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Thermal Mass Availability for Cooling Data Centers during Power Shutdown

Kishor Khankari[1], PhD
Member, ASHRAE

Abstract

During power outage servers in the data centers are powered by uninterrupted power supply (UPS). At the same time, the cooling system components such as CRACs, AHUs, and chillers stop operating for a short period until powered by alternate power sources. During this period servers continue generating heat in the data center room without active cooling. It is common notion that data centers contain large thermal mass, and hence, large heat capacity in the steel rack enclosures to protect servers from the thermal shock due to rising room air temperatures. However, the rate of air temperature rise and the availability of rack thermal mass depend on several factors including the height of the data center room, number of rack enclosures and their size, number of rack rows and their layout, and heat load density of a data center. It is crucial for design engineers and facility managers to know how much time can be available for restarting the active cooling systems before servers reach automatic shutoff temperatures. With the help of a heat transfer model this paper systematically analyzes the effect of various parameters and the impact of rack thermal mass on the time that air requires to reach the thermal shutoff threshold temperature.

INTRODUCTION

Continuous supply of electrical power to mission critical facilities is essential not only for uninterrupted operation of servers but also for providing continued cooling to maintain supply air temperatures within the acceptable range of 64.4 F (18 C) to 80.6 F (27 C) (as recommended by ASHRAE thermal guidelines (2). However, during power outage situations servers continue to operate by the power provided by uninterrupted power supply (UPS) units while the supply of cooling air is completely halted until alternate means of powering the cooling system are activated. During this time servers continue to generate heat and the server fans continue to circulate room air several times though the servers. This can result in

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[1] **Kishor Khankari** is Associate Partner at Syska Hennessy GrouP, Ann Arbor, Michigan.

sharp increase in the room air temperature to undesirable levels, which in turn can lead to automatic shutdown of servers and in some cases can even cause thermal damage to servers.

Often alternate means such as thermal storage systems or standby generators are provided to continue cooling operation during the power outage period (3). However it takes some time to restart these systems and resume normal cooling operation (1). It is crucial to understand the rate of temperature rise of the room air during this off cooling period and how long servers can sustain such a situation without automatic thermal shutdown. Data centers contain large number of rack enclosures constructed out of rolled carbon steel. It is important to know what role this large thermal mass can play during this off cooling period. Volumetric thermal capacity of this mass is equivalent to that of water (about 4000 kJ/m^{3}K). The goal of this paper is to evaluate contributions of this thermal mass in attenuating the rise of air temperature during the power outage situation. The rate of such temperature rise depends on several factors including heat load density of data centers, height of data center room, number of rack enclosures and their layout, and the extent of exposed surface area available for utilizing the thermal mass. This paper presents heat transfer analysis to systematically evaluate the effect of these parameters on the extent of air temperature rise of data center facilities.

DESCRIPTION OF HEAT TRANSFER MODEL

The heat transfer analysis developed during this study is based on the hypothesis that the total heat generated by servers during the off cooling period is primarily dissipated to the surrounding air through active recirculation induced by the server fans. Air then dissipates part of this heat to the surroundings through several pathways that includes rack enclosure mass, mass of the cold air trapped under the raised floor, and to the outside world through the building envelop. Thus, the total generated heat is dissipated through various heat transfer pathways is shown in Figure 1 and described by the following equations.

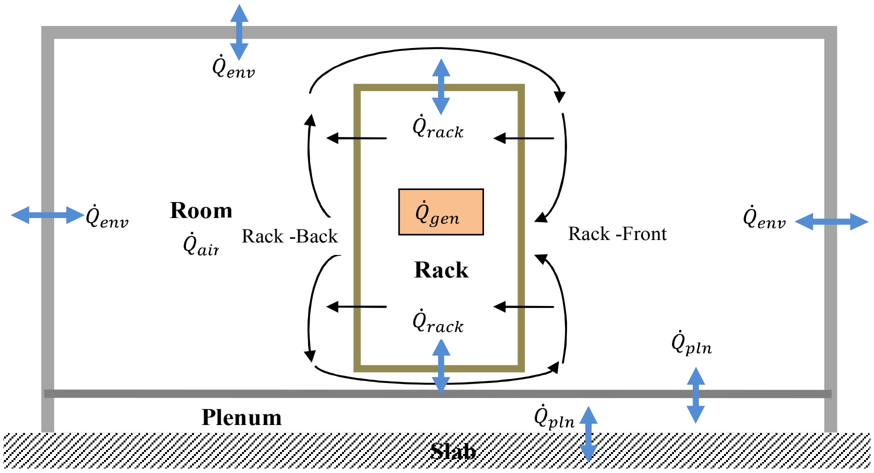

Figure 1: Schematic diagram showing various heat transfer pathways.

$$\dot{Q}_{gen} = \dot{Q}_{air} + \dot{Q}_{rack} + \dot{Q}_{env} + \dot{Q}_{pln} \qquad (1)$$

$$\dot{Q}_{air} = \left(\rho V c_p\right)_{air} \frac{dT_{air}}{dt} \qquad (2a)$$

$$\dot{Q}_{rack} = (UA)_{rack}(\Delta T)_{rack} = \left(mc_p\right)_{rack} \frac{dT_{rack}}{dt} \qquad (2b)$$

$$\dot{Q}_{env} = (UA)_{env}(\Delta T)_{env} \qquad (2c)$$

$$\dot{Q}_{pln} = (UA)_{Tpln}(\Delta T)_{Tpln} - (UA)_{Bpln}(\Delta T)_{Bpln} = \left(\rho V c_p\right)_{air} \frac{dT_P}{dt} \qquad (2d)$$

The rate of heat transfer mechanisms between the air and the other components, as shown in the equation (2), depends on their respective heat transfer coefficients (U), exposed surface area (A), and their respective temperature differences (△T) with the room air. The rate of air temperature rise can be potentially reduced if the rate of heat transport to these other components such as rack enclosures can be enhanced. However, these rates depend on the design and layout of the data center. This is further discussed under the results and discussion section.

The above heat transfer model is a zero dimensional model and assumes all spatial variations within the data center are negligible. It is assumed that all the heat generated by the servers is primarily carried away by convection mechanism of the circulating air. The air in the data center room is assumed to be well mixed, and hence, assumes a single mixed temperature. Since the air is rapidly moved by the server fans this assumption is quite reasonable. Also all the rack enclosure mass assumes a single temperature. The resistance to heat transfer within the rack mass is assumed to be small due to large thermal conductivity compared to the heat transfer coefficient on the surfaces. It should be noted the thermal mass of racks considered in this analysis does not include the thermal mass of servers. Unlike rack enclosures the servers are assumed primarily as a source of heat generation, and therefore, their associated thermal mass is not available for the room air to reject heat. All references to rack mass or rack surface area in this paper refer to those of rack enclosures. It is further assumed that initially, right after the power outage, the room air and the rack mass are in thermal equilibrium and assume a certain average initial temperature. Heat transfer due to the other thermal masses such as ducts, pipes, building components, and coils in the air handler units are not considered in this analysis. The rate of heat generation from servers is assumed to be constant over the period analysis.

When air handler fans are placed on UPS, then the cold air in the supply plenum can be circulated at least for some time to provide cooling right after the power outage (3). This analysis assumes air handler fans are not connected to UPS, and hence, due to thermal stratification the cold air in the supply plenum is trapped under the raised floor. In this situation as shown in the equation (2d), the hot air from the data center room can transfer heat into the cold plenum while the plenum air can exchange heat with the ground through the slab. Thus, the hot air in the data center room can indirectly exchange heat with the ground. In the case of flat floor data center, the room can directly exchange heat with the ground through slab. The analysis of flat floor data center is not part of this paper.

The rate of heat transfer to rack mass depends on the extent of the surface area of the racks exposed to the surrounding moving air. For most racks only top and bottom surfaces are available for exchanging the heat. In addition, side faces of the end racks located at the end of each rack row are available for such exchange. The net available surface area of the racks can be calculated by the following equation (3). Note the available surface area increases with the size of racks, number of racks, and with the number of rack rows.

$$A_{rack} = 2D(N_{rack}W + N_{row}H) \tag{3}$$

Ideally the maximum surface area of racks would be available if all the racks have side panels and are separated from each other to allow passage of air. However, such an arrangement is not practical first due to the requirement of large floor space and secondly to avoid any air leakage between the cold and hot aisles during the normal operation.

In order to understand the effect of thermal mass on lowering the air temperature rise in the data center, a hypothetical case is considered where all the heat generated by servers is entirely absorbed by the room air. In this situation, the heat transfer model in equation (1) becomes

$$\frac{dT_{air}}{dt} = \frac{\dot{Q}_{gen}}{(\rho V c_p)_{air}} \tag{4}$$

This trend in the rise in the air temperature is shown for comparison in a few cases to evaluate the impact of the rack thermal mass in reducing the air temperature.

DESCRIPTION OF THE CASES ANALYZED

A list of various parameters analyzed with their respective levels is shown in Table (1). A 2500 sq.ft. data center with heat load density of 200 W/sqft consisting of a total 100 rack enclosures arranged in 10 rack rows was considered as a base case. A total of five additional cases were analyzed by systematically varying room height (Case 1), heat load density (Case 2), weight of racks (Case 3), number of rack rows (Case 4), and number of racks (Case 5) from the base case parameters. As shown in the Table (1) efforts were made to vary only one parameter at a time to clearly understand its effect on the air temperature rise. A total 3 levels (1 base case level and 2 additional levels) of each parameter were analyzed. As shown in the Table (1) the initial average temperature of room air, rack mass, and that of the air in the under floor plenum were kept at the same levels for all the cases. Similarly the ambient and ground temperatures were kept constant in all the cases. Table (1) also shows values of various thermal conductances employed in this analysis. It should be noted that the value given for the rack thermal conductance is for a single rack. In the case of multiple racks as considered in this analysis, the value of rack thermal conductance becomes much larger compared to the conductnaces of other heat transfer pathways. The heat transfer model described in the previous section was employed to study the effect various parameters on the rise in air temperatures in a data center. The heat transfer equations were solved numerically for a total duration of 5 minutes of the off cooling period.

Table 1: List of parameters employed in the analysis.

Parameter	Base Case	Case 1 (room height)	Case 2 (heat load density)	Case 3 (rack weight)	Case 4 (number of rack rows)	Case 5 (number of racks)
Room Area, sq.ft.	2500 (232.2 m2)					
Room height, ft	10 (3 m)	15 ft (4.6 m) 20 ft (6.1 m)				
Supply plenum height, ft	3 (0.9 m)					
Heat load density, W/sqft	200 (2153 W/m2)		50 (538 W/m2) 100 (1076 W/m2)			
Heat load per rack, kW	5		1.25, 2.5			20, 10
Length (ft)	4 (1.2 m)					
Width (ft)	2 (0.6 m)					
Height (ft)	6.5 (1.98 m)					
Weight per rack (lb)	250 (113 kg)			200 (90.7 kg) 300 (136 kg)		
Racks per row	10				20, 5	
Number of rack rows	10				5, 20	2.5, 5
Number of racks	100					25, 50
Initial temperature of air, F	65 (18.3 C)	Thermal conductance (W/K)				
Initial temperature of rack mass, F	65 (18.3 C)	Single Rack	197			
Initial temperature of plenum air, F	60 (15.6 C)	Building Envelop	123			
Ambient air temperature, F	72 (22.2 C)	Plenum top	130			
Ground temperature, F	60 (15.6 C)	Plenum bottom	58			

RESULTS AND DISCUSSION

Results of the analysis are presented mainly in three formats: 1) variation of room air temperature with time (Figure 2); 2) time required for the air temperature to reach server shut off threshold temperatures of 95F and 125F (Figure 3); 3) how the total heat generated by servers is absorbed among various heat transfer pathways is expressed as percent of the total generated heat during the 5 minutes period (Figure 4).

A few general observations from the results of this analysis which are common in all the cases are as follows. Figure 2 indicates the rate of rise of air temperature reaches almost a constant value within five minutes in all the cases. This stage is generally reached when a certain constant temperature difference between the air temperature and the temperature of the racks mass is attained. Secondly, the results for all the cases as shown in Figure 3 indicate that higher server shut off temperature (125 F) provide significantly larger time window to power the alternate cooling systems than that for the lower temperature of 95 F. In fact in most cases, with couple of exceptions, air reaches 95F temperature within 50 seconds. Finally only less than 2 percent of the total generated heat is dissipated to the under floor plenum and through the building envelop while rest of the heat is mainly absorbed by the room air and the rack mass (Figure 4). The results for each case are discussed in detail below.

Case 1: Effect of Room Height

Increasing the room height increases the heat capacity of the room air. As a result, for identical data centers with the same number of racks and heat load, taller rooms can keep the air temperature lower and hold more heat. As shown in Figure 2a and Figure 3, for every 5 ft increase in the room height, the time required to reach 95 F threshold temperatures increased by about 50 percent and that by about 25 percent to reach 125 F temperatures. In other words, by increasing the room height from 10 ft to 20 ft, the time required for reaching 95 F threshold temperature increased almost by a factor of 2 and by a factor of 1.5 for the temperature of 125 F. It should be noted that room height has significant effect on the air temperature rise during the first few seconds when the temperature difference between the air and rack thermal mass is still low. Figure 2a also shows corresponding variations in the rack mass temperature. It should be noted the rate of heating of air and rack mass and the temperature difference between the room air and rack mass almost reaches a constant value after about 90 seconds. Figure 4 indicates with increase in room height the percent heat absorbed by the room air increases and that of the rack mass decreases. With respect to the air heat capacity, the rack containment systems have order of magnitude less heat capacity of the air than that in the data centers. Such systems with high heat load can reach very high air temperatures in a very short time during the power outage situation.

Case 2: Effect of Heat Load Density

The rate of heat generation directly affects the rate of heating of the room air. For identical data centers with similar dimensions and the same number of racks and layout, low density data centers can provide significantly larger time window to start cooling operation during the power outage than that for high density data centers. Figure 2b and Figure 3 show in the case of 50 W/sqft and 100 W/sqft heat load densities, the room air temperature did not rise beyond 84 F and 102 F, and hence, did not reach the threshold temperatures during the 5 minute period. On the other hand, in the case of 200 W/sqft heat load density, the room air temperature reached 140 F during the same time while reaching 95 F and 125 F threshold temperatures just after 45 and 193 seconds, respectively. It should be noted, as shown in Table 1, in all these cases the number of racks was kept to constant value of 100. This resulted in lower heat load per rack for low density data centers. Also, it kept the ratio of room heat capacity to the rack mass heat capacity constant. As a result, as shown in Figure 4, the heat load density did not affect the relative distribution of the heat absorbed between the room air and the rack mass.

Case 3: Effect of Weight of Racks

Increasing the weight of racks increases the thermal mass (heat capacity) of racks. This helps in keeping the rack mass temperature down, which in turn, can help in keeping larger temperature difference between the room air and the rack mass. However, this factor has only secondary effect on the room air temperature. The primary link between the room air and the rack thermal mass is the thermal conductance (UA factor) as shown in the equation (2b). Since the number of racks and number of rack rows were kept constant in all these cases, the surface area for heat transfer remained the same. Therefore, weight of the racks alone has marginal effect on keeping the air temperature down especially during a few initial seconds of the power outage. As indicated in Figure 2c, the effect of rack weight becomes significant only after 80 seconds of heating, and therefore, the threshold temperature of 95 F are reached almost at the same time of 45 seconds in all the cases. However, when the servers are set for higher threshold temperature of 125F, every 50 lb increase in the rack weight increased the time required to reach the threshold temperature by about 12 per cent. The curve for 0 lb rack weight indicates absence of any rack thermal mass and shows hypothetical rise in the air temperature according to equation (4). This trend in comparison with the other curves indicates how rack thermal mass helps in attenuating the rate of temperature rise of room air. As expected, Figure 4 shows due to increase in the heat capacity the rack mass absorbs more heat than that of room air.

Case 4: Effect of Number of Rack Rows

As mentioned before and indicated by equation (3), increasing the number of rack rows increases the available surface area for heat transfer between room air and the rack mass. This factor affects the availability of rack thermal mass for heat transfer, and therefore, affects the room air temperature more significantly than the weight of the racks alone. It should be noted that in all these cases all the other parameters including the weight of the racks are kept at the same levels. As shown in Figure 2d and in Figure 3, increasing the rack rows from 5 to 20, the time required to reach the server shut off temperature of 95 F and 125F increases by 26 and 48 percent, respectively. Due to increased surface area and resulting increase in the rate of heat transfer; increase in the number racks rows increases the percent of the total heat absorption by the rack mass as shown in Figure 4.

Case 5: Effect of Number of Racks

This factor combines the previous two factors together. Increase in the number of racks increases the thermal mass of racks as well as its availability by increasing the total heat transfer surface area. As shown in Table 1, the size of the data center as well as the heat load density kept at the same level as in the base case. Therefore, fewer racks mean more empty space in the data center resulting in higher heat load concentrated at one location with high heat density racks. On the other hand, increasing the number of racks resulted in more distributed heat load in the entire data center. As shown in Figure 2e and in Figure 3, increase in the number of racks from 25 to 50 and from 25 to 100 increased the time required for the room air to reach 95F threshold temperature by 13 percent and 45 percent, respectively. However, for similar increase in the number of racks air would take 28 percent and 180 percent more time to reach 125 F threshold temperatures, respectively. This analysis again indicates significant advantage of increasing the server shut off threshold temperatures to higher levels. Figure 2e also shows with fewer racks the rate of air temperature rise reaches close to the hypothetical maximum rate as per equation (4). With increased thermal mass and increased heat transfer surface area result in higher percentage of the total generated heat absorbed by the racks as shown in Figure 4.

SUMMARY AND CONCLUSIONS

A zero dimensional heat transfer model was developed to understand the rate of heating of the room air and the time it requires for room air to reach certain server shutoff temperature under the power outage situation in a data center. Several factors were evaluated to study the effect of rack enclosure thermal mass on attenuation of the rate of room air heating. This analysis indicated that rack thermal mass can play important role in keeping the room air temperature down during the power outage situation. However, availability of this thermal mass depends on the extent of the exposed surface area of the racks which can increase by increasing the number of racks and number of rack rows. Also the room height plays a significant role in keeping the air temperature low especially during the initial seconds of power outage. Servers with high thermal shutoff threshold temperatures can provide significantly longer time for cooling systems to activate. In general data centers with higher room heights, large number of rack enclosures arranged in large number of rack rows, and equipped with severs that can sustain higher temperatures before automatic thermal shutoff can provide substantially longer time for the cooling systems to activate. Low density data centers with these attributes have the lowest risk for server thermal shutoff and can provide even longer time than that of the high density data centers for activating the cooling systems.

NOMENCLATURE

A_{rack} = Surface area of rack thermal mass (m^2)

H = Height of rack enclosures (m)

D = Depth of rack enclosures (m)

W = Width of rack enclosures (m)

N_{rack} = Number of rack enclosures

N_{row} = Number of rack rows

$\dot{Q}_{gen}$ = Rate of heat generation from servers (W)

$\dot{Q}_{air}$ = Rate of heat absorbed by room air (W)

$\dot{Q}_{rack}$ = Rate of heat loss to rack enclosures (W)

$\dot{Q}_{env}$ = Rate of heat loss to building envelop (W)

$\dot{Q}_{pln}$ = Rate of heat loss to under floor plenum (W)

T_{air} = Temperature of room air (K)

T_{rack} = Temperature of rack thermal mass (K)

T_p = Temperature of air in the plenum (K)

T = Time (s)

$(\rho V c_p)_{air}$ = Heat capacity of room air (J/K)

$(mc_p)_{rack}$ = Heat capacity of rack mass (J/K)

$(UA)_{rack}$ = Thermal conductance between room air and rack thermal mass (W/K)

$(UA)_{env}$ = Thermal conductance between room air and building envelop (W/K)

$(UA)_{Tpln}$ = Thermal conductance between room air and raised floor (W/K)

$(UA)_{Bpln}$ = Thermal conductance between plenum air and ground slab (W/K)

$(\Delta T)_{rack}$ = Temperature difference between room air and rack thermal mass (K)

$(\Delta T)_{env}$ = Temperature difference between room air and ambient air (K)

$(\Delta T)_{Tpln}$ = Temperature difference between room air and plenum air (K)

$(\Delta T)_{Bpln}$ = Temperature difference between plenum air and ground (K)

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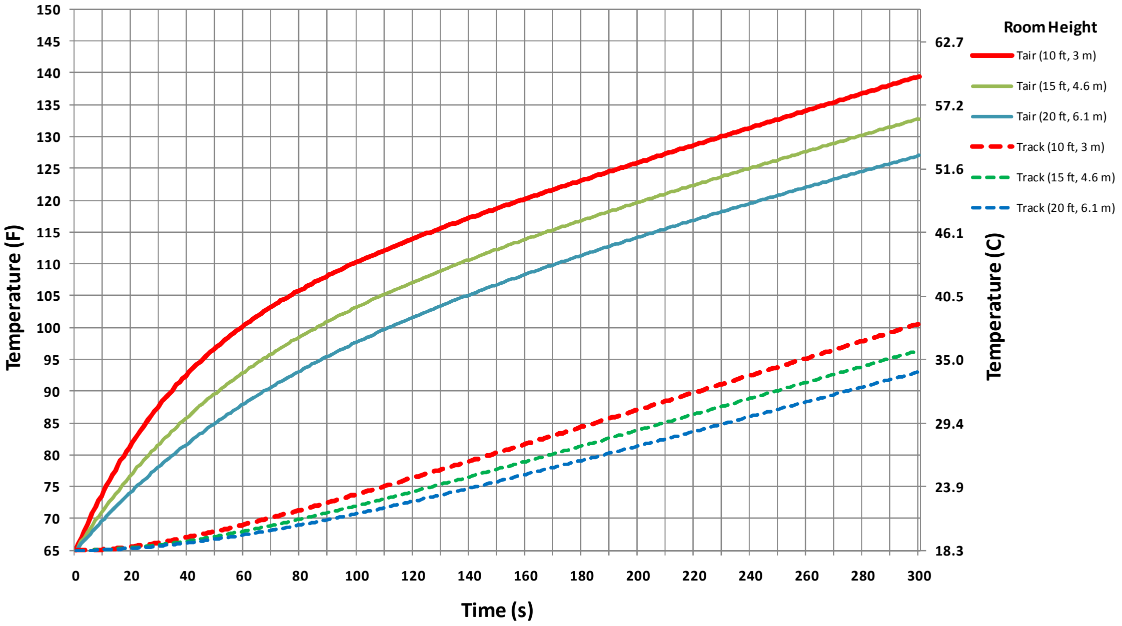


Figure 2a: Variation of room air temperature with time for various room heights (Case 1)

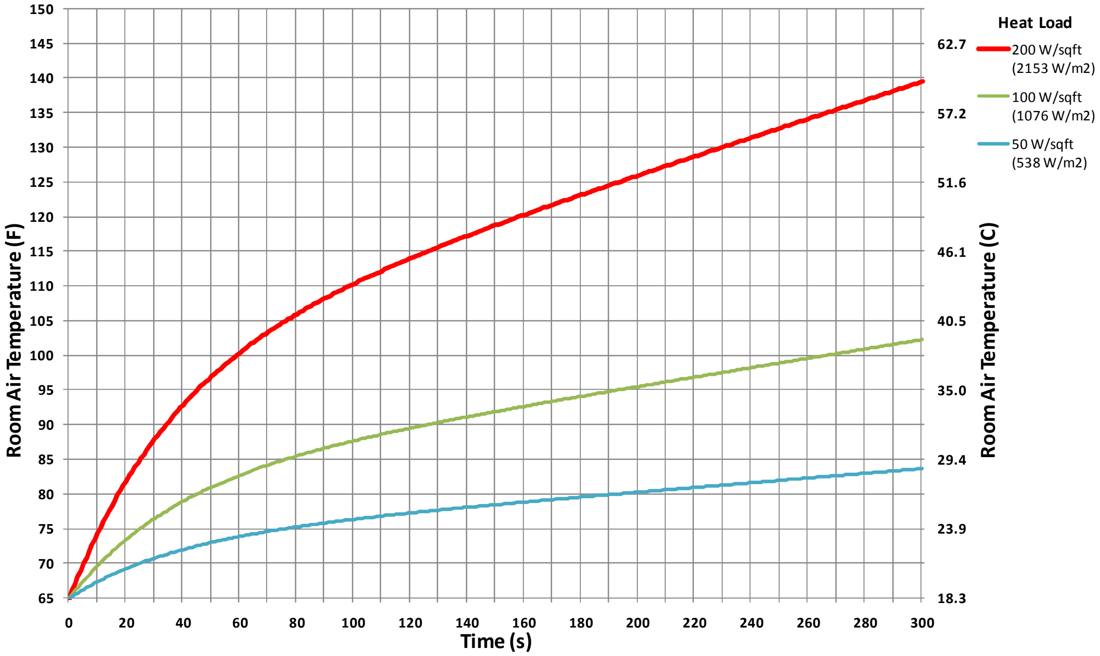


Figure 2b: Variation of room air temperature with time for various heat loads (Case 2)

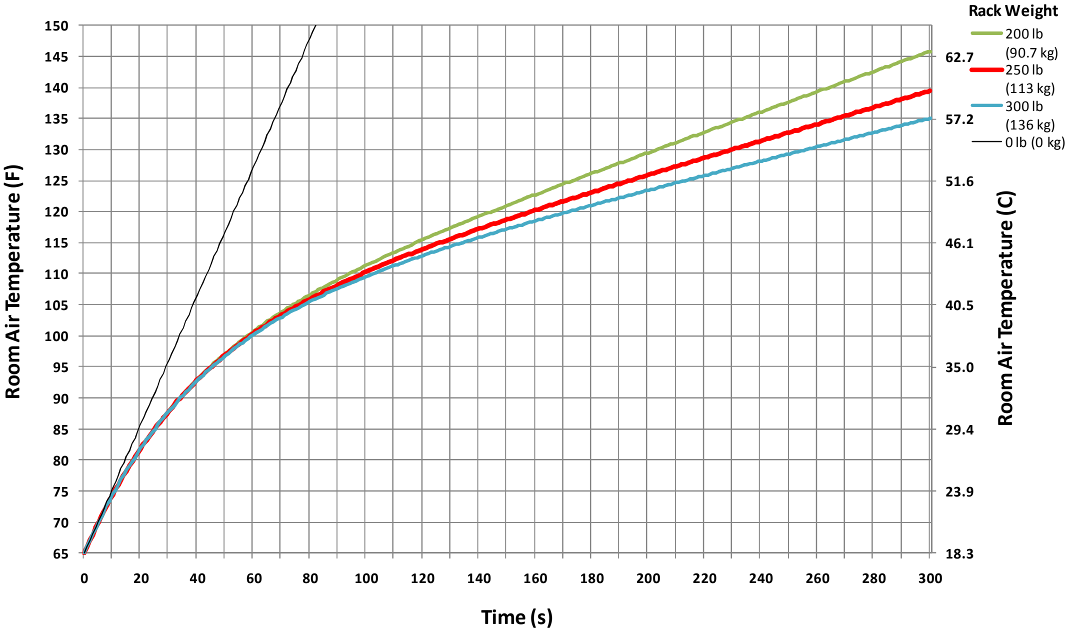


Figure 2c: Variation of room air temperature with time for various rack weights (Case 3)

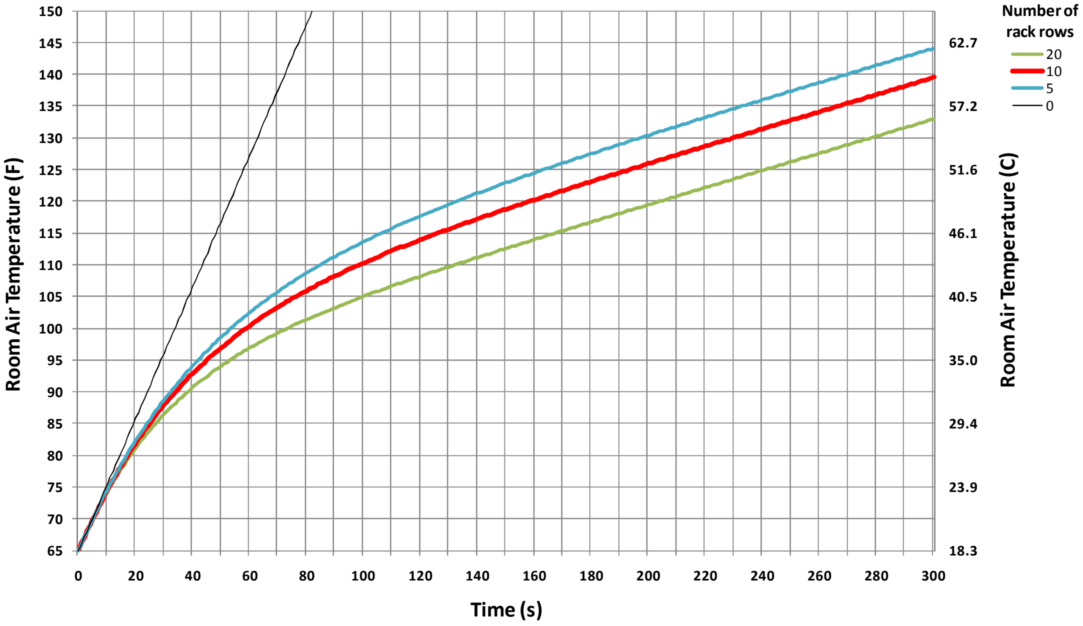


Figure 2d: Variation of room air temperature with time for various number of rack rows (Case 4)

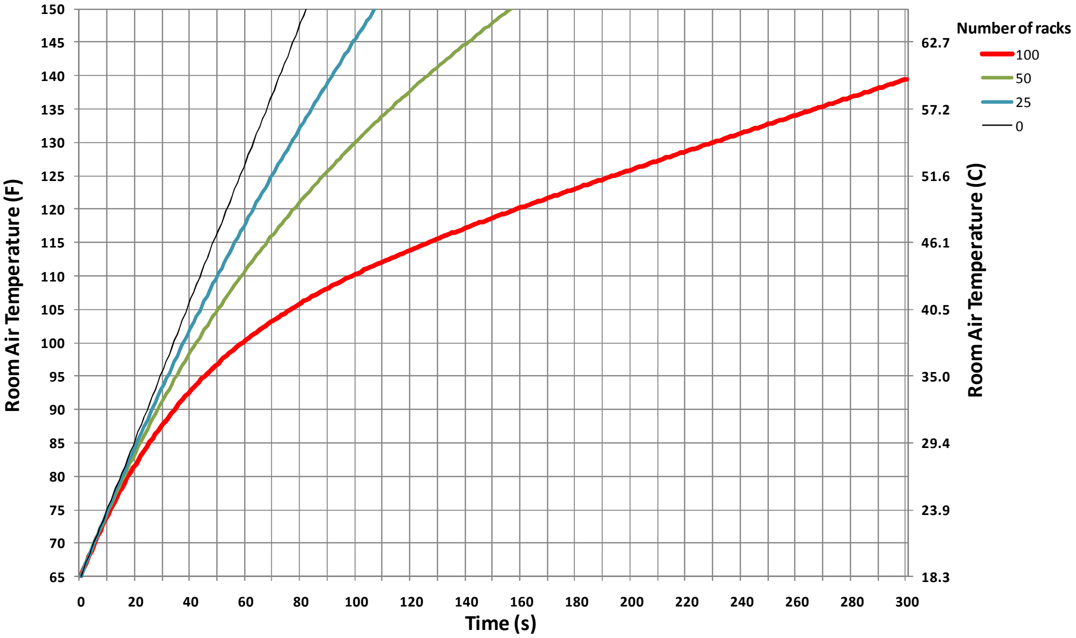
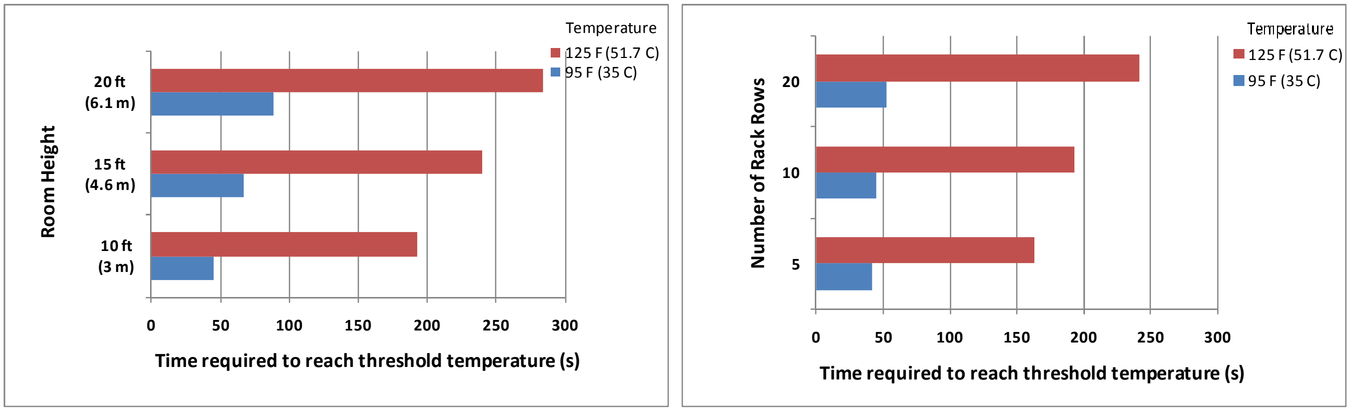
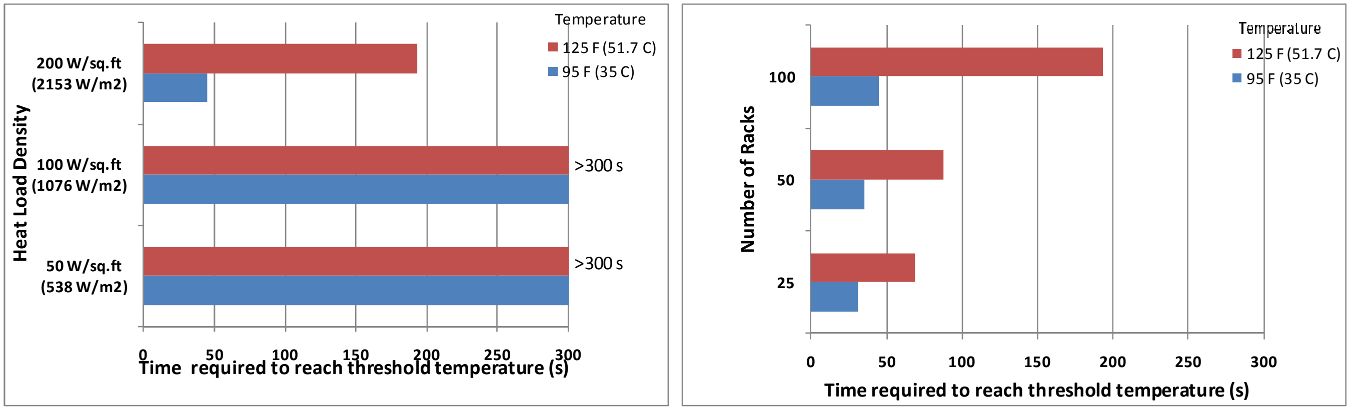


Figure 2e: Variation of room air temperature with time for various numbers of racks (Case 5)



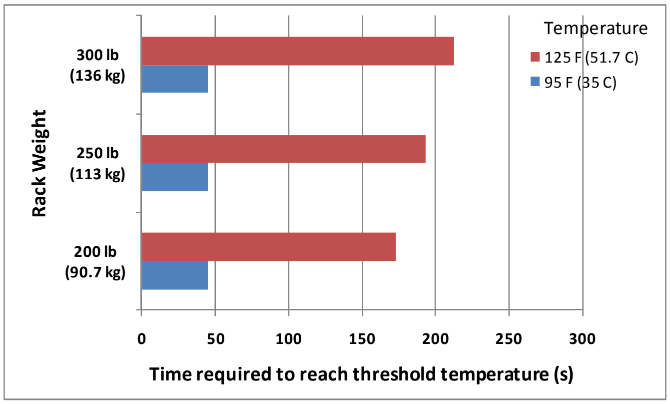
Case 1: Effect of room height

Case 4: Effect of number of rack rows



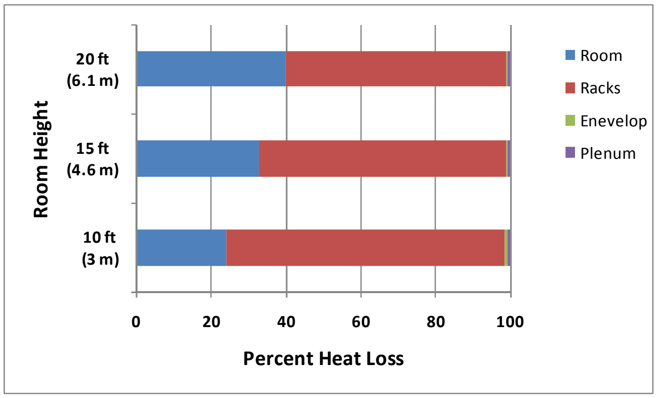
Case 2: Effect of heat load density

Case 5: Effect of number of racks

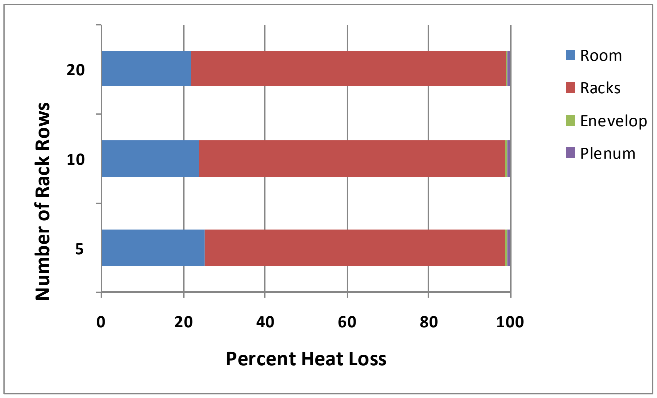


Case 3: Effect of rack weight

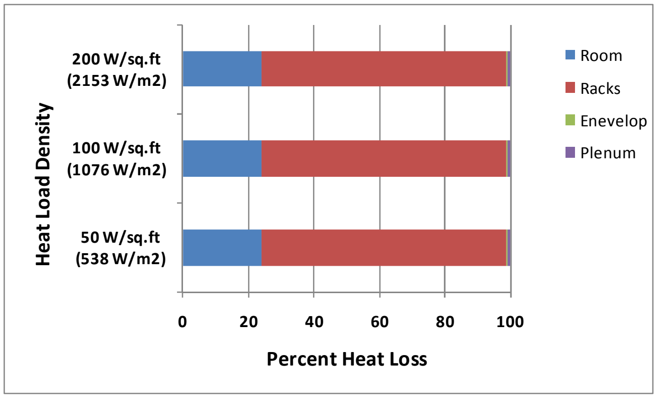
Figure 3: Effect of various parameters on the time required to reach server shutoff threshold temperatures in a data center.



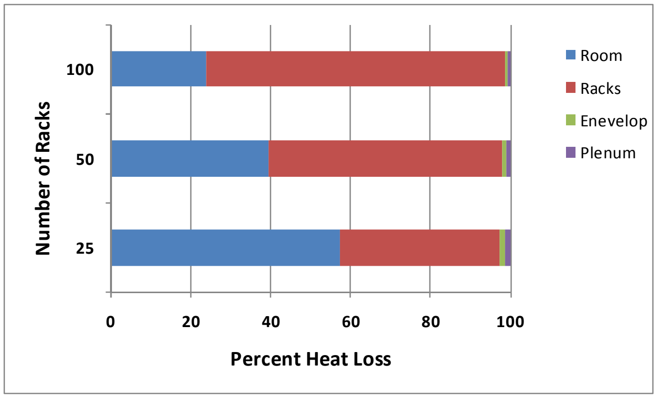
Case 1: Effect of room height



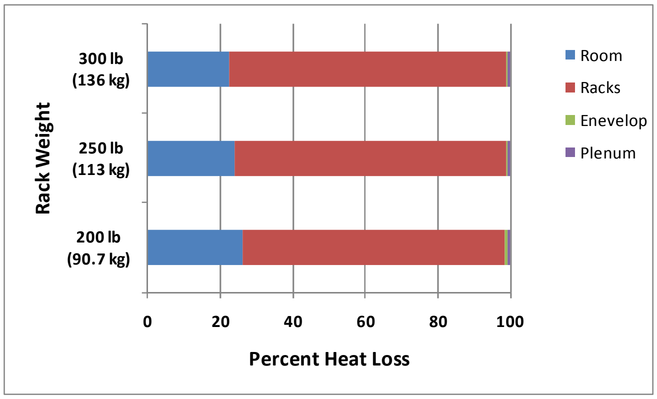
Case 4: Effect of number of rack rows



Case 2: Effect of heat load density



Case 5: Effect of number of racks



Case 3: Effect of rack weight

Figure 4: Effect of various parameters on the percent of the total heat loss to various components in a data center.