

[0226] Any feature described herein as a module may be implemented with structures including, but not limited to, one or more processors and at least one storage medium (e.g. a non-transitory storage medium) storing instructions that are operative, when executed on the one or more processors, to perform any functions associated with the module. Such a module may further include any appropriate environmental sensors (e.g. a thermometer, hygrometer, microphone) or input or output devices (e.g. screens, keyboards, network interfaces) used to implement the functions associated with the module. In some embodiments, computing operations may be implemented by circuitry other than a processor, such as by a field-programmable gate array (FPGA) or other logic circuitry. The componentry used to implement a module may in some embodiments be distributed among different physical devices that communicate with one another to perform the associated functions.

Example heating/cooling monitoring systems and methods.

[0227] Example systems and methods perform HVAC monitoring to monitor the health of an HVAC system. HVAC systems are designed to heat, cool, and move air. Examples of HVAC components as the term is used herein include a furnace, air conditioner, heat pump, portable air conditioner, window units, and the like. In general, an HVAC system operates by blowing hot or cold air into the room. The HVAC turns on and off to control the temperature of the room. The thermostat sets when to turn off/on the HVAC based on the temperature of the thermostat. HVAC performance may be measured by reference to how quickly it can increase/decrease the temperature of the room. As the HVAC deteriorates, it takes longer to heat/cool the room. In the worst case, it won't affect the room temperature at all. Example causes of deterioration include a coolant leak, dirty condenser, dirty filter, clogged blowers, and broken motors.

[0228] FIGs. 25 and 26 provide schematic overviews of HVAC monitoring according to some embodiments. In some embodiments, as shown in FIG. 25, an HVAC AI classifier is implemented at a dwelling, while HVAC system analysis is performed by a cloud service. However, example embodiments are not limited to such an arrangement. FIG. 26 schematically illustrates a flow diagram of an overall HVAC monitoring process that may be implemented in some embodiments.

[0229] In some embodiments, an adaptive late sensor fusion (LSF) algorithm is implemented. The Adaptive LSF algorithm may be implemented as a plug-in to a probabilistic event finder. As described herein, an event finder adapter may be used with the probabilistic event finder to obtain adaptive thresholds instead of fixed thresholds. The embodiments described herein may be used for any type of time series data. However, example embodiments are described here with reference to the example of temperature data as applied to HVAC monitoring.

[0230] In some embodiments, an event finder adapter provides a learning operation, an adapting operation, and a use operation. In some embodiments, in the learning operation, at the end of each HVAC cycle, the derivative of the second-degree polynomial fitted on the temperature data is used to determine the rate of heating or cooling. The cycle may be categorized in one of the following buffers:

- If the HVAC was off, the slope is positive, and the outdoor temperature was greater than 27C: Add the slope to the 'up and off' buffer.
- If the HVAC was on, the slope is negative, and the outdoor temperature was greater than 15C: Add the slope to the 'down and on' buffer.
- If the HVAC was on, the slope is positive, and the outdoor temperature was smaller than 27C: Add the slope to the 'up and on' buffer.
- If the HVAC was off, the slope is negative, and the outdoor temperature was smaller than 15C: Add the slope to the 'down and off' buffer.

[0231] In the adapting operation, at the end of each HVAC cycle, the system adapts to the new information that was added in the learn phase. In some embodiments, for each of the four buffers (up/down and on/off combinations), for all sensors, the 95th percentile of the buffer is determined. These four values per sensor are stored as thresholds.

[0232] In the use operation, when the HVAC LSF is called, the slope of the temperature data is determined for each sensor. If there are at least 200 values in the 'up' or 'down' buffer, depending on the slope that was found, the threshold found in the adapt phase is used. Otherwise, a default, hardcoded value of 75 minutes per degree Celsius is used as a threshold. The LSF is performed using the appropriate threshold.

[0233] As described above, a method according to some embodiments, for each of a plurality of cycles of an HVAC system, data is obtained representing a measured rate of indoor temperature change during the cycle and an outdoor temperature during the cycle. Each of a plurality of the cycles is classified in one of a plurality of predetermined cycle categories, based at least in part on the associated measured rate and the outdoor temperature. The categories may include some or all of the categories “up and off,” “down and on,” “up and on,” and “down and off” as described above, although the categories may differ in different embodiments. For at least one of the categories, a report is provided regarding statistics of the cycles in the reported category.

[0234] In some embodiments, the report provides an indication of an average time per temperature change for the cycles in the reported category, though other statistics may alternatively be used such as the median, mode, or some other value.

[0235] In some embodiments, the classifying of the cycles is further based at least in part on a threshold rate of temperature change. In some embodiments, the threshold rate of temperature change for each category is adjusted based at least in part on cycles previously classified in the respective category.

[0236] Some embodiments further categorize the cycles based on a separate determination of whether the HVAC system is on or off. Such a determination may be made based, for example, on a neural network classifier operating on audio information received by a sensor node. In some embodiments, a cycle may be classified as “up and on” or “down and on” only in response to a determination that the HVAC system is on, and the cycle may be classified as “up and off” or “down and off” only in response to a determination that the HVAC system is off.

[0237] In some embodiments, a change (e.g. a fault) in heating performance may be detected based on a change in statistics of cycles in the “up and on” category. In some embodiments, a change (e.g. a fault) in cooling performance may be detected based on a change in statistics of cycles in the “down and on” category. In some embodiments, a change (e.g. a fault) in insulation performance may be detected based on a change in statistics of cycles in the “up and off” and/or the “down and off” categories.

[0238] In some embodiments, HVAC analysis is performed as follows. For each HVAC cycle, the hub node, calculates the HER values for each individual sensor. The HER values are stored on a cloud database. A histogram of the HER data is generated. On the cloud, analysis is performed to generate an overlay that removes statistical noise. Using the overlay, a calculation is made of the typical (mode) and average HER value.

[0239] In some embodiments, HER calculations may be performed as follows. HER values are calculated for each sensor individually. A smoothing function may be applied that results in linearized temperature segments (same function as the LSF). A determination is made of whether the cycle is a heating or cooling cycle. (As the

air handler can be on longer than the actual cooling or heating event, there is sometimes ambiguity.) This may be done as follows: over the HVAC cycle duration, calculate the duration where the linearized temperature is increasing and the duration where it is decreasing; if it spends more time increasing in temperature, it is considered it a heating cycle. If it spends more time decreasing in temperature, it is considered a cooling cycle. If the change in the smoothed temperature is $< 0.14^{\circ}\text{C}$, or the slope is less than $1^{\circ}\text{C}/\text{hour}$, the state may be considered unsure. In some embodiments, a threshold temperature is used that is based at least in part on an indoor temperature. For example, a cycle may be considered a cooling event only when the outdoor temperature is greater than the indoor temperature. It may be considered a heating event only when the outdoor temperature is less than the indoor temperature. In other embodiments, the threshold temperatures may be independent of the indoor temperature.

[0240] Using methods as described above, a method according to some embodiments includes, for each of a plurality of cycles of an HVAC system, obtaining data representing a measured rate of indoor temperature change during the cycle and an outdoor temperature during the cycle. Each of a plurality of the cycles is classified in one of a plurality of predetermined cycle categories. The classification is based at least in part on the associated measured rate and on the outdoor temperature. Some cycles may not be classified in any category (e.g. because of ambiguous or corrupted data or because some categories may not be of interest in some embodiments). For at least one of the categories, a report is provided as described herein regarding statistics of the cycles in the reported category. The report may indicate, for example, an indication of an average time per temperature change (e.g. minutes per $^{\circ}\text{C}$) for the cycles in the reported category.

[0241] In some cases, the classifying of the cycles is further based at least in part on a threshold rate of temperature change, and in some such embodiments, the threshold rate of temperature change for each category is adjusted based at least in part on cycles previously classified in the respective category.

[0242] In some embodiments, the categories are as follows: a first category in which the rate of indoor temperature change is positive and the outdoor temperature is above a first threshold temperature (e.g. 27°C); a second category in which the rate of indoor temperature change is negative and the outdoor temperature is above a second threshold temperature (e.g. 15°C); a third category in which the rate of indoor temperature change is positive and the outdoor temperature is below a third threshold temperature (e.g. 27°C); and a fourth category in which the rate of indoor temperature change is negative and the outdoor temperature is below a fourth threshold temperature (e.g. 15°C). Not all categories may be used in all embodiments, and different criteria may also be used as an alternative or in addition to the criteria described here.

[0243] In some embodiments, a cycle is classified in the first or fourth category only in response to a determination that the HVAC system is off during the respective cycle. Such a determination may be made

using a classifier operating on audio data, for example. In some embodiments, a cycle is classified in the second or third category only in response to a determination that the HVAC system is on during the respective cycle.

[0244] The threshold temperatures may be determined in various ways. For example, as in examples above, the first and third threshold temperatures may be the same, and the second and fourth threshold temperatures may be the same, but not all embodiments necessarily follow this constraint. In some embodiments, the threshold temperatures are based at least in part on an indoor temperature.

[0245] Some embodiments include detecting a change in heating performance based on a change in statistics of cycles in the third category. Some embodiments include detecting a change in cooling performance based on a change in statistics of cycles in the second category. Some embodiments include detecting a change in heat retention properties based on a change in statistics of cycles in the first and/or fourth categories.

[0246] Some embodiments include an apparatus comprising one or more processors configured to perform any of the methods described herein.

[0247] In some embodiments, overlay calculations are performed. The goal of the overlay is to summarize the HER statistics with a minimal number of variables. The model may be based on a steady state heating/cooling and random heating cooling. The model has been found to map to Brownian motion with an inverse gaussian distribution. An example overlay calculation uses two variables and is based on the average and variance of the data. This mathematical model has been found to match real life and simulation data.

[0248] Examples of sensor node data are shown in FIGs. 27A-27B. The overlay is calculated for each individual room and uses 200 entries in this embodiment for a statistically significant sample size. The lower 95% of the data may be selected to calculate the parameters to account for false positives. Parameters of the overlay are calculated by:

$$\mu = \text{mean of the HER values}$$

$$\lambda = \frac{\mu^3}{\text{variance of the HER values}}$$

[0249] Statistical analysis may be performed with scaling for different rooms. The temperature swings at different sensor nodes may vary throughout the house, depending for example on the distance to a vent, the size of the room, and obstacles such as furniture. The temperature rate of change is relative, but when rescaled, they have been found to have similar statistical profiles.

[0250] FIG. 27A illustrates histograms of data from two rooms, Room 1 and Room 2, each of which is fitted with a respective inverse Gaussian. FIG. 27B illustrates a histogram in which the data from Room 2 has been scaled to align with the data of Room 1, resulting in substantially similar distributions and largely overlapping inverse Gaussian curves.

[0251] Some example embodiments of statistical scaling use scaling factors. Each sensor node may have a scaling factor associated with it to account for the variation in temperature swings throughout the house. A learning period may be used that consists of reaching 200 entries. Rooms with lower temperature swings typically report fewer entries as they are more likely to trigger the “unsure” threshold. In some embodiments, the first sensor node that reaches 200 entries (or other threshold as appropriate) is labelled as the reference node and given a scaling factor of 1. If multiple nodes reach the threshold at the same time, one of them may be chosen arbitrarily to be the reference sensor node. When subsequent sensor nodes reach the 200 entries threshold, the scaling factor is applied to the data for those nodes. Overlay parameters may be calculated. The time period where the subsequent sensor had entries may be used to account for later installed sensor nodes. The scaling factor of the i th sensor node may be calculated by: $s_i = mode_{i-ref} / mode_i$

[0252] Example embodiments allow for multiple nodes in a single histogram. With multiple sensor nodes throughout a house, each may have its own statistical distribution with different modes and means. Some embodiments operate to combine them together to generate a single histogram. Example embodiments scale the HER values, $s_HER_{i,j}$, where: $s_HER_{i,j} = s_i * HER_{i,j}$ where s_i is the scaling factors. All these terms are combined together to form one total binned histogram, $total_HER$ that combines and counts all individual scaled $s_HER_{i,j}$ values that fit into their relevant bins.

[0253] Some embodiments analyze the last N cycles (e.g. the last 200 cycles). The performance chart may show the histogram of all the cycles recorded in the last 12 months and may also include a plot of only the last 200 cycles. The typical (mode) HER value may likewise be calculated for all cycles from the last 12 months as well as only the last 200 cycles. A comparison between the typical (mode) HER values shows possible changes in recent behavior of the HVAC effectiveness. Changes in the recent HVAC effectiveness may be due to different weather conditions, thermostat setting changes or changes in the HVAC system. If the outdoor temperature has been stable, increased amount of time for the typical performance could be due HVAC degradation, and an alert may be provided.

[0254] Example embodiments provide for the display of historical trends, as shown in FIGs. 28-29. Using the entries within a calendar month, if there are over 200 HVAC cycles, an example embodiment calculates the overlay and corresponding mean and modes. The mean and modes are plotted as a function of time, along

with the outdoor temperature. This allows for comparison over time. It also enables monitoring over multiple seasons.

[0255] In some embodiments, historical trends are calculated as follows. At a regular interval (e.g. each day at midnight), the performance histogram is updated as follows. The overlay is calculated for the last 200 cycles. A database is used to store the results of the overlay, e.g. the typical (peak) value, the mean value, and the number of days for the previous 200 cycles. The minimum/maximum for the performance is calculated from the list of stored typical overlays stored in the database. Add to the historical trend daily. The darkness of the color for the trend-line changes depending on the number of days required to measure the 200 past cycles. For example, the darkest shade may be used when the number of days for the past 200 cycles is less than 20, the lightest shade may be used when the number of days is 80, and results with greater than 80 days are not shown.

[0256] In some embodiments, performance is shown with needle gauges as shown in FIG. 30. On an overview page, needle gauges may be used as a quick summary of the HVAC performance for both heating and cooling. The scaling may be set by the historical HVAC performance, where the “12 o’clock” position is the typical performance over the last 12 months. The needle then may be used to indicate the typical performance from the last 200 HVAC cycles.

[0257] Variables used for HVAC calculations in some embodiments are shown in the following table:

Variable	Definition
$HER_{i,j}$	The HVAC efficiency rate for the sensor node i for the j^{th} HVAC cycle
$mean_i$	The mean of HVAC efficiency rate for sensor node i .
var_i	The variance of HVAC efficiency rate for sensor node i .
$mode_i$	The mode of HVAC efficiency rate for sensor node i .
$i\text{-short}$	The sensor node with the smallest mode.
s_i	Scale factor for HE-fit _{i} so that the modes are equal.
$s_HER_{i,j}$	The scaled HVAC efficiency rate for sensor node i for the j^{th} HVAC cycle
N_i	The total number of HVAC events for the i^{th} sensor node
total_HER	The overall binned histogram formed by binning all the individual scaled histograms $s_HER_{i,j}$ together in one final binning array. This binned histogram counts all the $s_HER_{i,j}$ values that fit into a given bin.

[0258] To calculate a whole house HVAC efficiency, the array of $HER_{i,j}$ is rescaled to match the various sensor nodes. Each sensor node has been found to follow an Inverse Gaussian behavior, though different

distributions may be used in other embodiments. To get a whole-house display, some embodiments use the following procedure.

[0259] At least a threshold number, such as 200, of HER_{ij} terms are collected. The number of HVAC cycles vary for each sensor and some may reach this number before others. There may be multiple sensor nodes for a given zone, but the point of this display is to have a whole house or whole residence view that combines all the zones together. So any sensor node i which has more than 200 HER_{ij} terms may be included in that combination view. In some embodiments, if a particular sensor node i has less than 200 HER_{ij} terms, in some embodiments it is excluded from the summary histogram. In some embodiments, for the following steps, only the sensor nodes that satisfy this criterion are to be used.

[0260] The parameters μ_i , λ_i , $mode_i$, and β_i are calculated for each sensor node. This may be done for each sensor node i by using the following formulas applied to just the HER_{ij} terms for sensor node i :

$$\begin{aligned}\mu_i &= mean_i = \frac{1}{N_i} \sum_j (HER_{i,j}) \\ \lambda_i &= \mu_i^2 / var_i, \text{ where } var_i = \frac{1}{N_i} \sum_j (HER_{i,j} - \mu_i)^2 \\ mode_i &= \mu_i * \left[\left(1 + \frac{9\mu_i^2}{4\lambda_i^2} \right)^{1/2} - \frac{3\mu_i}{2\lambda_i} \right] \\ \beta_i &= N_i \times \left(\sum_t \sqrt{\frac{\lambda_i}{2\pi t^3}} \exp \left[\frac{-\lambda_i(t - \mu_i)^2}{2\mu_i^2 t} \right] \right)^{-1}\end{aligned}$$

[0261] The value $i-short$ may be determined, with: $i-short = \text{argmin over } i (mode_i)$. This amounts to picking the sensor node with the smallest mode or the one where the peak is furthest to the left on the chart.

[0262] Scale factors s_i are computed, where: $s_i = mode_{i-short} / mode_i$. Note that, by design, all s_i will be ≤ 1 . In some embodiments, the scale factor s_i not change with each view so that tracking is possible. Some embodiments set it based on the first 200 HER_{ij} terms for the past 12 months. This means that it is likely more efficient for this scale factor s_i to be pre-computed and then used for various histogram views.

[0263] The values s_HER_{ij} are calculated, where: $s_HER_{ij} = s_i * HER_{ij}$ and all of these terms are binned together to form one total binned histogram, total_HER that combines and counts all individual scaled s_HER_{ij} values that fit into their relevant bins. It is helpful to keep the individual s_HER_{ij} values in addition to the count because those scaled values are used to calculate the overlay formula.

[0264] The binned histogram total_HER is plotted, which now reflects the aggregated binned values of all the sensor nodes in the house with enough values to be counted.

[0265] The overlay function in some embodiments is given by the taking the sum of the Inverse Gaussian Functions for each sensor node i:

$$Overlay(t) = \sum_i \frac{1}{s_i} \times f(t/s_i, \beta_i, \mu_i, \lambda_i), \text{ where } f(t, \beta, \mu, \lambda) = \beta \sqrt{\frac{\lambda}{2\pi t^3}} \exp \left[\frac{-\lambda(t - \mu)^2}{2\mu^2 t} \right]$$

[0266] Peak and Average calculations are performed in some embodiments. The average is calculated by taking the mean of the scaled HER values.

$$Average = \frac{\sum_{i,j} s_{i,j} HER_{i,j}}{\sum_i N_i} = \frac{\sum_{i,j} s_i \times HER_{i,j}}{\sum_i N_i}$$

[0267] The peak is the value of t where it is most typical. Example embodiments determine this by finding the t_{peak} where it is the time corresponding to the peak value of the overlay.

$$t_{peak} \text{ where is such that } Overlay(t_{peak}) = Max(Overlay(t))$$

[0268] In some embodiments, the following values are used in calculating HVAC performance.

Variable	Definition
$HER_{x_{i,j}}$	The HVAC efficiency rate for the sensor node i for the j^{th} HVAC cycle. x is either heat or cool. For the below variables, we have $x_{...}$, where x is either heat or cool. The calculations may be performed the same way for either heating or cooling.
$timestamp_{x_{i,j}}$	The timestamp associated with the $HER_{x_{i,j}}$
$duration_{x_{i,j}}$	The duration of the cycle
x_{cycles}	The number of heating/cooling cycles
x_{i-ref}	The sensor node which we use to scale and calculate the number of cycles.
$x_{mean_i}(t_1, t_2)$	The mean of HVAC efficiency rate for sensor node i . This is calculated from $x_{HER_{i,j}}$ values with timestamps between t_1 and t_2 .
$x_{var_i}(t_1, t_2)$	The variance of HVAC efficiency rate for sensor node i . This is calculated from $x_{HER_{i,j}}$ values with timestamps between t_1 and t_2 .
$x_{mu_i}(t_1, t_2)$	The mu term used for the overlay. This is calculated from $x_{HER_{i,j}}$ values with timestamps between t_1 and t_2 .

$x_lambda_i(t_1, t_2)$	The lambda term used for the overlay. This is calculated from $x_HER_{i,j}$ values with timestamps between t_1 and t_2 .
$x_mode_i(t_1, t_2)$	The mode of HVAC efficiency rate for sensor node i . This is calculated from $x_HER_{i,j}$ values with timestamps between t_1 and t_2 .
x_s_i	Scale factor for HE-fit _i so that the modes are equal.
$x_s_HER_{i,j}$	The scaled HVAC efficiency rate for sensor node i for the j^{th} HVAC cycle
x_N_i	The total number of HVAC events for the i^{th} sensor node
x_t200_i	The timestamp that corresponds to x_N_i reaching 200 HER values.
x_total_HER	The overall binned histogram formed by binning all the individual scaled histograms $s_HER_{i,j}$ together in one final binning array. This binned histogram counts all the $s_HER_{i,j}$ values that fit into a given bin.
$timestart200$	The start time of the time window for 200 HVAC cycles.
x_i-freq	The i -th sensor node with the most number of heating/cooling HER events
$x_runtime$	The runtime of heating/cooling cycles.
$days_operation$	The number of days of operation

[0269] Days of heating/cooling operation may be calculated as follows. If there exists an HER value (either heating or cooling) for the day (24 hours), then $days_operation \neq 1$. Calculating the number of heating/cooling cycles may be performed as follows. We initially are learning to reach 200 cycles. In this stage, the number of heating/cooling cycles may be calculated as:

$heat_cycles = \text{Max}(\text{set of all } heat_N_i) \text{ for all sensor nodes}$

$cool_cycles = \text{Max}(\text{set of all } cool_N_i) \text{ for all sensor nodes}$

Once $N_i \geq 200$, we calculate the scaling parameters.

if $x_cycles == 200$ then: $x_i-ref = \text{argmin}(x_mode_i)$ for all i such that $N_i == 200$. For any instance where it is desirable to calculate the overlay parameter and no result is obtained (does not fit properly), that sensor may be ignored until it is able to obtain usable results.

Once x_i-ref is determined, it does not change and may be stored to be used indefinitely to scale HER values.

(Note, for systems where there is historical data before this algorithm started, it can be calculated as:

$x_i-ref = \text{argmin}(x_mode_i) \text{ for all } i \text{ such that } N_i \geq 200$)

[0270] Information regarding the heating/cooling cycles in the last n-number of days may be obtained as follows.

$x_cycles = \text{Max}(\text{Number of HER}_{x_{i,j}} \text{ for all } i \text{ where the time is within the last n-number of days})$

Total runtime of heating/cooling cycles in the last n-number of days

$x_i\text{-freq} = \text{argmax}(\text{Number of HER}_{x_{i,j}} \text{ for all } i \text{ where the time is within the last n-number of days})$

$x_runtime = \text{Sum}(\text{duration}_{x_i\text{-freq},j} \text{ for all } j \text{ within the last n-number of days})$

[0271] Plots for heating/cooling cycles may be determined as follows.

The heating and cooling performance plot is a histogram of the scaled HER values, $x_s_HER_{i,j}$.

The scaled HER values are calculated by:

$$x_s_HER_{i,j} = x_s_i * HER_{x_{i,j}}$$

[0272] The scaling factor x_s_i may be calculated using the following procedure. When a sensor node reaches 200 HER values, which means $N_i = 200$, the scaling factor for that sensor node, x_s_i may be calculated by the following steps:

1. When $x_N_i = 200$, that may be referred to as x_t200_i . Determine x_mode_i ($t1 = 0$, $t2 = x_t200_i$) for all $x_HER_{i,j}$ values where $x_timestamp_{i,j} < t200_i$
2. The $x_mode_{x_i\text{-ref}}$ ($t1 = 0$, $t2 = x_t200_i$) is determined, the mode of all the $x_HER_{i,j}$ values of the reference sensor node, $x_i\text{-ref}$, where the timestamp is $< t200_i$.
3. $x_s_i = x_mode_{x_i\text{-ref}} / x_mode_i$

[0273] The scaling factor, x_s_i , once determined, remains constant and may be stored for future use. In cases where the scaling factor, x_s_i , is not determined until $x_N_i > 200$, it is not necessary to plot a sensor node's HER values until it has recorded 200 HER values. The case of $t1 = 0$ implies that the time window begins from the very start. So in step 2, the mode is calculated using all the HER values prior to x_t200_i .

[0274] The heating/cooling performance for the last 200 cycles may be determined as follows.

1. Find the sensor node with the most number of HER events:
 1. $x_i\text{-freq} = \text{argmax}(x_N_i)$
2. Find the time window for the last 200 cycles. The start of the time window may be the timestamp of the 200th previous HER value of the sensor node with the most HER events.
 1. $timestamp200 = x_timestamp_{x_i\text{-freq}, (j_max - 200)}$, where j_max is the highest/most recent index
3. Only looking at HER values since $timestamp200$, determine the overlay parameters for each sensor nodes with ≥ 50 HER values. Only these sensor nodes may be plotted in the histogram.

4. Determine the overlay for the last 200 cycles with the overlay parameters in the previous step and the scaling factors (fixed, should not change) determined above.
5. Determine the peak/typical performance by finding the mode of the overlay calculated from the previous step.

[0275] The heating/cooling performance for the last 12 months may be determined as follows.

1. Only looking at HER values since 365 heating/cooling operational days ago, determine the overlay parameters for each sensor nodes with ≥ 50 HER values. Only plot these sensor nodes in the histogram.
2. Determine the overlay for the last 12 months with the overlay parameters in the previous step and the scaling factors (fixed, should not change) determined above.
3. Determine the peak/typical performance by finding the mode of the overlay calculated from the previous step.

[0276] Example embodiments have been found to work well when the sensor node is placed near a vent when the HVAC unit is inaccessible because of the Adaptive Threshold feature that automatically calibrates in situ. The Adaptive Threshold dynamically adjusts to circumstances.

Example temperature retention monitoring systems and methods.

[0277] An example report regarding insulation performance according to some embodiments is illustrated in FIG. 31. Similar to HER values, the Temperature Retention Ratio (TRR) is calculated to measure how well the home keeps the temperature. The TRR values are calculated over time and the statistics may be shown to the user. The TRR values may be plotted in a box & whisker plot as a function of outdoor temperature. As the outdoor temperature is further away from the room temperature, the TRR value decreases.

[0278] An overview of approximate equations describing home heat loss is as follows. The home may be approximated as a cube of side length l with no ground contact. The walls are considered to have a thickness d with $d \ll l$. There is considered to be a uniform but time-varying temperature $T_i(t)$ inside the house. The temperature outside the house is considered to have a constant value T_o . The temperature difference is thus given by $\Delta T(t) = T_o - T_i(t)$. The wall has a thermal conductivity of κ , and the R value is given by $R = d/\kappa$. The heat flux into the house is given by

$$q = \kappa \frac{T_o - T_i(t)}{d}$$

[0279] The house has an area of $A = 6l^2$, so the total heat flow into the house is given by

$$\frac{dQ}{dt} = \frac{A\kappa}{d}(T_o - T_i(t)) = \frac{A}{R}(T_o - T_i(t))$$

[0280] The temperature change is given by

$$Q = -C(T_s(t_o) - T_i(t_f))$$

[0281] Taking the derivative gives

$$\frac{dQ}{dt} = C \frac{dT_i(t)}{dt}$$

[0282] Combining the above equations gives

$$\frac{dT_i(t)}{dt} = \frac{A}{RC}(T_o - T_i(t))$$

[0283] Therefore

$$\frac{d\Delta T(t)}{dt} = -\frac{A}{RC}\Delta T(t)$$

[0284] The time required to change the temperature by 1°C, in the case where $\Delta T \gg 1^\circ\text{C}$, is approximately

$$\left(\frac{dT(t)}{dt}\right)^{-1} = \frac{RC}{A}\Delta T^{-1}$$

As the heat capacitance is dependent on the specific heat (c) and the mass $m = \rho V$, this result may be expressed as

$$\left(\frac{dT(t)}{dt}\right)^{-1} = \frac{Rc\rho V}{A}\Delta T^{-1}$$

[0285] In some embodiments, the product ($c\rho V$) is empirically assigned a typical or average value, e.g. for a certain type of home or for all homes. Based on that assigned value, on measurements regarding the time required to change the temperature by 1°C, and on known ΔT values, an estimated R value may be determined. While the estimate itself may have relatively low accuracy due to the assumptions made in its calculation, it can be expected to remain relatively stable in the absence of any problems. Thus the estimated R value may be used as a “relative” R value for which the absolute value provides little insight, but changes in the value may be detected as an indication of a potential new defect in the heat/cold retention properties of a home.

[0286] In some embodiments, thermal retention is calculated as follows.

1. TRR values are calculated for each sensor node individually
2. The TRR value is calculated from the temperature data after a HVAC heating/cooling cycle. "TRR heat" would be measured after a heating cycle. "TRR cool" would be measured after a cool cycle.
3. Perform a smoothing function that results in linearized temperature segments (same function as the LSF)
4. Measure the first linearized slope after the HVAC cycle.
 - a) "TRR heat" measures how quickly the house is cooling after a heating cycle
 - b) "TRR cool" measures how quickly the house is heating after a cooling cycle
 - c) If the slope is the same sign as the HVAC cycle, then consider it invalid. E.g. after a heating HVAC cycle, if temperature is increasing after the HVAC cycle, then we have an invalid TRR value and do not record it.
5. If the temperature change in the smoothed temperature is $< 0.14^{\circ}\text{C}$, or the slope is less than $1^{\circ}\text{C}/\text{hour}$, the state is considered unsure.
6. "TRR cool" is calculated only when the outdoor temperature is greater than the indoor temperature. "TRR heat" is considered only when the outdoor temperature is less than the indoor temperature.

[0287] Examples of temperature retention data are shown in FIG. 32. The TRR value decreases as the difference between outdoor temperature and room temperature increases. This trend has been found in both real-life data and simulations. The slope of this trend relates to the insulative property of the house.

[0288] FIG. 33 shows the slope of the best fit line for the TRR vs temperature as a function of thermal conductivity of the wall in simulated data. The higher the thermal conductivity of the wall (less insulative), the slope is slower.

[0289] FIG. 18A shows an example temperature retention report. It may be seen in the report that there are different slopes for heating and cooling seasons and different effective R-values for the two seasons. It may also be noted that the effective R-value is room dependent.

Example air filter monitoring systems and methods.

[0290] An example air filter dirtiness report is shown in FIG. 6. Air filter calculation in some embodiments includes an assumption of a 3 month air filter lifespan. Some embodiments assume 8.9 hour HVAC usage per

day. When the runtime reaches $90 * 8.9 = 801$ hours of runtime, the filter may be considered to be fully used. the cleanliness of the filter as a function of time may be approximated by an exponential relation.

[0291] FIG. 34 illustrates an example graph of dirtiness versus time that may be used in some embodiments. In some embodiments, whenever the user replaces the filter, they are asked for a filter type. A lookup table may be used to determine expected life. Some embodiments calculate an expected remaining lifetime. The calculated expected remaining lifetime may be calculated in various ways. Typical usage from the general population may be used. Calculations may be based off runtime over last period of time with the expectation that this usage will. Some embodiments learn the user behavior over several seasons and make predictions based off the expected outside temperature. Some embodiments seek feedback from the user whenever they check the filter.

[0292] As used herein, the singular forms “a,” “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0293] Other variations of the described embodiments are contemplated. The above-described embodiments are intended to be illustrative, rather than restrictive, of the present invention. The scope of the invention is thus not limited by the examples given above but rather is defined by the following claims.

CLAIMS

1. A method comprising:
 - for each of a plurality of cycles of an HVAC system, obtaining data representing a measured rate of indoor temperature change during the cycle and an outdoor temperature during the cycle;
 - classifying each of a plurality of the cycles in one of a plurality of predetermined cycle categories, based at least in part on the associated measured rate and the outdoor temperature; and
 - for at least one of the categories, providing a report regarding statistics of the cycles in the reported category.
2. The method of claim 1, wherein the report provides an indication of an average time per temperature change for the cycles in the reported category.
3. The method of claim 1, wherein the classifying of the cycles is further based at least in part on a threshold rate of temperature change, and wherein the threshold rate of temperature change for each category is adjusted based at least in part on cycles previously classified in the respective category.
4. The method of claim 1, wherein the categories include at least two categories from among the following:
 - a first category in which the rate of indoor temperature change is positive and the outdoor temperature is above a first threshold temperature;
 - a second category in which the rate of indoor temperature change is negative and the outdoor temperature is above a second threshold temperature;
 - a third category in which the rate of indoor temperature change is positive and the outdoor temperature is below a third threshold temperature;
 - a fourth category in which the rate of indoor temperature change is negative and the outdoor temperature is below a fourth threshold temperature.
5. The method of claim 4, wherein a cycle is classified in the first or fourth category only in response to a determination that the HVAC system is off during the respective cycle.
6. The method of claim 4, wherein a cycle is classified in the second or third category only in response to a determination that the HVAC system is on during the respective cycle.

7. The method of claim 4, wherein the first and third threshold temperatures are the same, and the second and fourth threshold temperatures are the same.
8. The method of claim 4, wherein at least one of the threshold temperatures is based on an indoor temperature.
9. The method of claim 4, further comprising detecting a change in heating performance based on a change in statistics of cycles in the third category.
10. The method of claim 4, further comprising detecting a change in cooling performance based on a change in statistics of cycles in the second category.
11. A system comprising one or more processors configured to perform at least:
for each of a plurality of cycles of an HVAC system, obtaining data representing a measured rate of indoor temperature change during the cycle and an outdoor temperature during the cycle;
classifying each of a plurality of the cycles in one of a plurality of predetermined cycle categories, based at least in part on the associated measured rate and the outdoor temperature; and
for at least one of the categories, providing a report regarding statistics of the cycles in the reported category.
12. The system of claim 11, wherein the report provides an indication of an average time per temperature change for the cycles in the reported category.
13. The system of claim 11, wherein the classifying of the cycles is further based at least in part on a threshold rate of temperature change, and wherein the threshold rate of temperature change for each category is adjusted based at least in part on cycles previously classified in the respective category.
14. The system of claim 11, wherein the categories include at least two categories from among the following:
a first category in which the rate of indoor temperature change is positive and the outdoor temperature is above a first threshold temperature;
a second category in which the rate of indoor temperature change is negative and the outdoor temperature is above a second threshold temperature;

a third category in which the rate of indoor temperature change is positive and the outdoor temperature is below a third threshold temperature;

a fourth category in which the rate of indoor temperature change is negative and the outdoor temperature is below a fourth threshold temperature.

15. The system of claim 14, wherein a cycle is classified in the first or fourth category only in response to a determination that the HVAC system is off during the respective cycle.

16. The system of claim 14, wherein a cycle is classified in the second or third category only in response to a determination that the HVAC system is on during the respective cycle.

17. The system of claim 14, wherein the first and third threshold temperatures are the same, and the second and fourth threshold temperatures are the same.

18. The system of claim 14, wherein at least one of the threshold temperatures is based on an indoor temperature.

19. The system of claim 14, further comprising detecting a change in heating performance based on a change in statistics of cycles in the third category.

20. The system of claim 14, further comprising detecting a change in cooling performance based on a change in statistics of cycles in the second category.

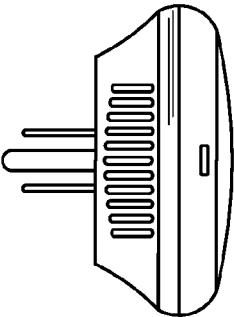


FIG. 1A

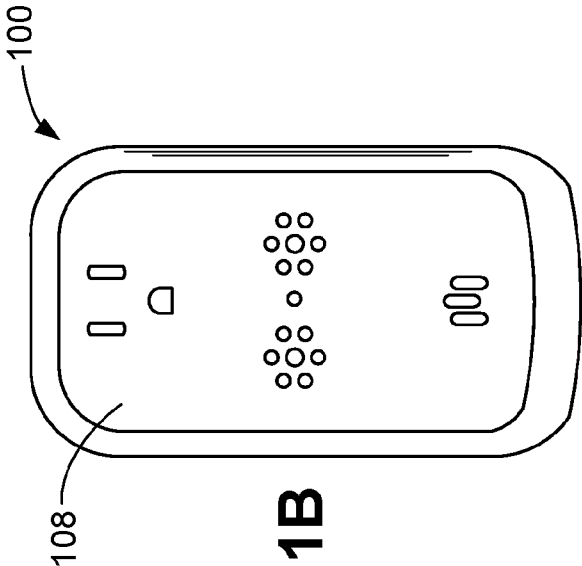


FIG. 1B

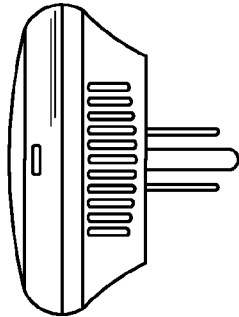


FIG. 1C

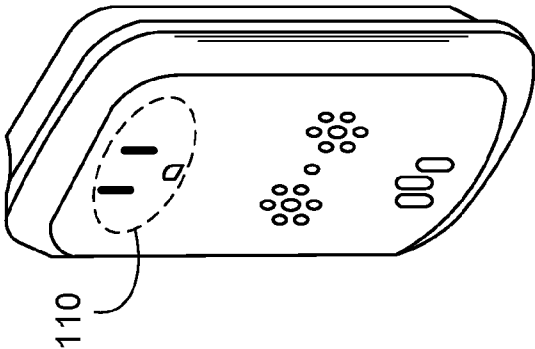


FIG. 1E

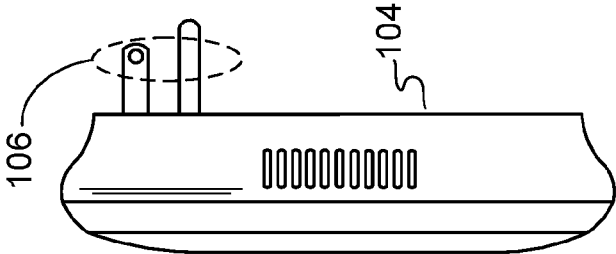


FIG. 1D

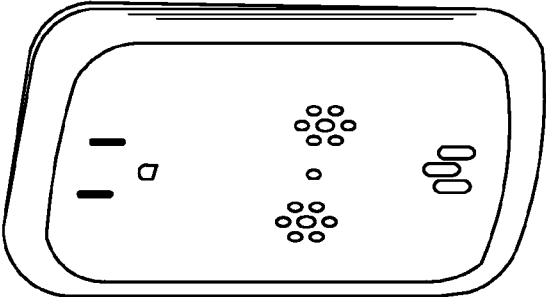


FIG. 1F

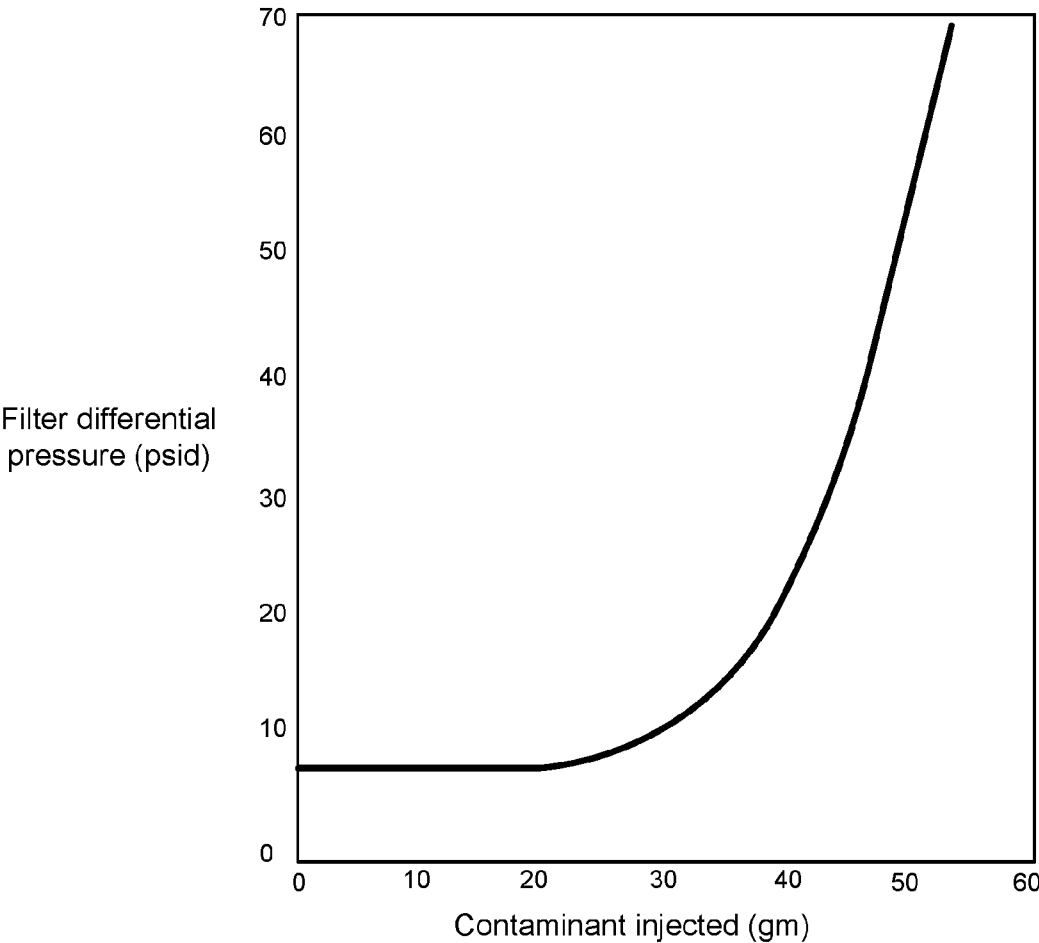


FIG. 2

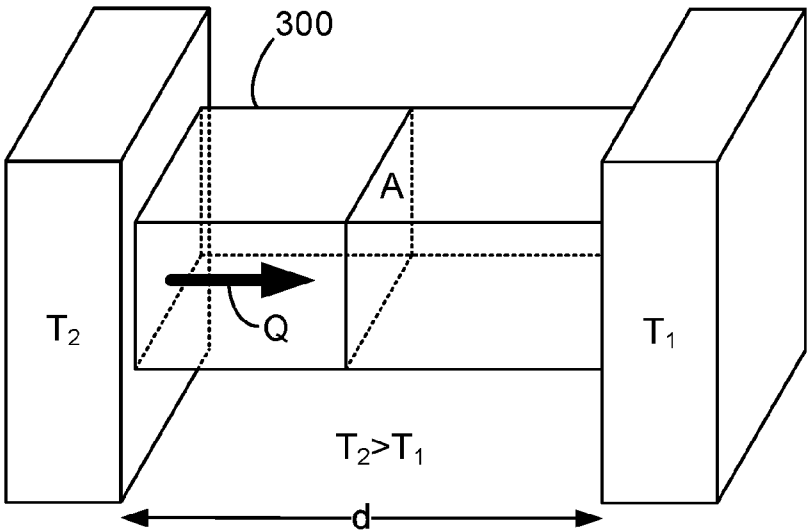


FIG. 3

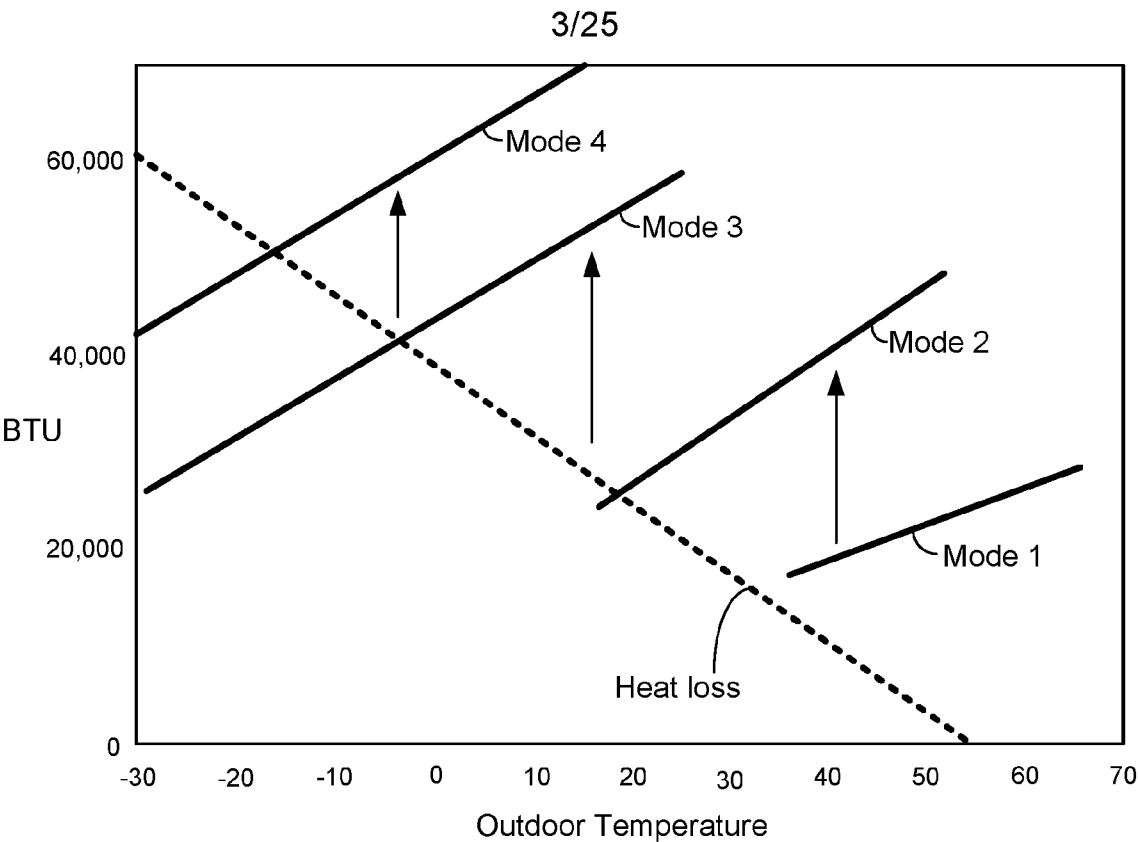


FIG. 4

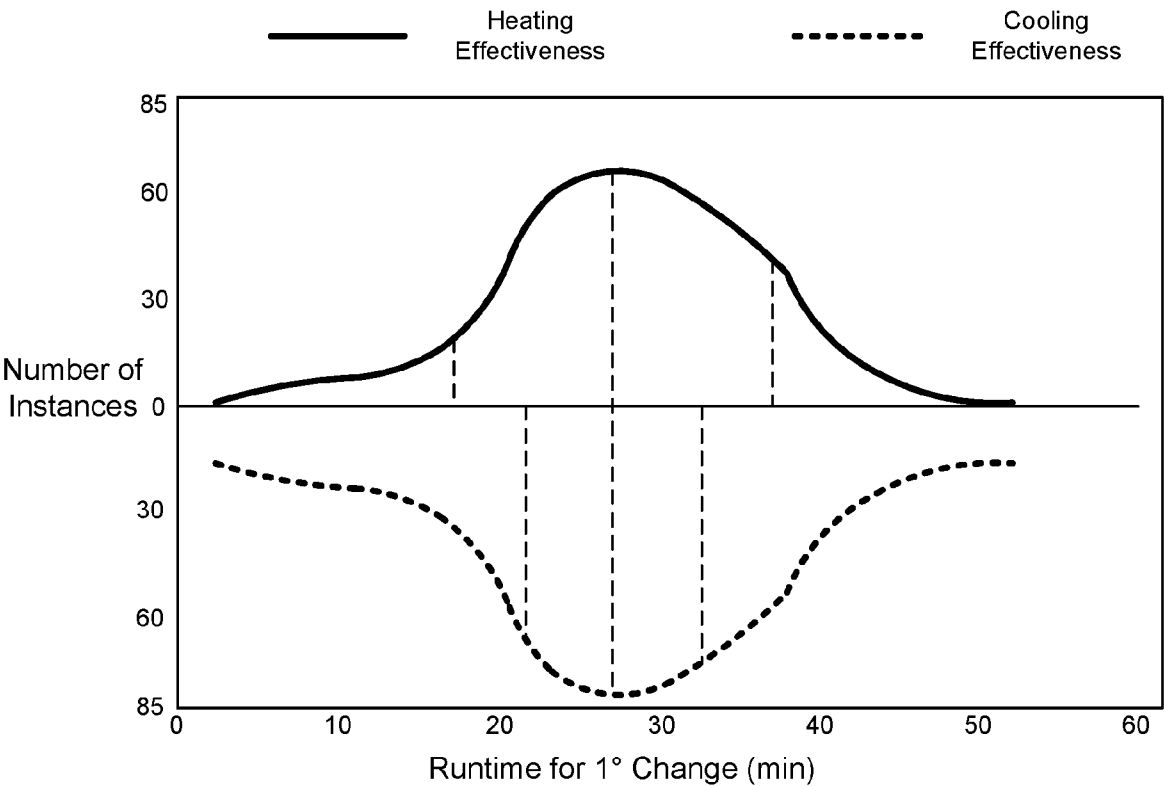


FIG. 5

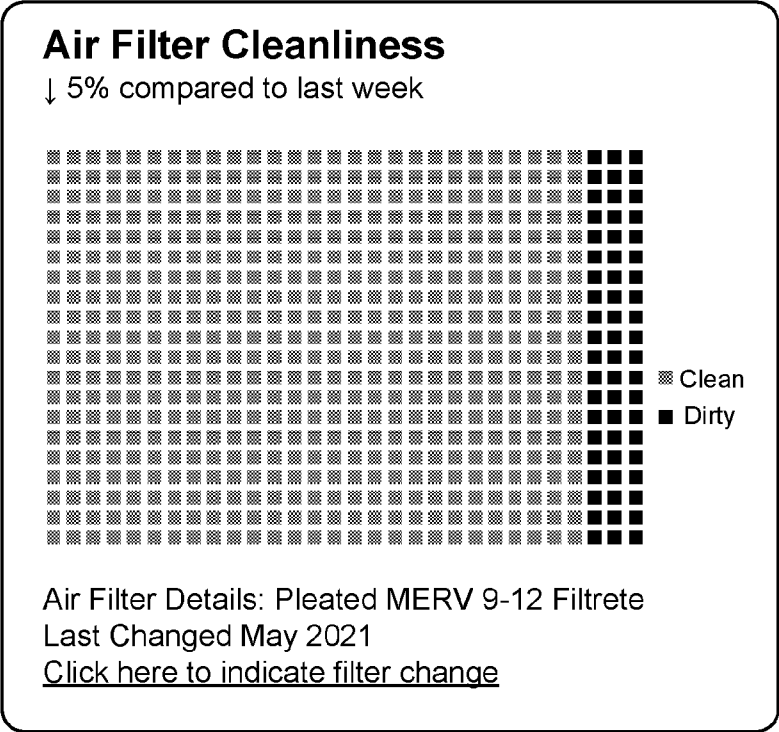


FIG. 6

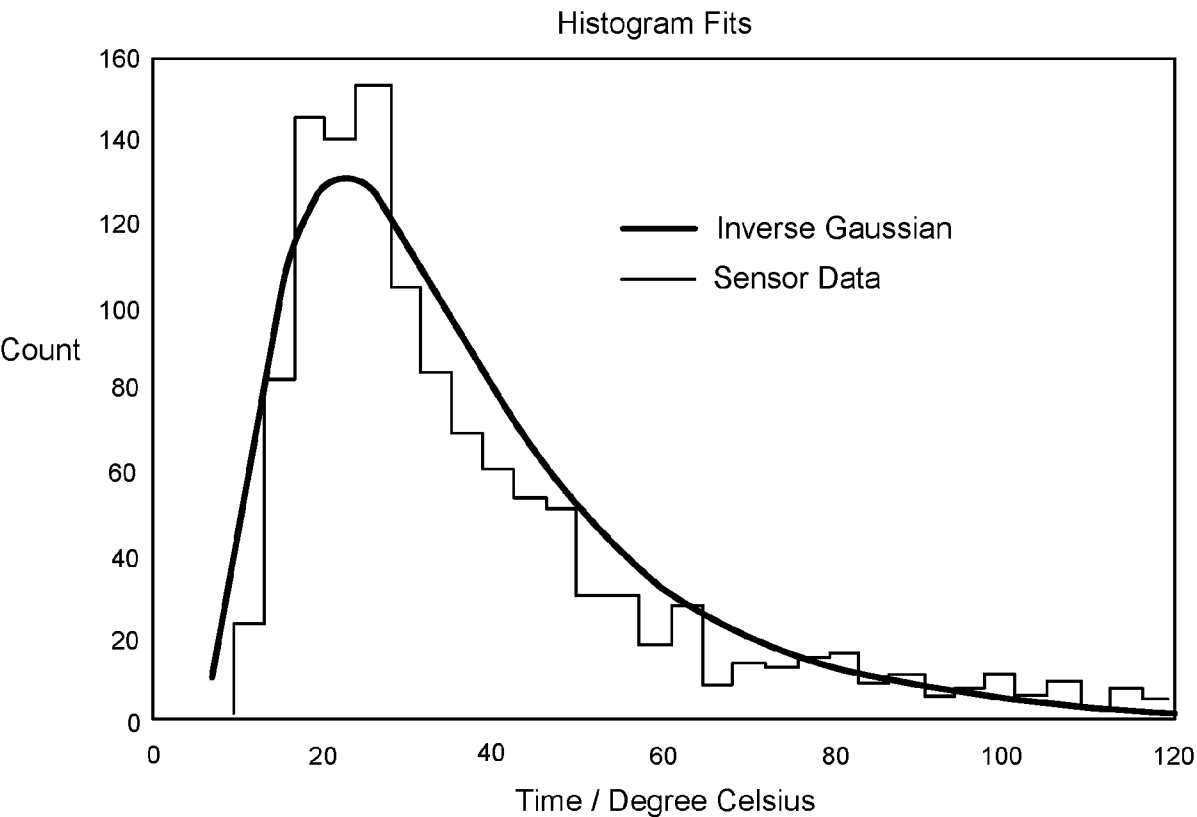
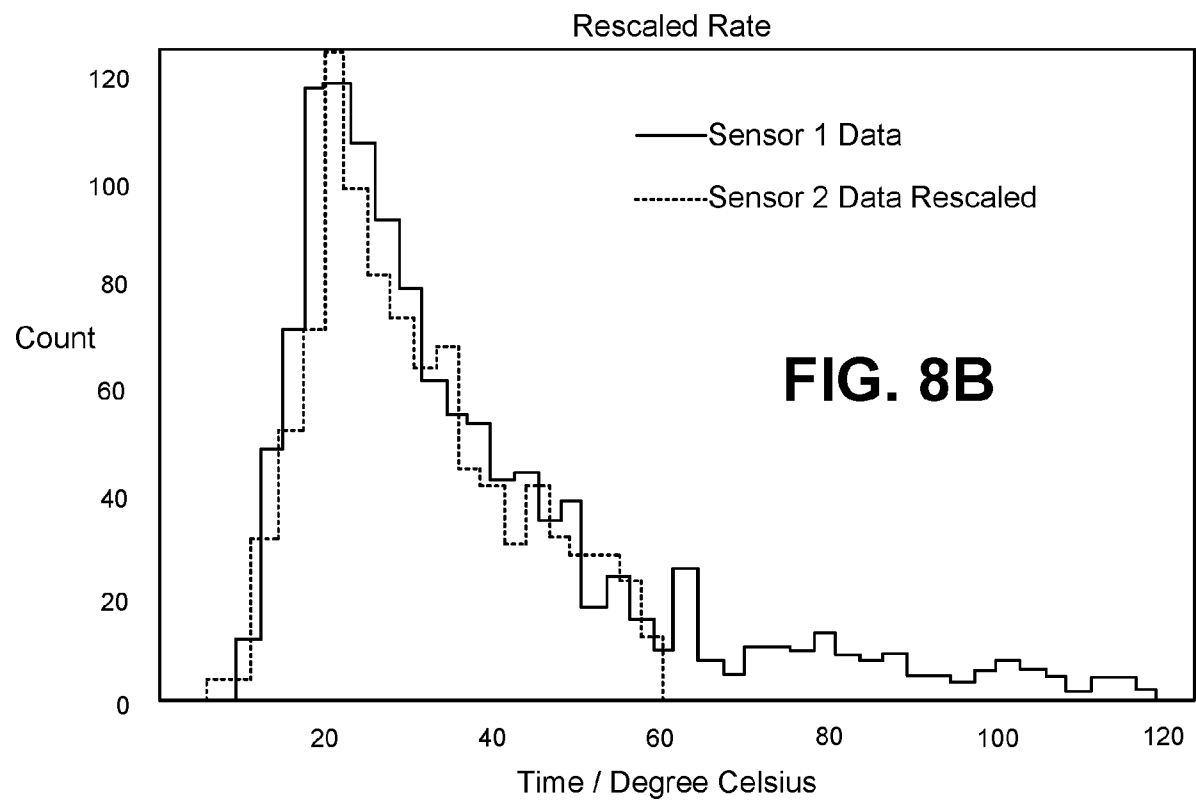
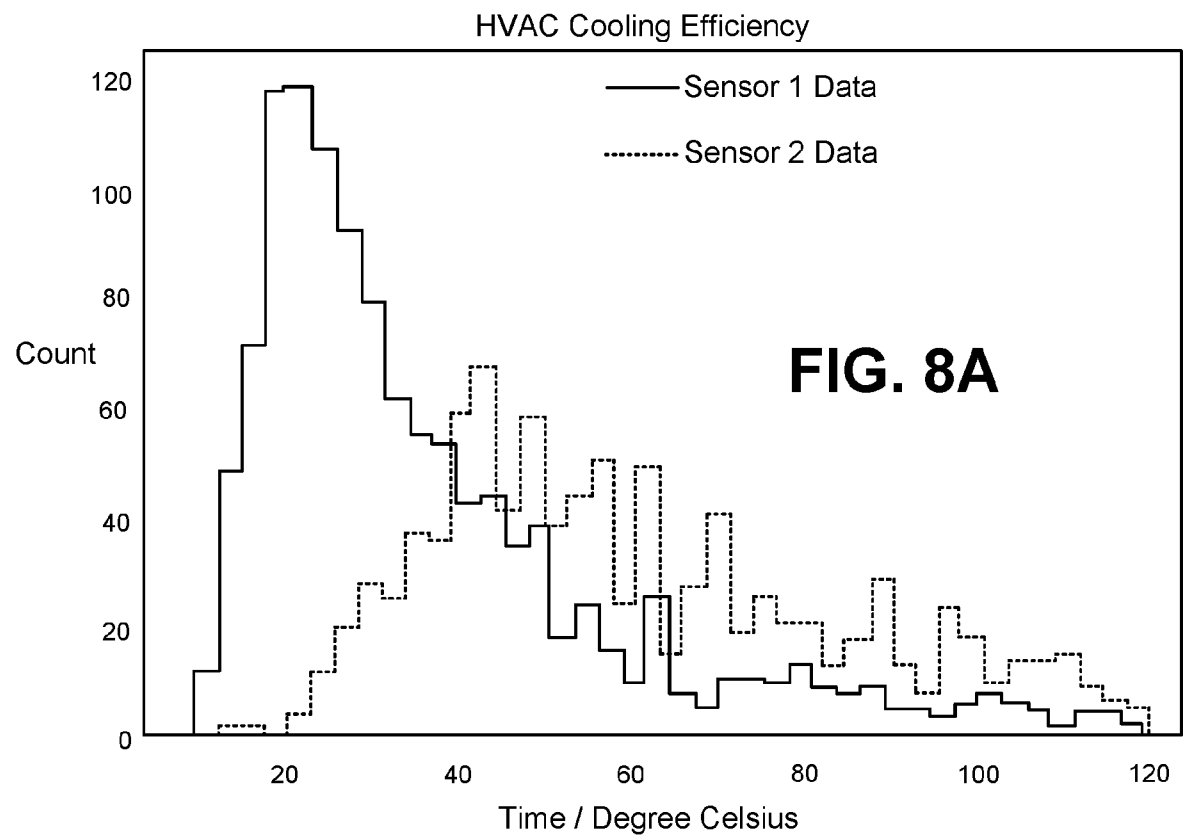


FIG. 7

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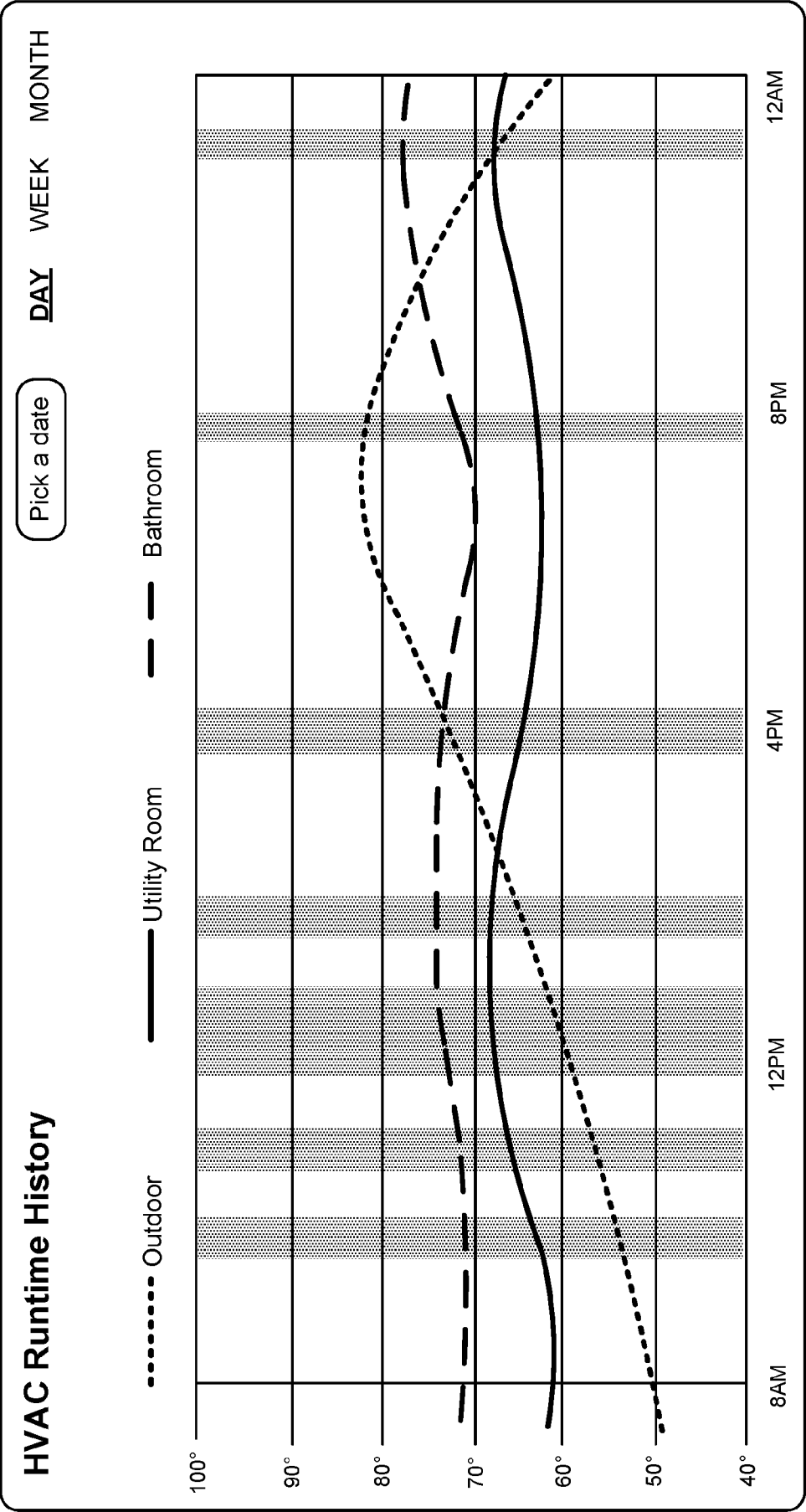


FIG. 9

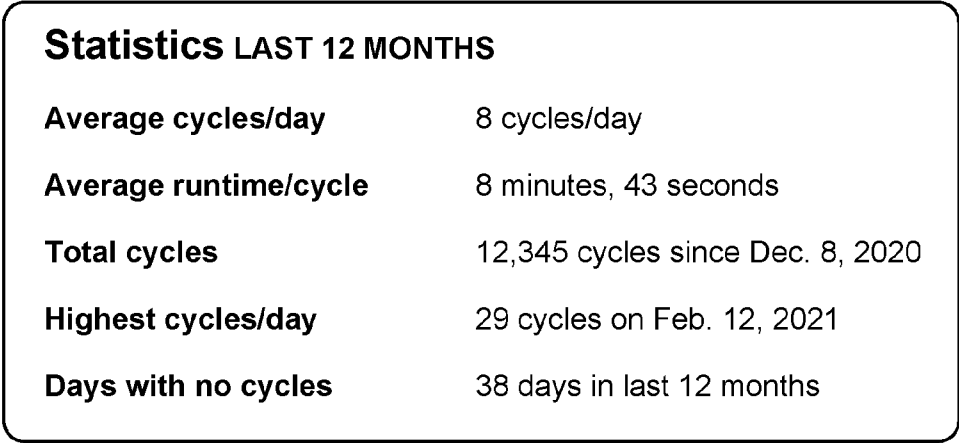


FIG. 10

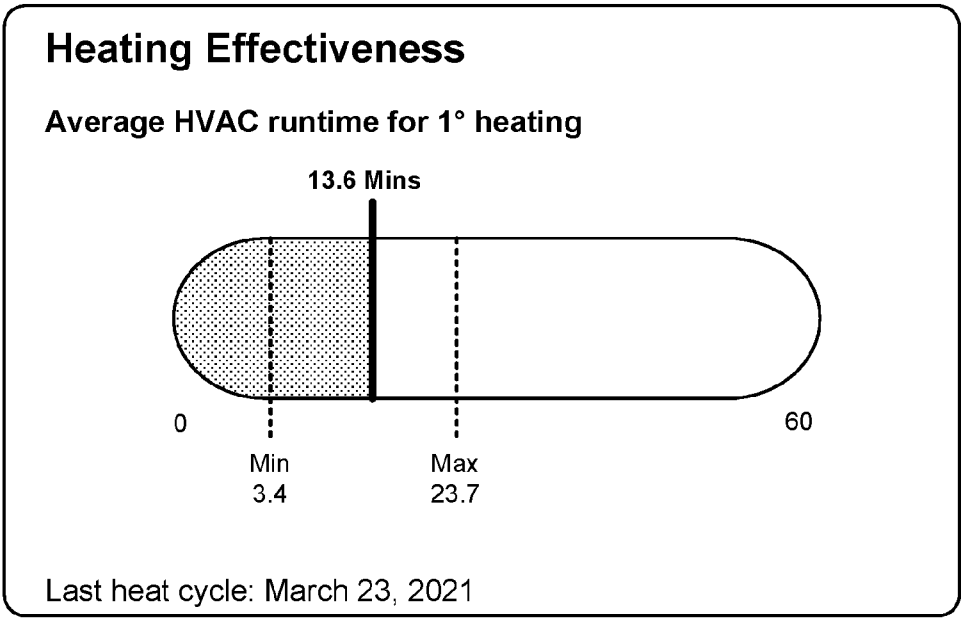


FIG. 11

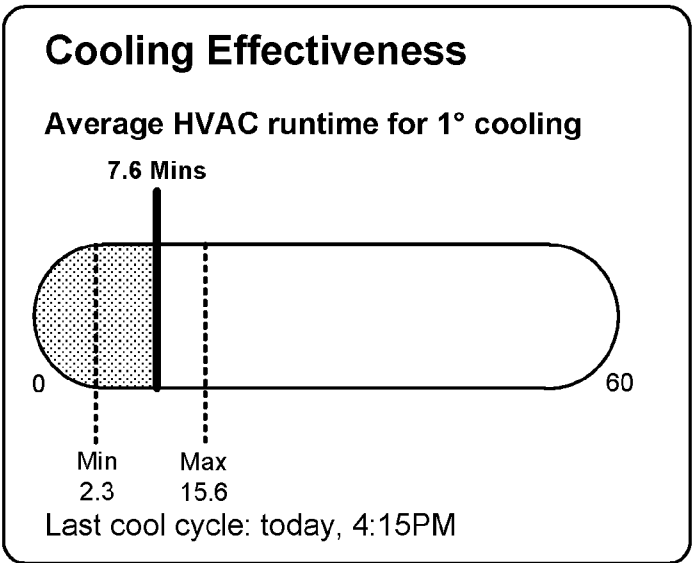
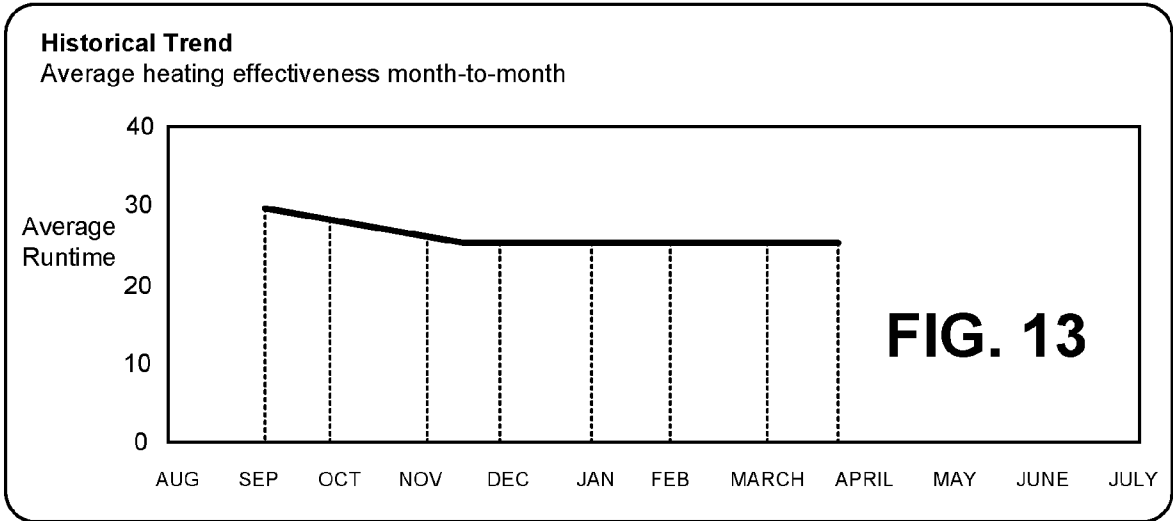
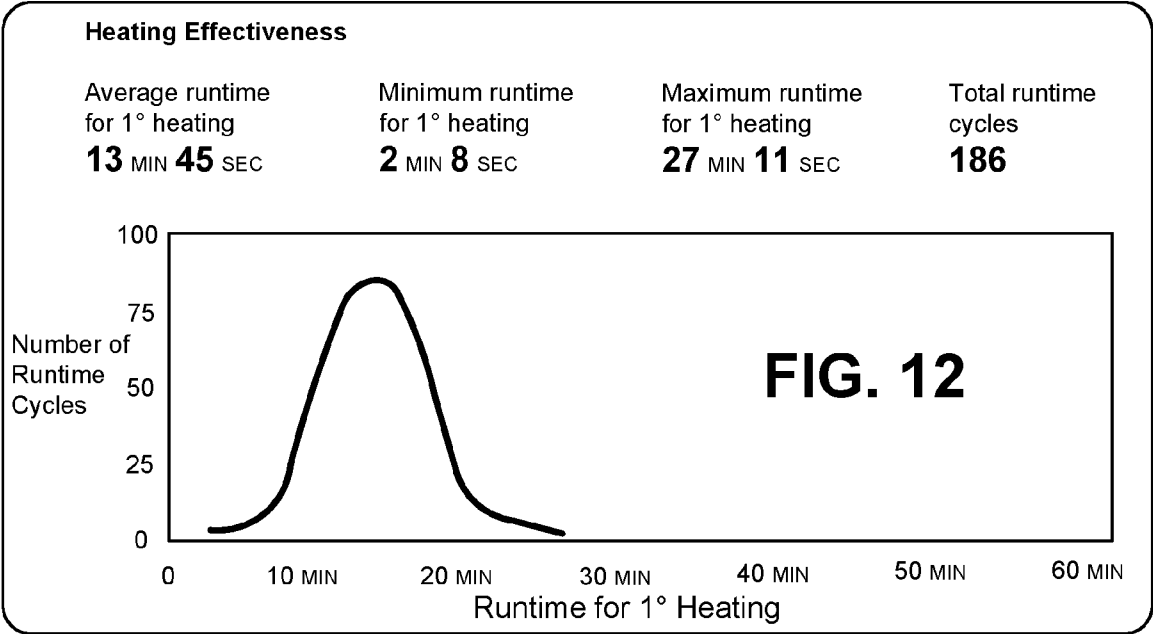


FIG. 14

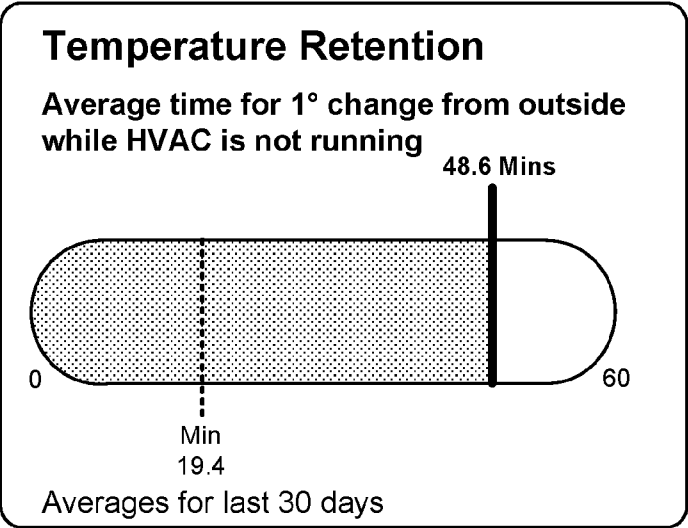
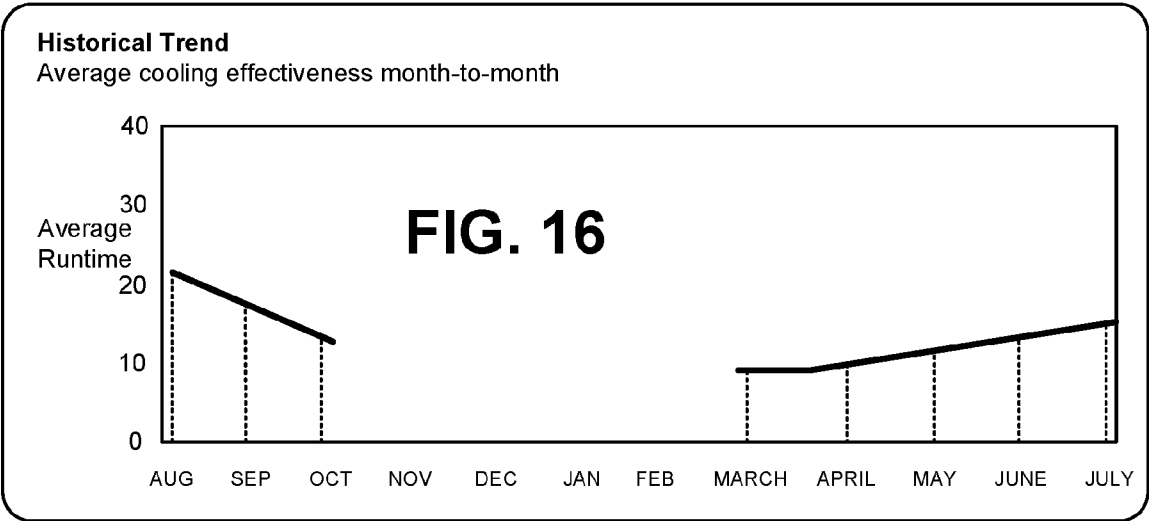
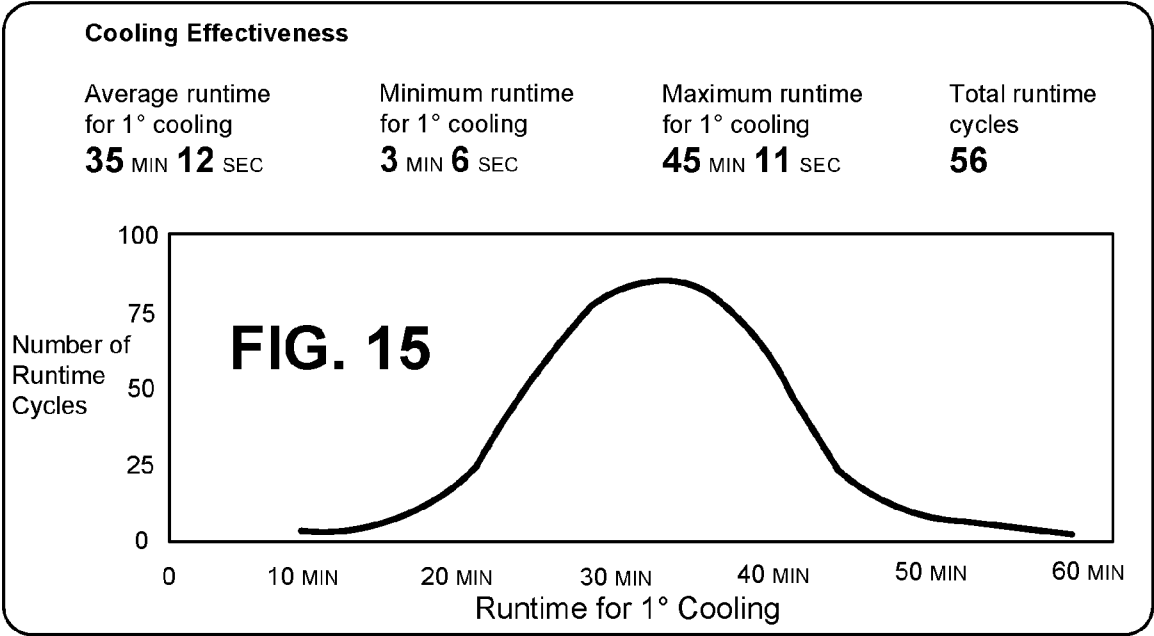
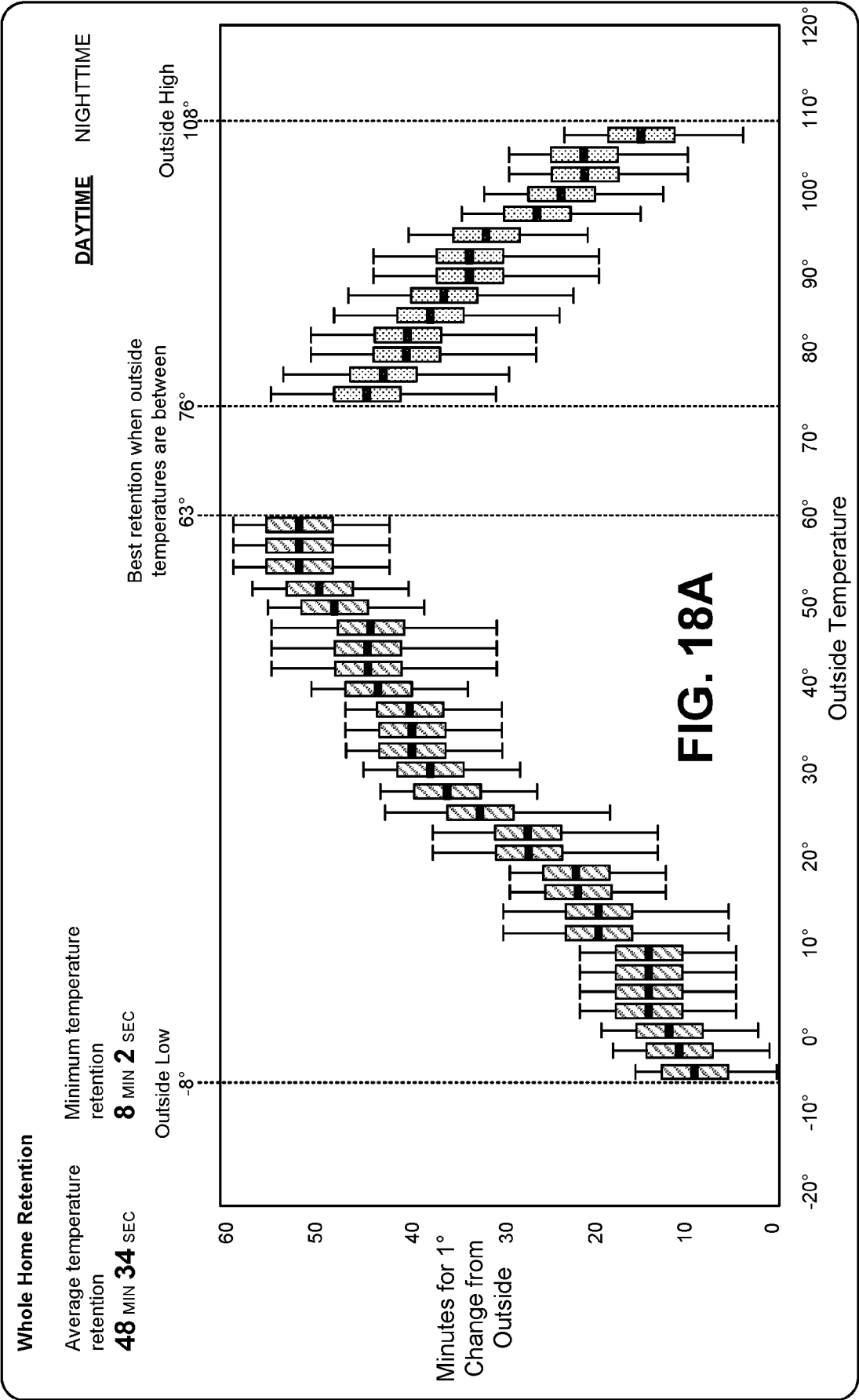


FIG. 17

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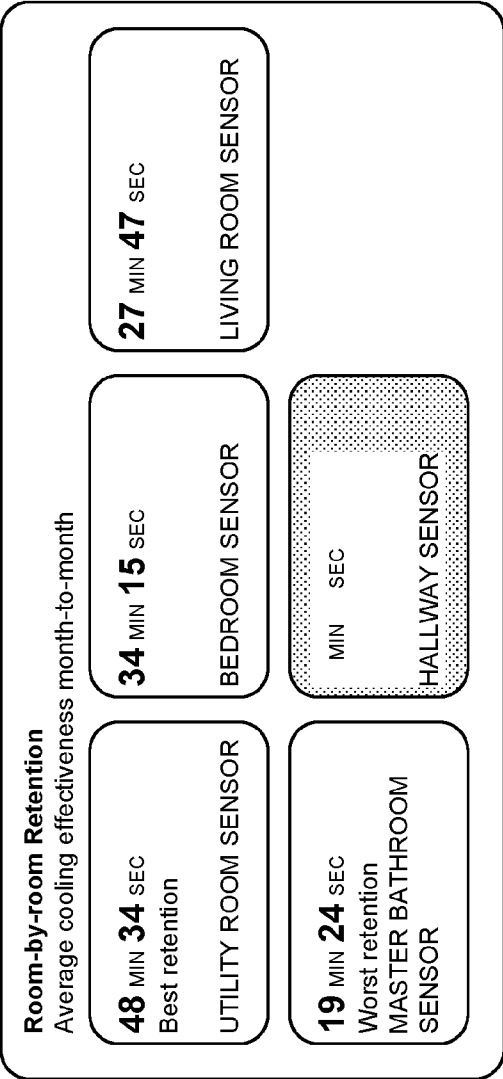


FIG. 19

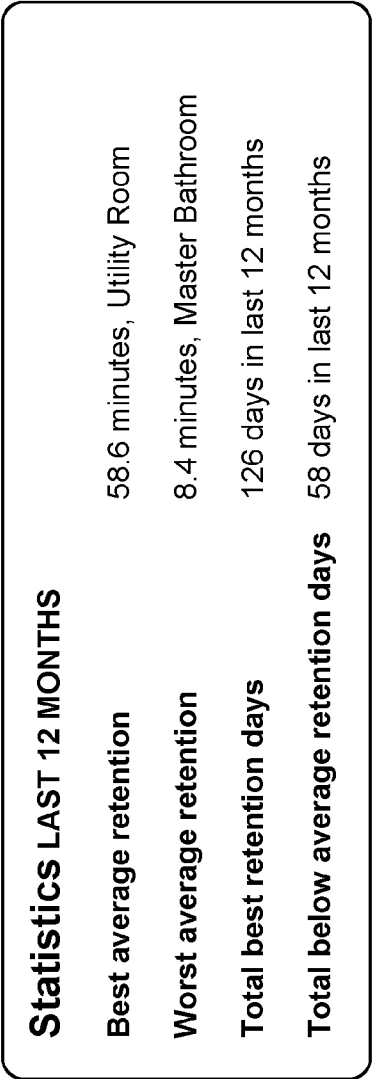


FIG. 20

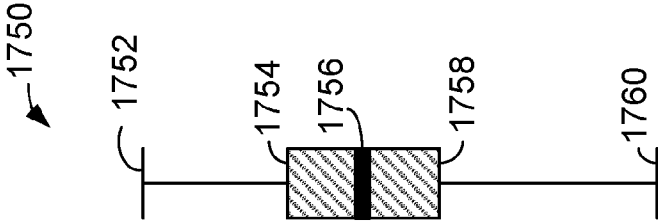


FIG. 18B

FIG. 21

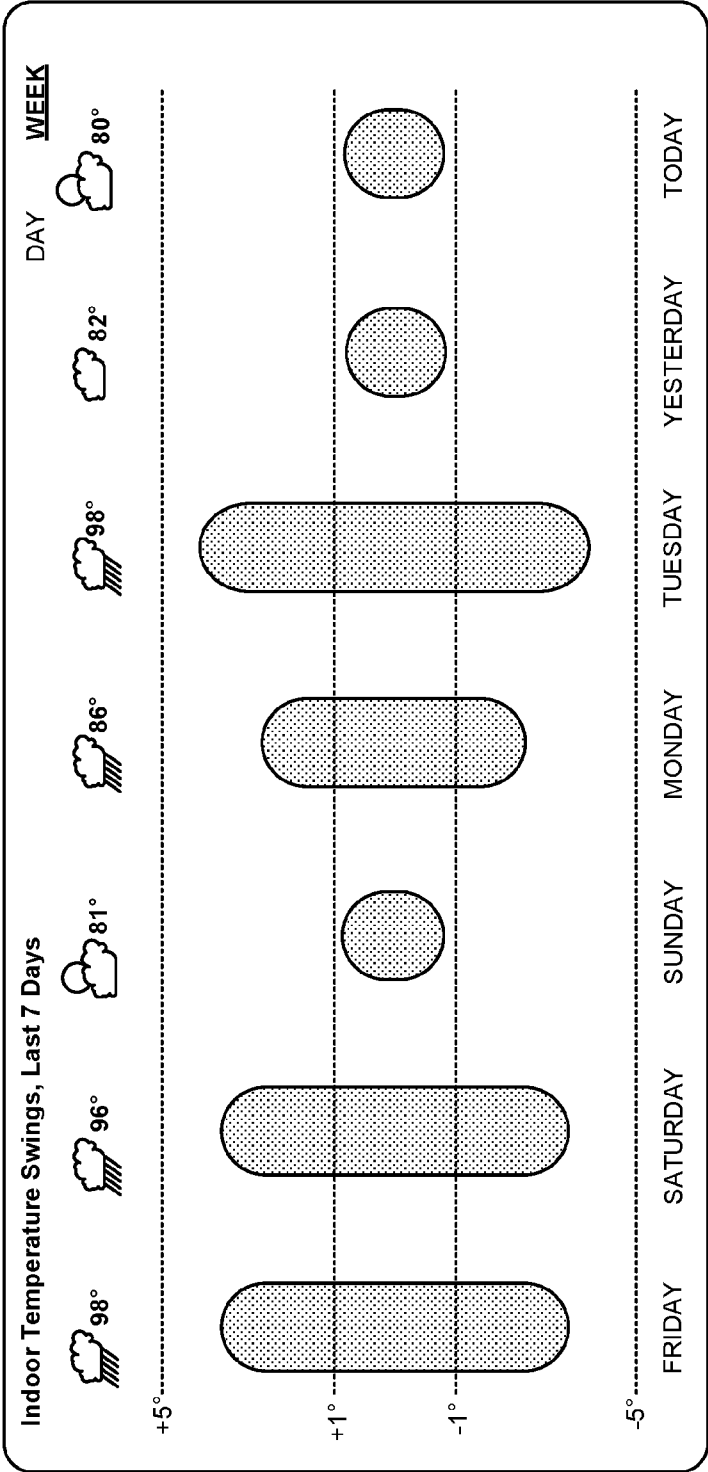


FIG. 22

Statistics LAST 12 MONTHS			
Warmest Room	Master Bathroom, 84°-89° most days		
Coollest Room	Guest Bedroom, 68°-71° most days		
Biggest Swing	Master Bathroom, 72°-89° swing on Tuesday July 23		
Smallest Swing	Utility Room, 67°-68° on Wednesday July 24		

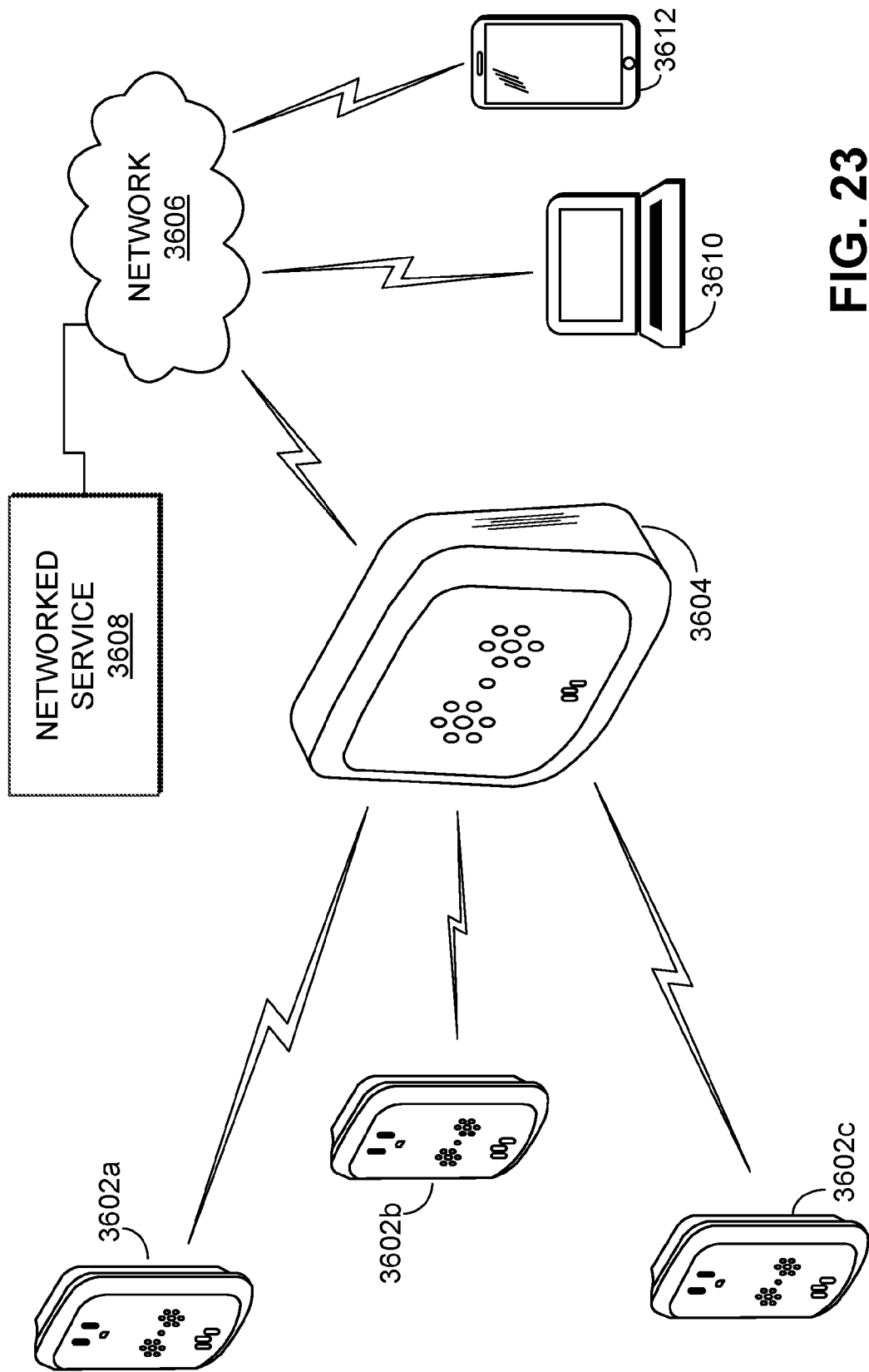
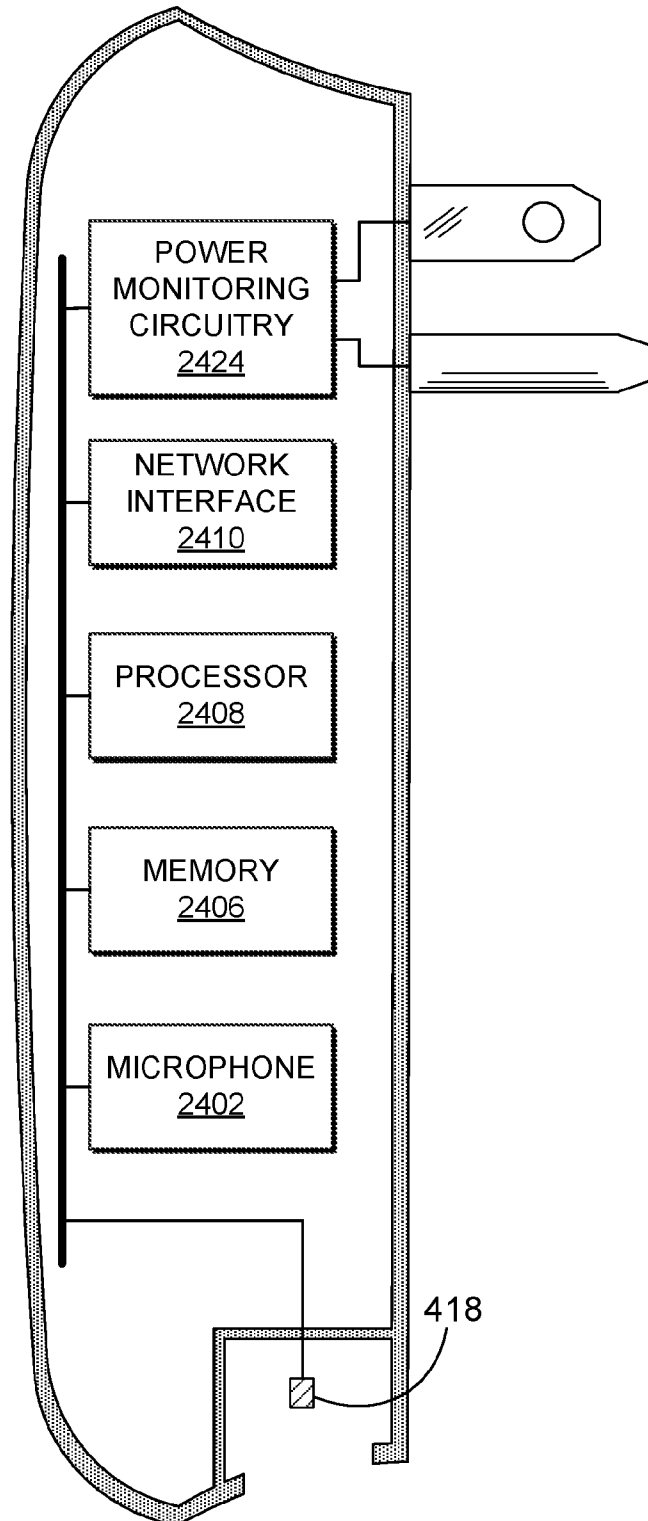


FIG. 23

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**FIG. 24**

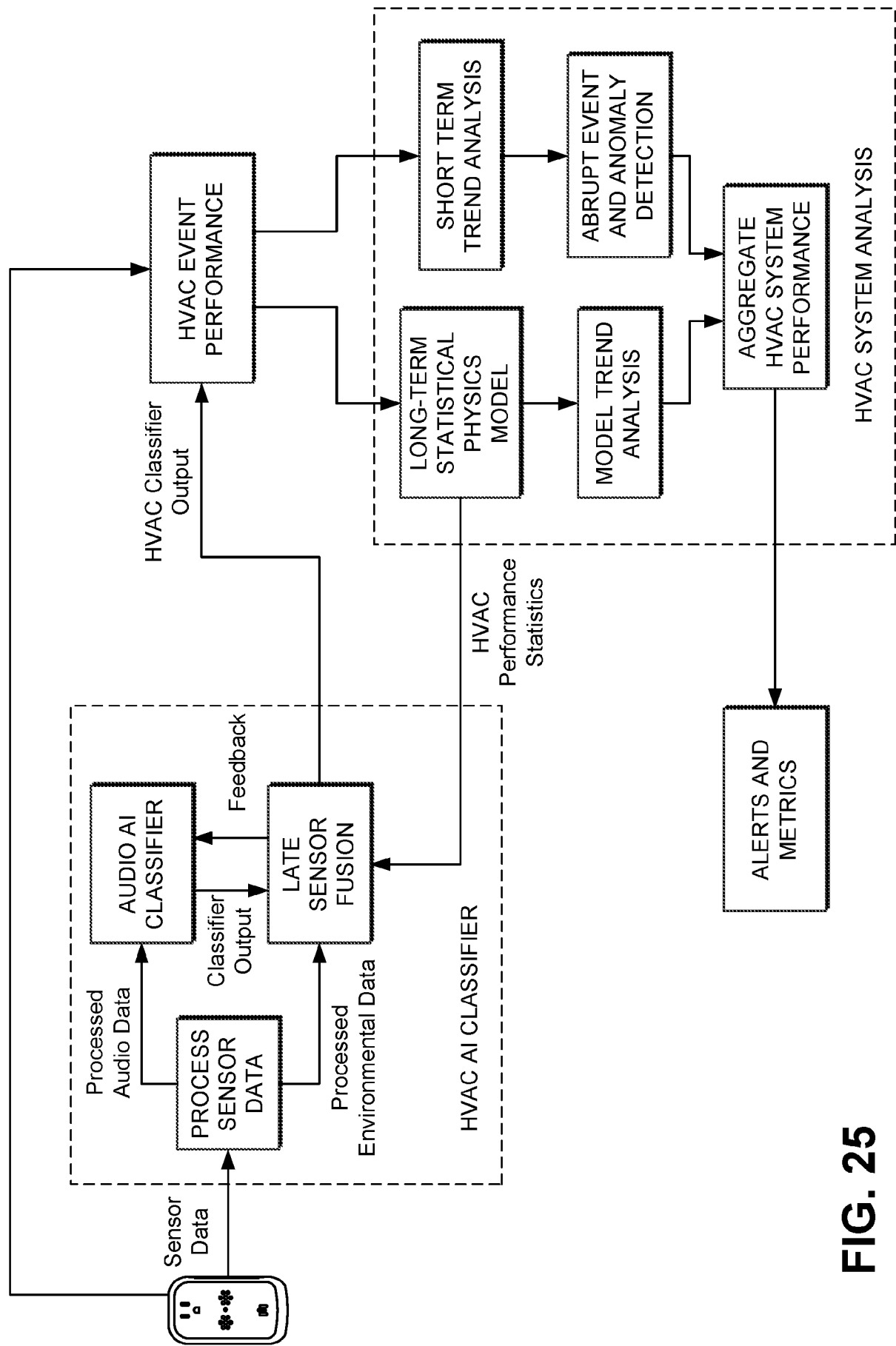


FIG. 25

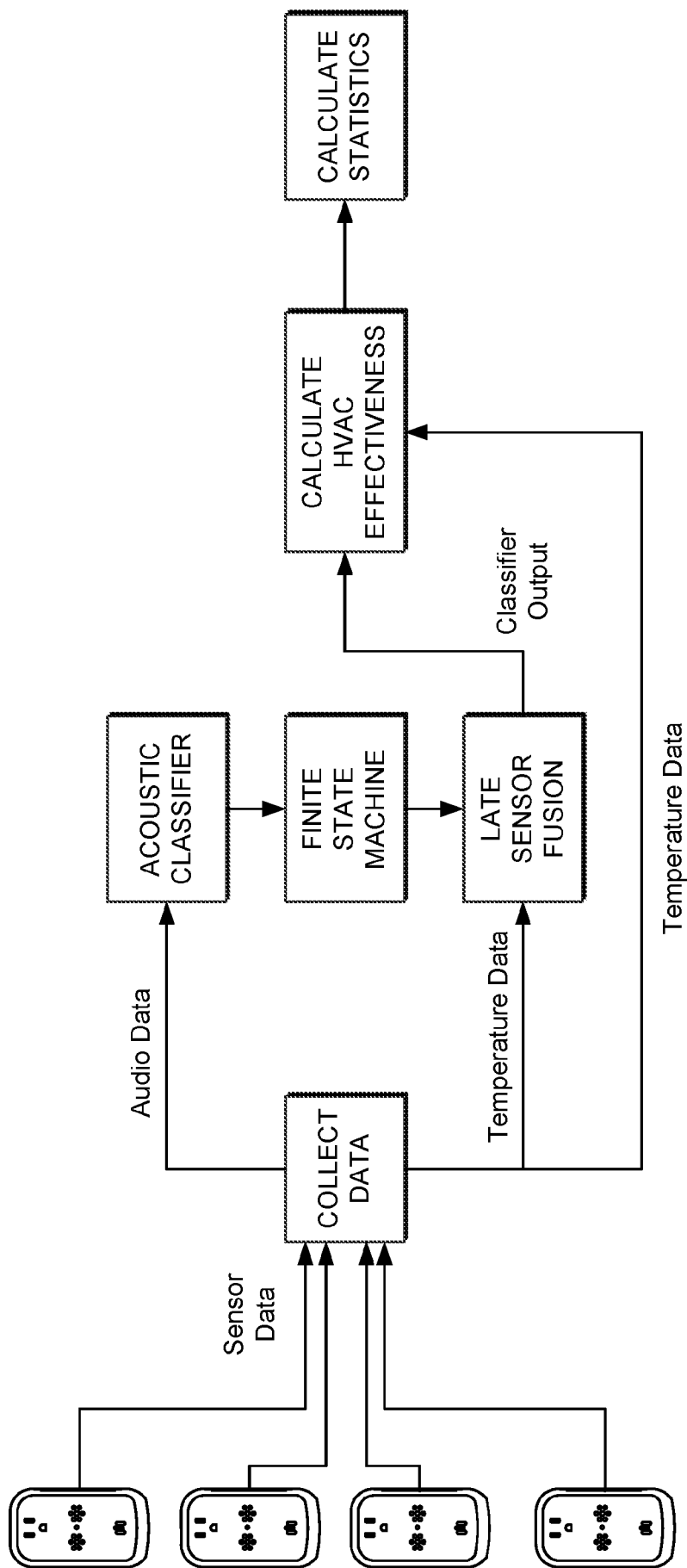


FIG. 26

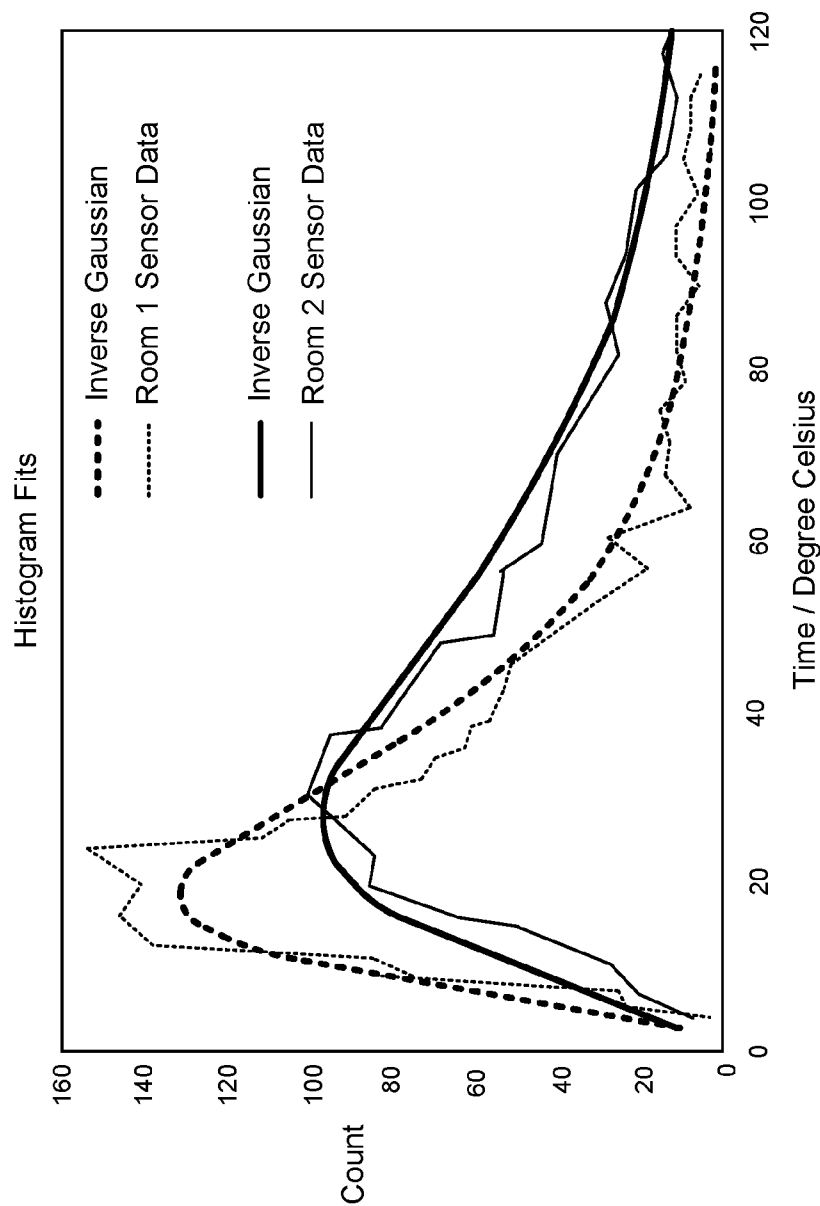


FIG. 27A

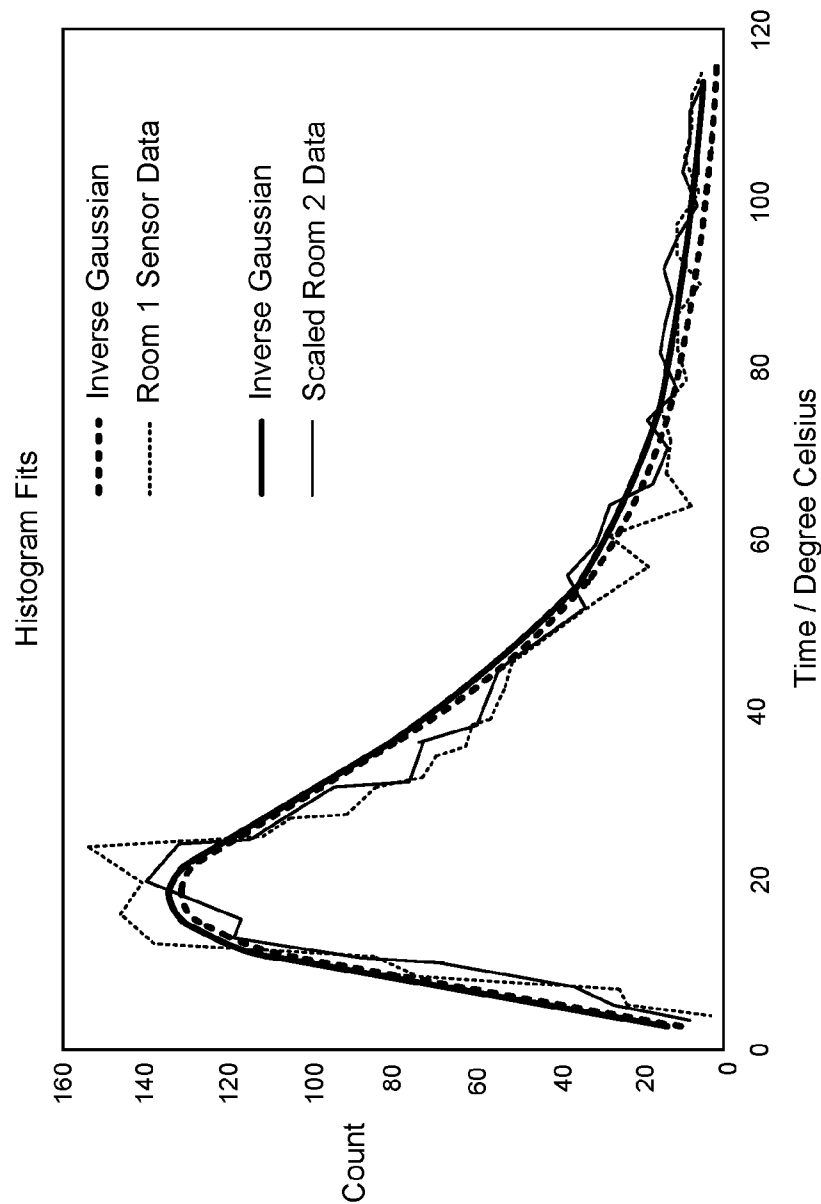


FIG. 27B

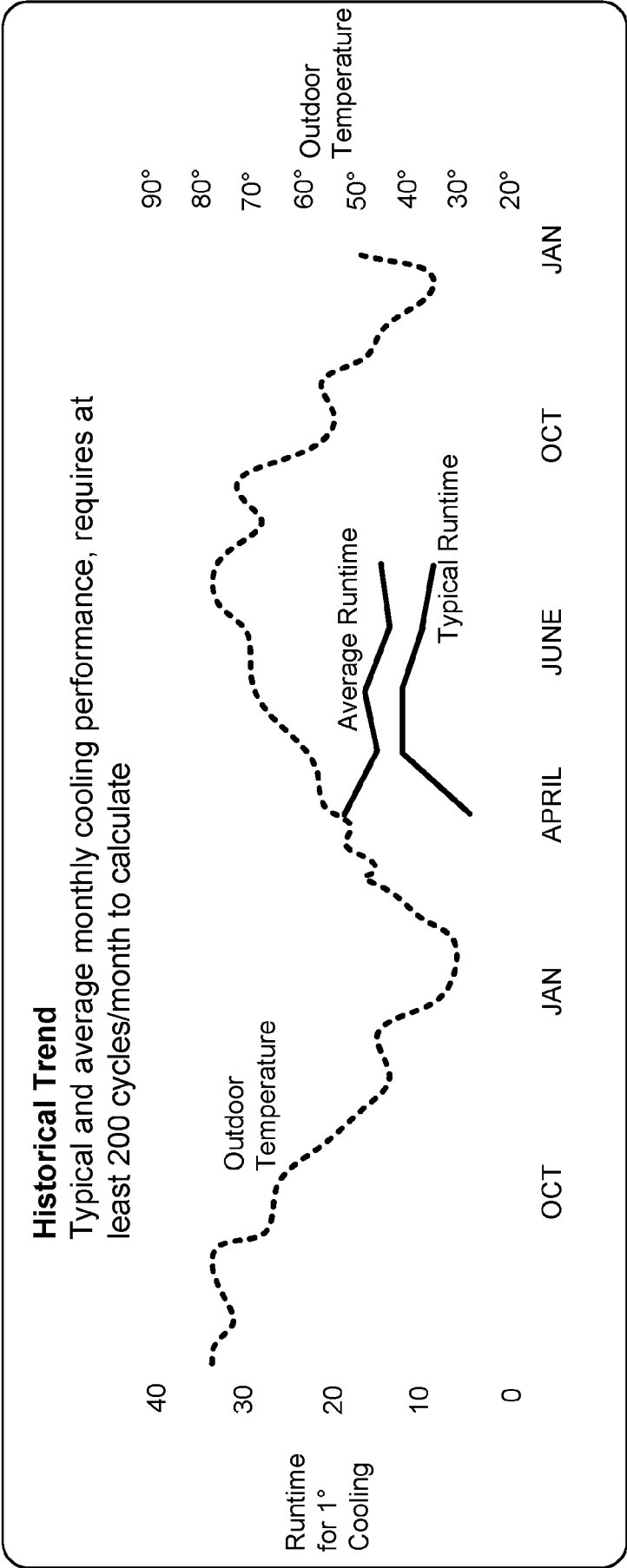


FIG. 28

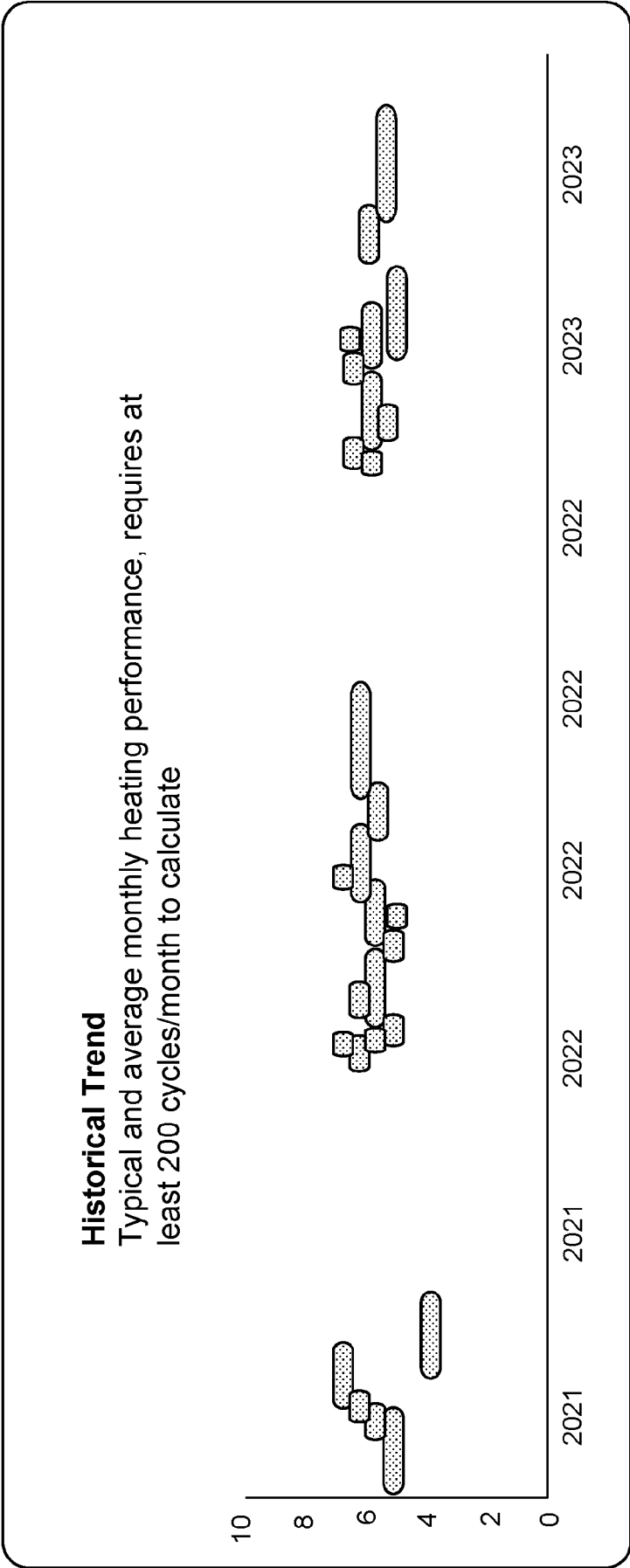


FIG. 29

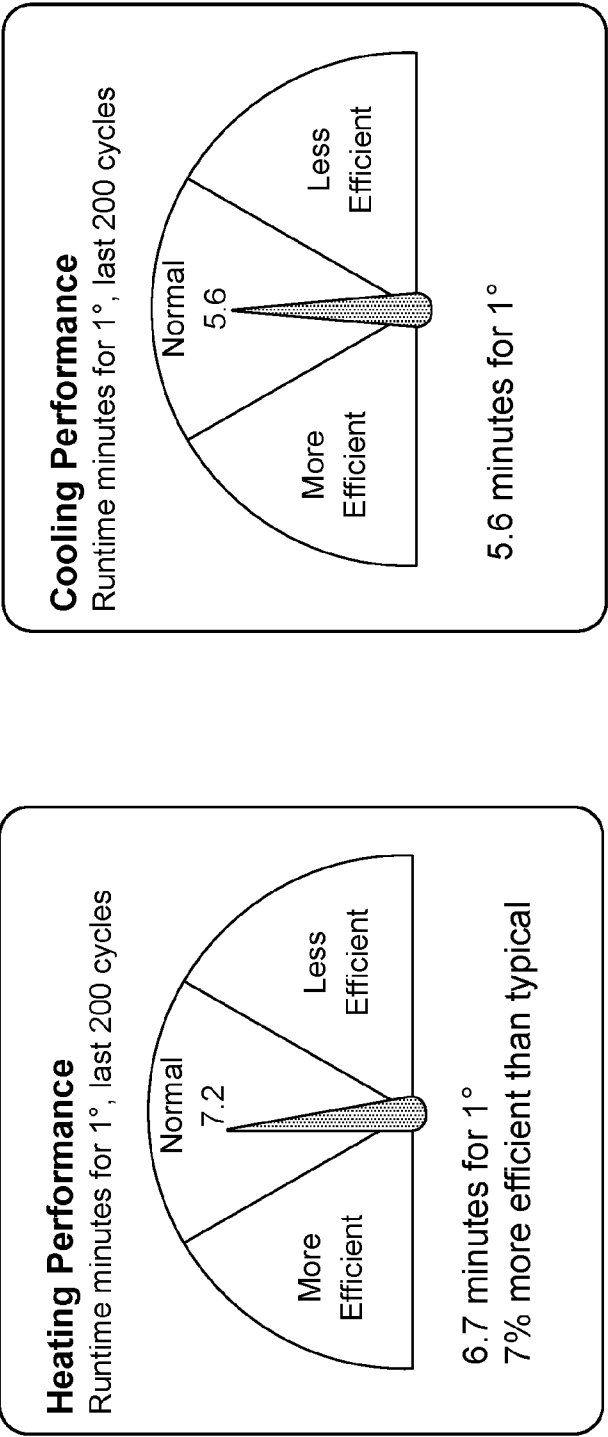


FIG. 30

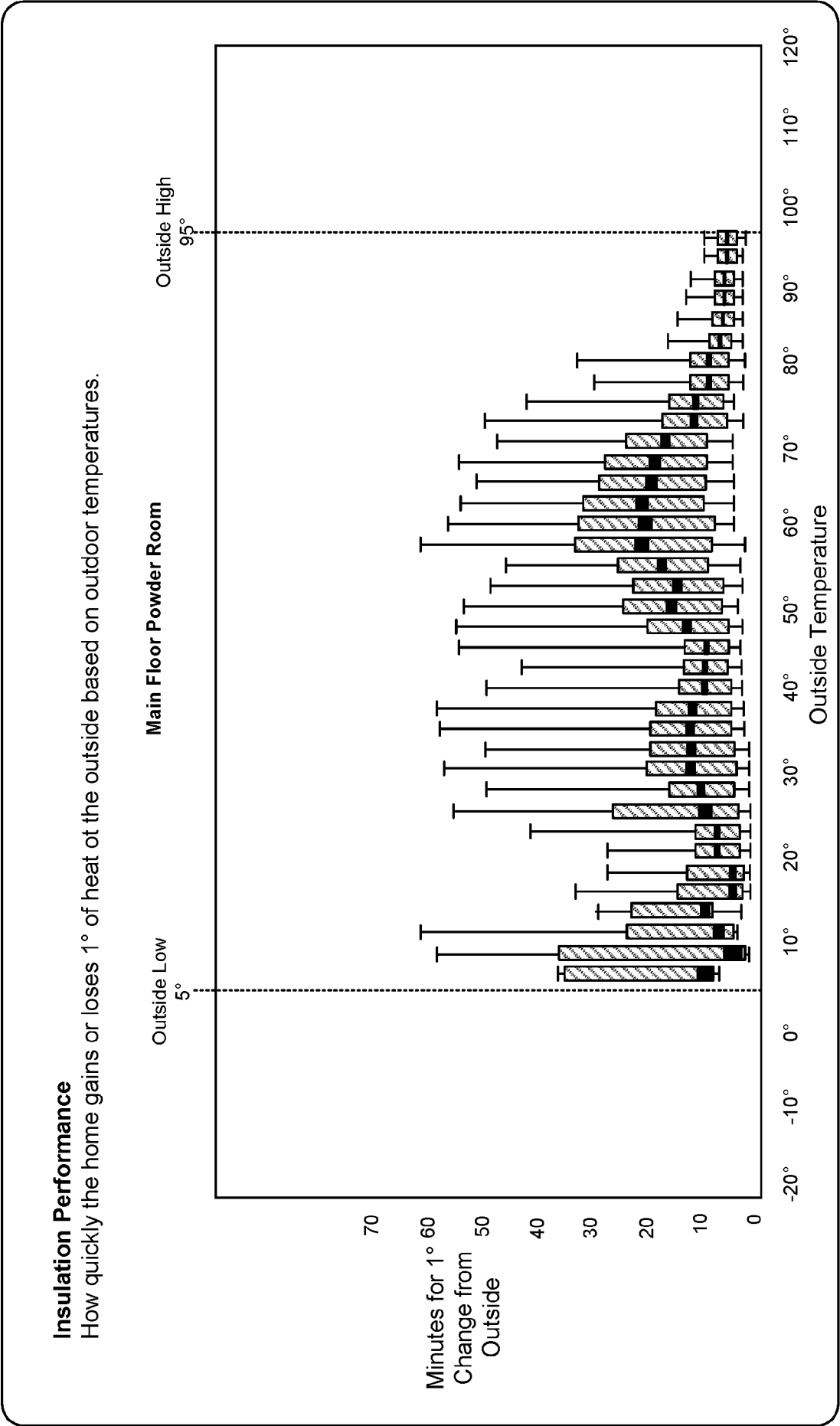


FIG. 31

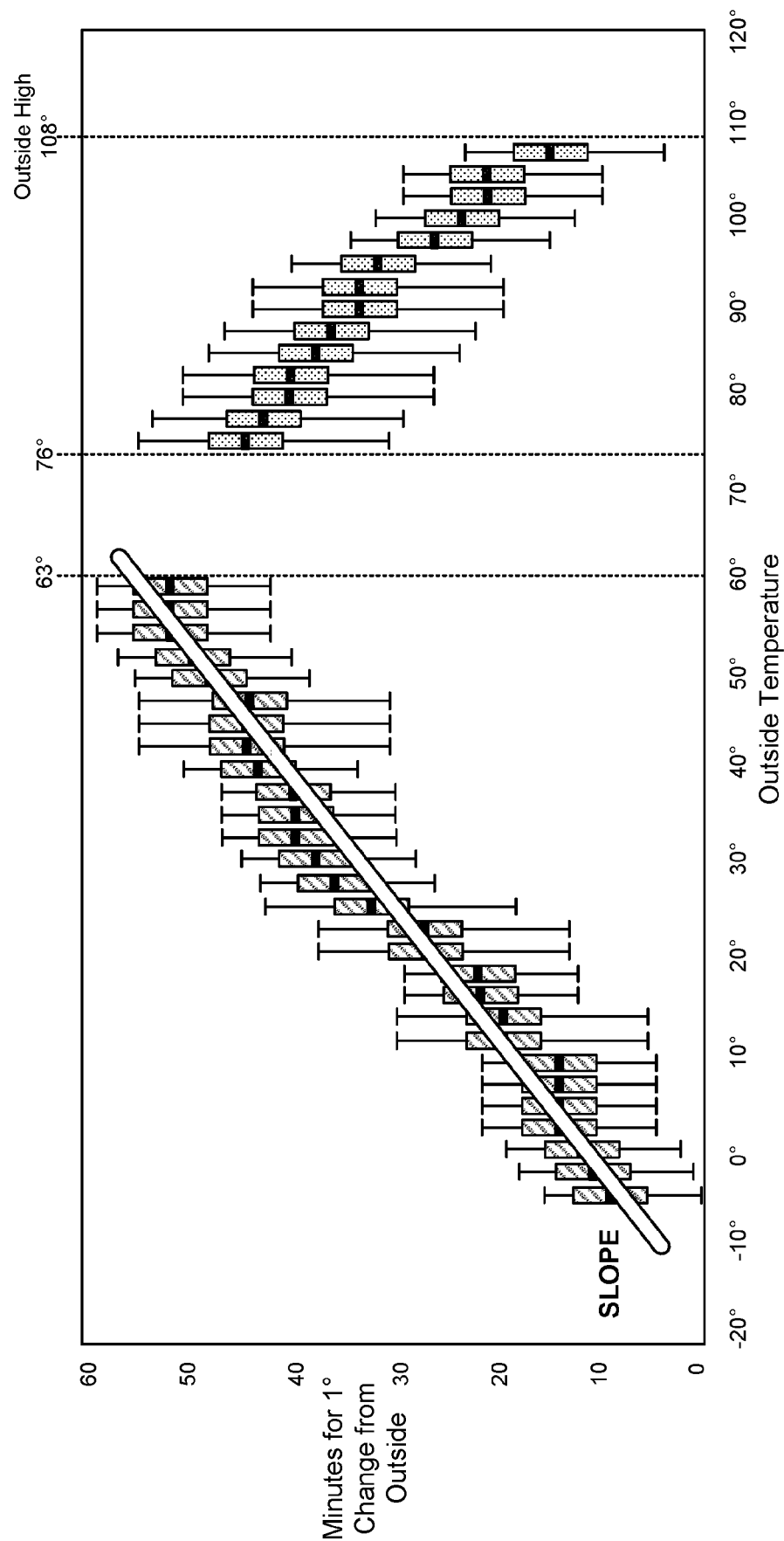


FIG. 32

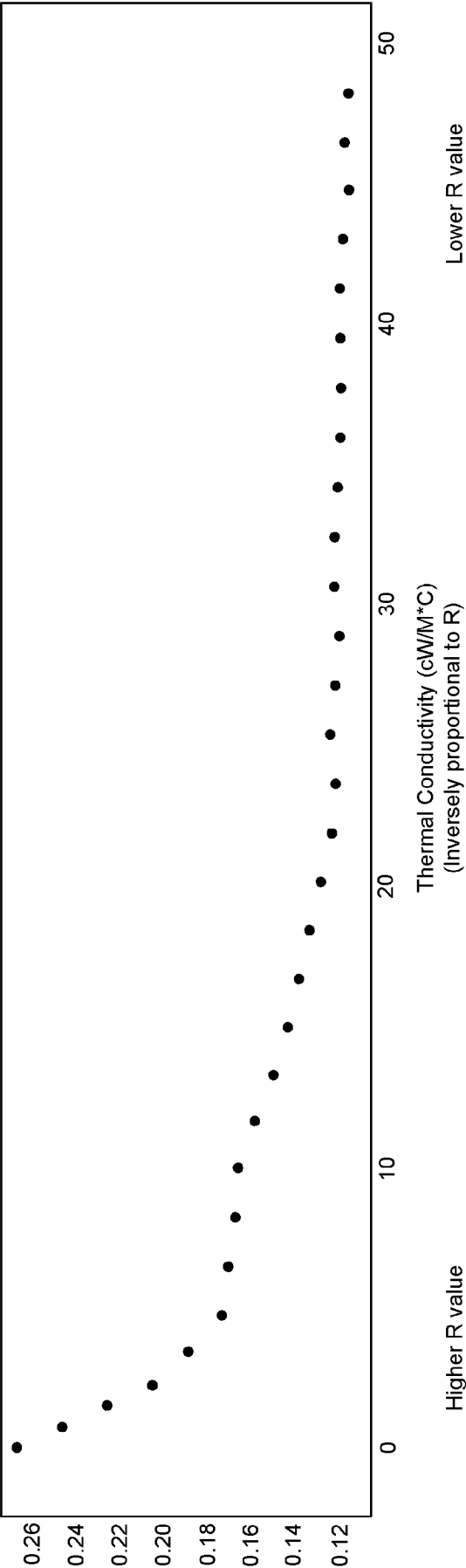


FIG. 33

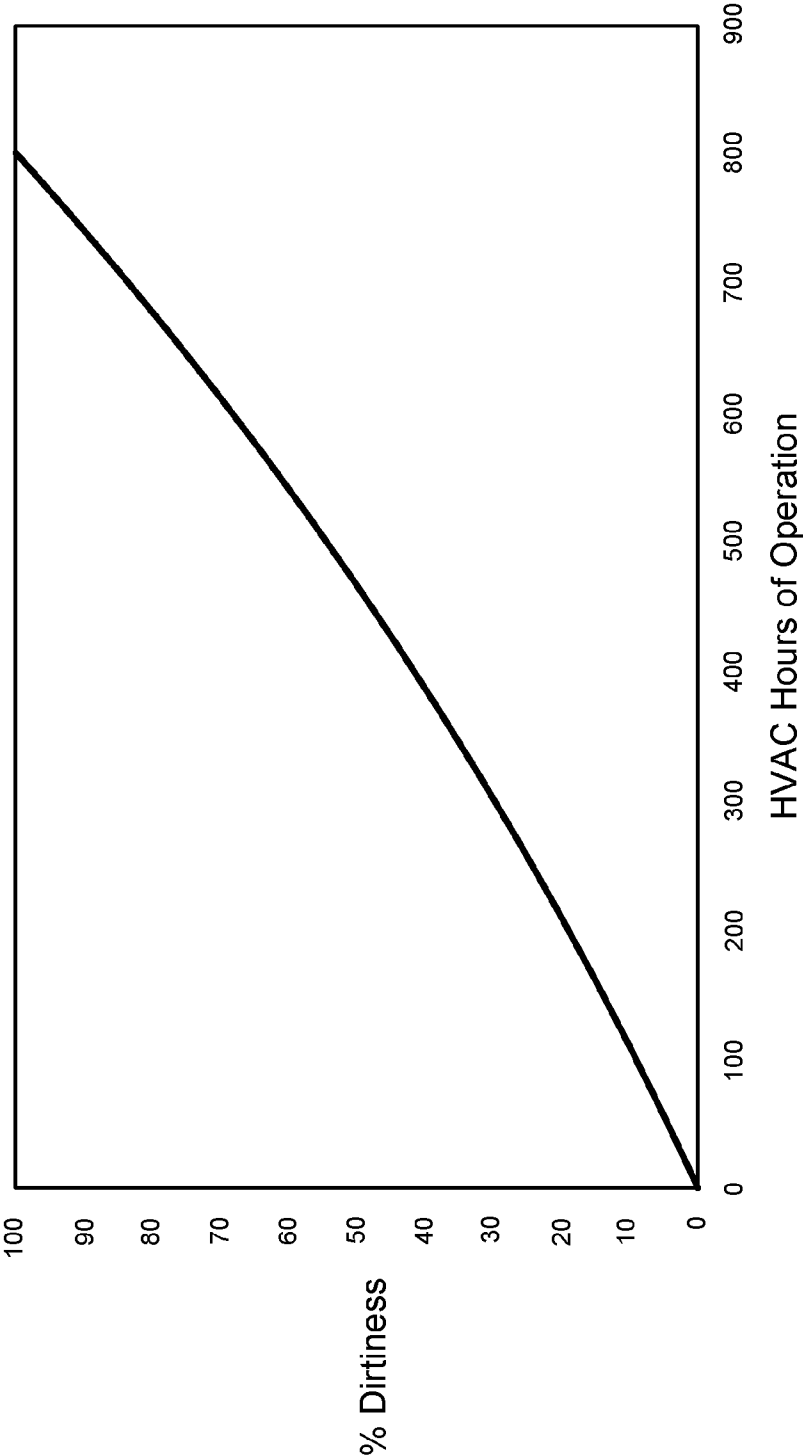


FIG. 34