COMPUTER ROOM COOLING

WHITE PAPER

Best Practices & Concepts for Computer Room Cooling

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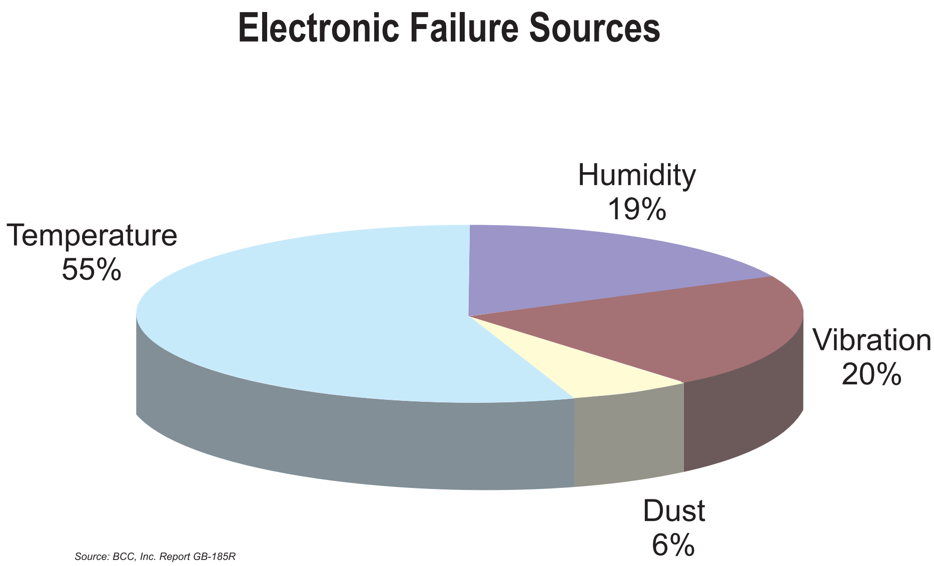
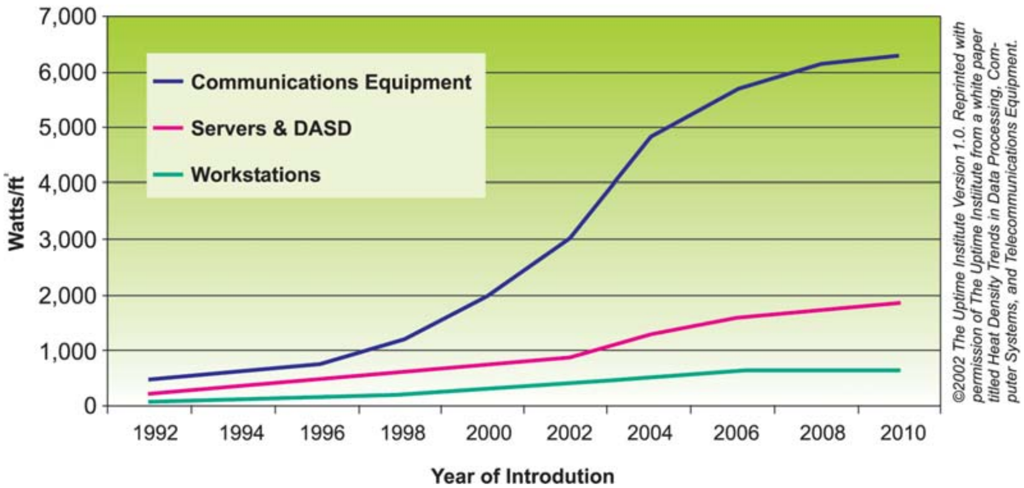
Computer equipment cooling air delivered from a raised floor air source can be optimized by applying some basic thermal management concepts, which sometimes contradict conventional wisdom or intuition. This optimization can either produce increased cooling or reduced cooling costs, and often both apparently mutually exclusive objectives can be met simultaneously. This paper will review the effects of heat on computer equipment and some of the benefits of improving cooling, before offering some insights on how to actually deliver that improved cooling, based on some simple principles of conduction and forced convection heat transfer and an understanding of fluid dynamics both under the raised floor and within an equipment enclosure.



Heat is the enemy of electronic equipment. According to BCC, Inc. "Report GB-185R," over half of electronic failures are caused by temperature, and, since those heat sources are transistor densities and speed, which are continuing to increase, the logical conclusion, everything else being equal, is that those failure rates will continue to climb. As a matter of fact, according to the Industry Cooling Consortium, consisting of IBM, HP, Dell, Nortel, Cisco among others, we are right now in the middle of the steepest growth slope in heat densities (watts per square foot) for most computing and communication electronic equipment, as reported in a white paper by the Uptime Institute.

Data Center Thermal Load Forecast

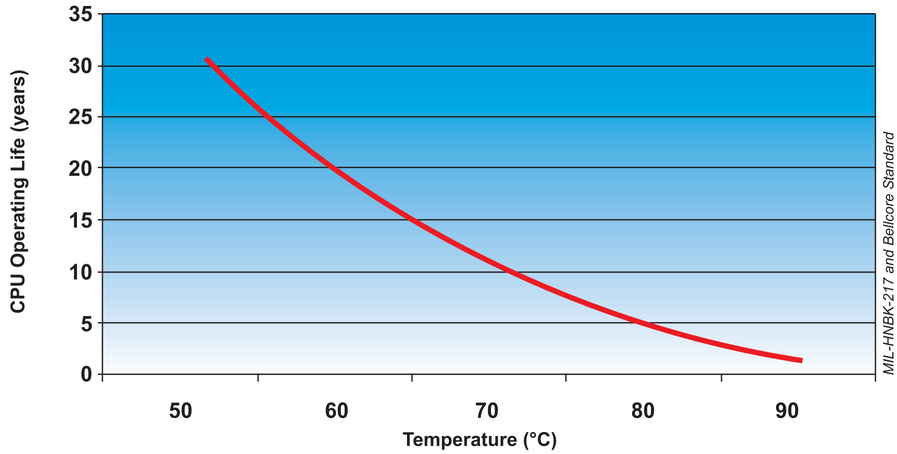


The flattening out of these curves around the years 2005-2007 should not be interpreted as reason to believe we only need to cool heat loads that will not quite be doubling over the foreseeable future. This forecast was based on the Consortium's original assumption that Moore's Law, a primary heat driver wherein transistor counts per chip double every eighteen to twenty four months, would finally start to reach its physical boundaries. Subsequent to the release of this report, Gordon Moore has forecasted at least another decade of this density growth trend, so we can now plan on dealing with communication equipment heat loads that will double by the year 2005 to a sizzling 6000+ watts per square foot and server and storage equipment heat loads increasing to 2000 watts per square foot in another three years and then increase another 1000 watts in another six years, conservatively assuming a continuing linear relationship between transistor-count growth and temperature increases.

The grapevine noise is that some chipmakers already are capable of producing significantly faster and more powerful microprocessors, but are not able to deploy them in real applications in the market because of the lack of solutions for the extra heat. Therefore, everyone who contributes to cooling those microprocessors, whether at the chip level, board level, shell level or rack/cabinet level, becomes a technology-enabler for new generations of computing power.

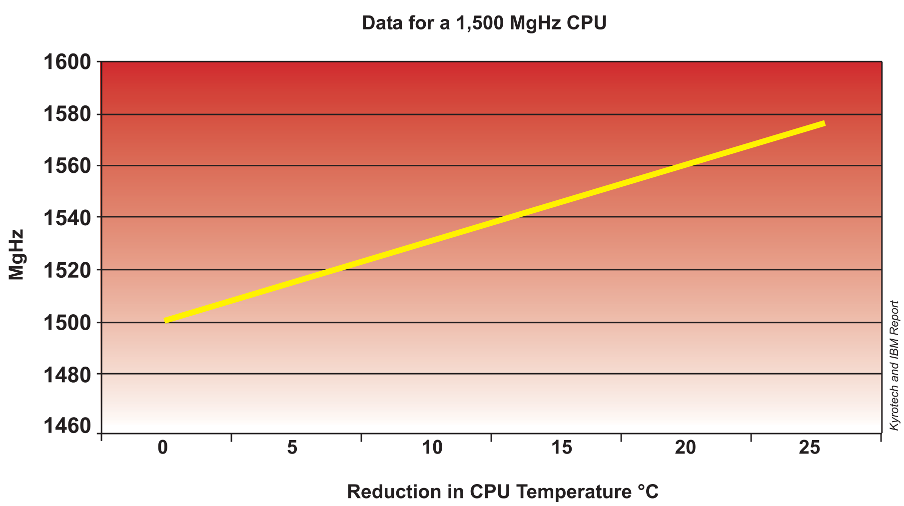
Temperature affects IT hardware in a variety of ways and often seemingly inconsequential changes can have significant performance and economic impacts. Arrhenius reactions result in shortened capacitor life and semiconductor degradation at elevated temperatures. A good rule of thumb is that every 10°C increase in ambient temperatures produces a 50% reduction in long-term reliability of IT hardware. In fact, both military standards and Telcordia standards have correlated CPU operating life to temperature. It is interesting to note that most CPU operating temperature ranges have upper limits around 95°C, but the MIL-HNBK-217 and Bellcore data suggest that running continuously at that temperature level will limit CPU life to a year or less, while a 5°C reduction can actually triple the life expectancy of that equipment.

Thermal Management Protects Against Premature Failure



Temperature also effects clock speed. For a 1500 MHz CPU, every 10°C temperature reduction results in a 2% increase in clock speed. While 2% may not seem particularly significant, in a larger data center dedicated to processing large numbers of transactions with 2 RMU servers, losing that extra 2% of transaction turnover means having to buy and install an otherwise unnecessary server every two and-a-half racks.

2% Clockspeed Increase For Every 10C° CPU Reduction



With an understanding of the impact of high temperatures on CPUs and the promise of performance and economic benefits to be derived from applying more cooling to IT hardware, our informed and exuberant computer room manager needs to guard against the temptation to invest in more computer room air conditioning units (CRAC) or to merely crank down the thermostat. In some instances, these actions will merely be wasteful; in others, the colder air may actually result in creating a more serious heat problem. The first recommended course of action is to manage the air movement under the floor tiles and then to manage how the cooled air is actually delivered to the equipment. When this is done well, we have seen CRACs removed from service and thermostat temperatures raised while cooling has improved.

Proper air management depends on having at least a basic understanding of how the principles of forced air convection heat transfer rates are responsible for equipment cooling. Most rack-mounted equipment is fan-cooled. Typically, these are 10-30 CFM axial fans that draw the air in the front and exhaust it out the rear, though there are an isolated handful of product platforms that move the air from side-to-side. Inside the equipment, conduction heat transfer takes place in the direct-contact molecular interaction between a microprocessor (or its socket) or other heat source and a heat sink. Then forced air convection heat transfer takes place as the air that is drawn in the front of the equipment by the small axial fans passes across the heat sink. That function is described in the following equation:

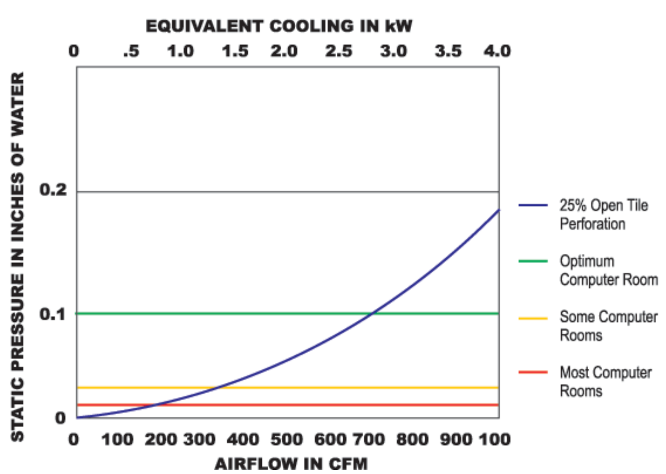
$$Q = hA(T_w - T_f)$$

Where q = the heat transfer rate
h = the convection heat transfer coefficient
A = the surface area
Tw= the temperature of the surface
Tf= the temperature of the fluid

While historical practice and conventional wisdom have typically focused on getting the heat out of the cabinet and fretting over hot spots (usually somewhere around the upper rear of the cabinet), the principles of forced air convection heat transfer indicate clearly that the real benefit to CPU performance and life results from the delivery of the coldest available air directly to the conductive surface area attached to the microprocessor. In fact, in the dynamics of heat transfer, the temperature of the delivered air (Tf) is the only variable over which the equipment installers and users have any control and is the objective of air movement management.

Managing air movement is quite simply just a matter of putting the air to work where it is needed and the first step in that process is to reduce bypass air – air that is escaping from under the floor to places where it is not doing its cooling work. Triton Technologies has mapped the under floor cooled air in over a hundred computer rooms and data centers and has found that in the vast majority of sites 50-80% of the air delivered into the room is bypass air. Reducing bypass air has multiple benefits. First, sealing off all the escape points for bypass air will raise the static pressure under the raised floor which will in turn increase the air flow (CFM) at the points of need. The chart below correlates static pressure to CFM to cooling delivered.

Relationship Between Under-Floor Static Pressure & Cooling



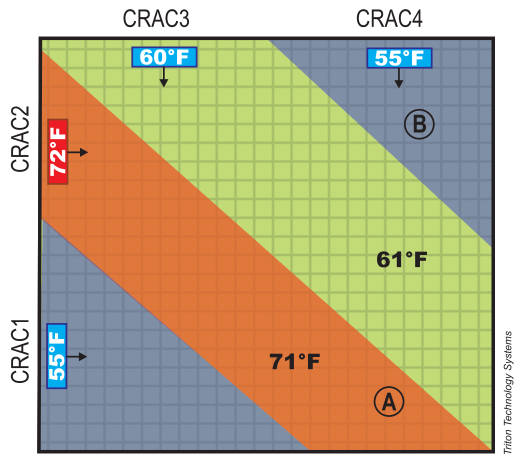
Computer rooms with 50-80% bypass air will have static pressure under the raised floor of approximately 0.01″ of water, which will deliver around 200 cubic feet of air per minute through a 25% open perforated floor tile. That air delivery equates to around 700 watts of cooling, which, based on the heat load curve developed by the Industry Cooling Consortium previously discussed, is well short of the cooling required for one fully loaded cabinet. Furthermore, since typical computer rooms will be laid out so two to four cabinets will share the air from one perforated tile, the cooling is woefully inadequate that is delivered by that 200 CFM air flow. By blocking off enough of the bypass air to raise the static pressure under the floor to 0.025″ of water, the air flow through that floor tile will increase from 200 CFM to 350 CFM thereby delivering, without any changes to the CRAC or air handler settings, nearly double the cooling at around 1.3 kW. That cooling may now be adequate for at least one cabinet full of equipment. However, by sealing off enough bypass air to raise that static pressure to 0.1″ of water, the air flow through that floor tile is increased to 700 CFM and the resultant cooling delivered is increased to 2.8 kW.

There are three primary sources of bypass air to contend with to realize the cooling benefits of optimized static pressure. Cooled air can actually escape the room through open doors and through the access points into the room under the raised floor for cable, power and plumbing. Keeping doors closed is a simple matter of common sense discipline. Under the floor, however, most FM200 fire suppression systems will require that points of entry are already sealed. Otherwise, those points of entry should be sealed with any standard plenum-rated foam, fabric or other pliable material. A second source of bypass air is removed floor tiles. Again, a little information-based discipline is usually adequate to keep floor tiles where they belong when access under the floor is not immediately required. The largest source of bypass air is innocent, intentional mis-location of floor tile openings.

Floor tile openings may be any holes cut in the floor tiles, primarily for cable pass-through, or any of a wide variety of standard grills and perforation patterns and these openings are typically deployed around computer rooms in counter-productive arrangements. As noted in the static pressure discussion, the only cold air escape should be where cold air is required for forced air convection to drive a higher heat transfer rate across the heat sources. Therefore, perforated tiles located around open work areas for human comfort are effectively reducing under-floor static pressure, reducing cold air CFM at points of need, reducing heat transfer rates, and thereby reducing CPU performance. Even worse, however, are floor tile openings located where the heat is. I have seen a data center organized correctly into hot aisles and cold aisles and then a manager had complained about being too hot while walking behind cabinets and had some perforated floor tiles installed in those aisles to “help move the hot air out.” Not only is this action reducing the effective cooling delivered to the servers and other equipment mounted in the cabinets, it is cooling the heated air before it returns to the CRAC to be chilled and re-circulated. CRAC efficiency is driven by the wide difference between the source air temperature and return air temperature and the general rule of thumb is that every two degree reduction in that difference results in a 10% reduction in CRAC efficiency, primarily due to energy required to maintain a stable relative humidity. For example, a 2°F reduction in that temperature difference would lead one 20 ton CRAC to produce 2000 gallons of water in a year to re-humidify source air after the cooled return air had been dehumidified. Leaving the cable access ports in floor tiles in the rear of cabinets unsealed around the cable is the worst source of bypass air. Since there will be one opening per cabinet, the sheer volume of escaped air will be greater than any other source. In addition, by delivering the coldest available air directly to the warmest equipment exhaust air, the whole problem of reducing the temperature differential between source air and return air is multiplied. Cable can be sealed around with plenum pillows, plenum foam or special panel cut-out inserts with brushes to close around the cable.

Increasing static pressure alone does not guarantee an optimum flow of chilled air to the most critical points of need – air delivered under the raised floor is directional and must be managed properly. Triton Technology Systems, a marketer of raised floor air management products and services, has accumulated an extensive body of empirical research indicating not only that air streams from CRACs tend not to mix, but if the CRACs are located at right angles to each other they will cause their cooled air output patterns to be diverted in angles that cannot be predicted by return air patterns in the computer room above the floor. At best, these patterns will result in the wasted expense of inefficiently operating cooling equipment; at worst, they will create hot spots in a computer room that will jeopardize the performance of computing equipment and the integrity of data.

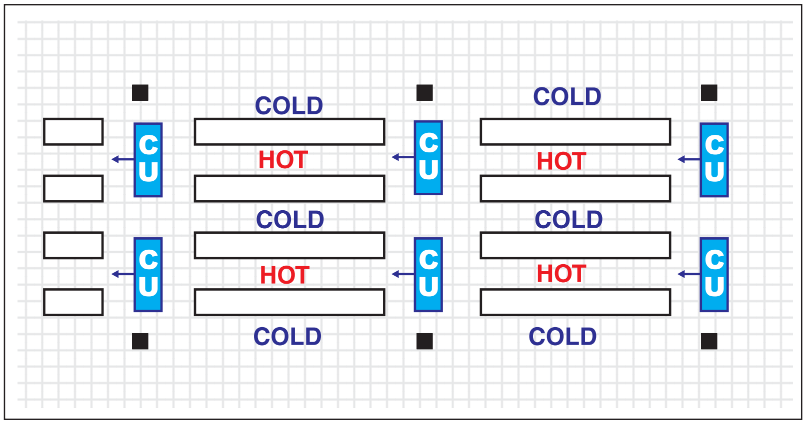
Under-Floor Air Dynamics



The "Under-Floor Air Dynamics" graphic illustrates an example of the effects of these air movement patterns. The different colored areas indicate likely paths for the under-floor air movement, while above the floor in the computer room, the return air to the CRACs may more likely be exactly opposite the expected delivery path indicated by the arrows at each CRAC. Therefore, CRAC-2 may be getting return air from point B, mixed with some of the return air originally delivered by CRAC-3, whereas CRAC-4 may be seeing return air from point A with some mixing with return air originally delivered by CRAC-3, or CRAC-1 could also be seeing return air from Point A. Assuming something like a 15°F temperature rise on the cooled air as it passes through all the equipment in a cabinet, confusion and even disaster can be predicted. CRAC-1 is seeing return air at 86°, driven by the hot spot at Point A and continues to drop its temperature to deliver more cooling, which fails to be delivered to the hot spot. CRAC-4 is seeing 86° return air from point A mixed with some 75° return air in the CRAC-3 path, which keeps it running cool. CRAC-2, on the other hand, is seeing 70° return air from Point B passing through some 75° return air from the CRAC-3 path. If the chiller thermostat is set at 72°, it is conceivable that CRAC-2 may shut down its chiller and just blow unchilled air into the under-floor space. Unfortunately, that ambient air will be delivered to the hottest spot in the room. Meanwhile, the astute site administrator will notice the hot spots and drive down the temperatures further on either or both CRAC-1 and CRAC-4, which unfortunately will conspire to drive down the return air temperature that much further to CRAC-2, thereby preventing any cooling from being delivered to the hottest spot in the room. Once this train is boarded, it is darned difficult to get off.

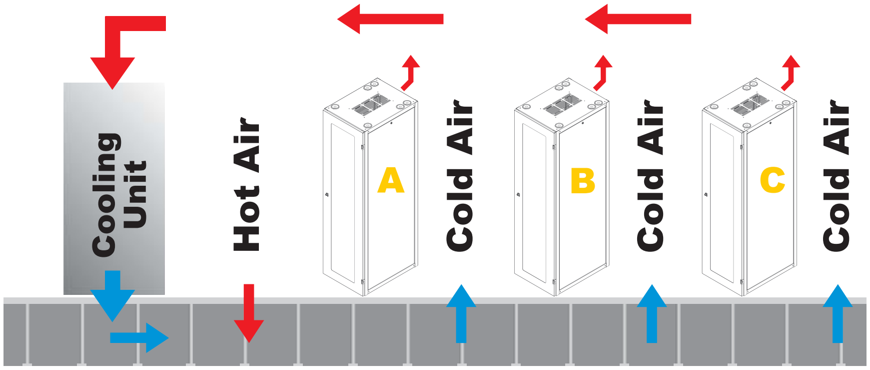
A computer room with all the air and all the cable running in the same parallel direction, commonly referred to as a "hot aisle-cold aisle" set-up, is the best way to make air direction both below and above the floor predictable, create some redundancy for protection against CRAC failures or service down-time, and remove cable obstruction as a source of turbulence, reduced static pressure and lost CFM.

Ideal Data Center



Finally, with maximized static pressure under the floor for optimum CFM delivery of chilled air and an ideal organization of CRACs and equipment cabinets in the data center, the site administrator must avoid the normal inclination to locate the hottest equipment closest to the CRAC. Often the air velocity straight out of the CRAC may be too high to be diverted up through a perforated floor tile located too close to the CRAC. In fact, by the physics of the Venturi Effect, the velocity of that chilled air racing by a nearby perforated floor tile may very well be sufficient to draw ambient room air and/or heated return air into the under-floor space. Therefore, not only will that proximity fail to deliver cooling to the hottest equipment, but it may also result in raising the temperature of the chilled air delivered into the entire room. The recommendation here is to avoid locating perforated tiles too close to the CRAC and, where possible, locate passive, connectivity equipment closest to the CRAC, to maximize space utilization.

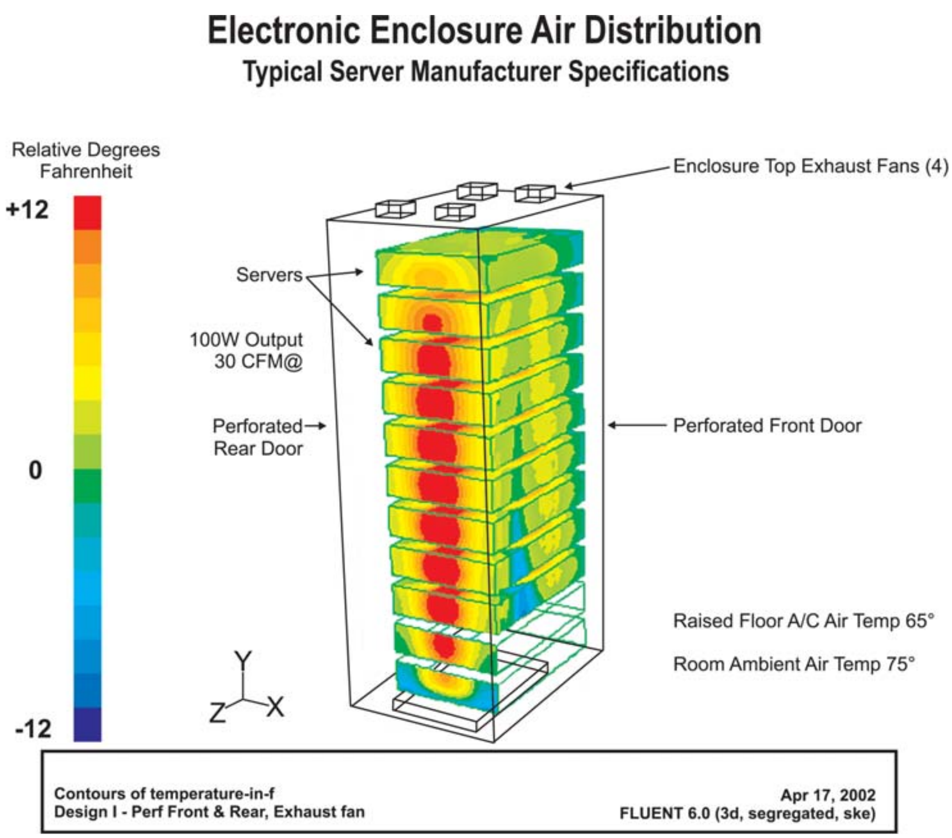
Effect of Under-Floor Air Velocity



Once the computer room is organized effectively, the same principles should be applied to the cabinet/enclosure itself. Attention to static pressure and airflow management within the cabinet serve to realize the greatest benefits from the attention paid to organizing the room itself for maximum cooling. These principles will be applied in different ways, depending on the total environment and the heat load. For example, if the bypass air elimination exercise produced adequate CFM through all the perforated floor tiles, the cabinet should either have no doors or, if required for security, doors with a minimum 60% open mesh for maximum airflow and is best not equipped with top mounted fan kits. "Adequate CFM" will be defined by the heat load in cabinet or cabinets served by a perforated floor tile versus the cooling delivered, which can be plotted on the "Relationship Between Under-Floor Static Pressure and Cooling" line graph. For example, 700 CFM will deliver nearly 3kW of cooling, or 1.5kW per facing cabinet. Top mounted fan kits can be counterproductive to the degree they allow some mixing of return air with the source air in the cold aisle and any resultant temperature increase will produce a commensurate decrease in the heat transfer rate within the mounted equipment. If cabling obstacles in the rear of the cabinet or other concerns will make it difficult for the small server fans (10-30 CFM) to push the hot air out of the cabinet, rear door-mounted fans that push that air directly into the hot aisle and keep the cabinet between the source air and the return air will keep the total system running more efficiently and effectively.

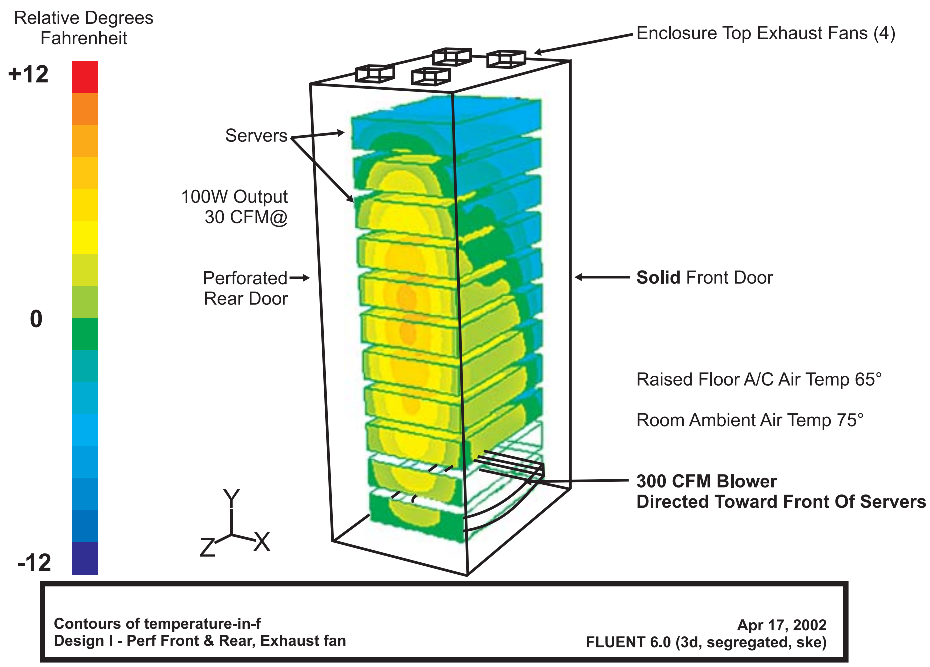
If, on the other hand, not enough static pressure improvements can be made to deliver the CFM through the perforated tile in the center of a cold aisle to provide the cooling required by the heat load in the cabinet or cabinets, then a more focused approach of pumping the air directly into the cabinet and distributing it with some kind of booster may be required. In this scenario, static pressure is again important in the space in front of the rack-mounted equipment where the air in-takes are located. Static pressure is increased by utilizing a solid panel front door (though peripheral venting is acceptable and sometimes desirable), filler panels in unused RMU spaces between equipment, and some means of sealing between the equipment and the cabinet side panels. For this reason, even where cabinets are bayed together, typically without side panels, it will be preferable for two cabinets to at least share a side panel. In addition to maximizing the static pressure in that three cubic foot space of air in the front of the cabinet, this sealing will also discourage the exhaust return air in the rear of the cabinet from re-circulating and mixing with the cool source air before it is drawn into the servers. Top mounted fans may be deployed in this configuration because their output will not mix with the equipment input air. The "boost" is provided by mechanisms designed to focus the coldest available air directly on the most critical point of use. Products are available which do this with centrifugal blowers which direct the chilled under-floor air through a nozzle up the front of the equipment or with fans which direct the air into a "plenum" door with vents or baffles that will direct the air into the cabinet to points of need.

The effectiveness of these focused approaches is shown in the comparison of the two Electronic Enclosure Air Distribution computational fluid dynamics models. The "Typical Server Manufacturer Specifications" model shows expected cooling toward the bottom of the cabinet and some counter-intuitive cooling at the top of the cabinet. The upper cooling results from the top mounted fans drawing air in through the top of the high air flow mesh front door. Hot spots remain in the center of the cabinet as the top-mounted fans fail to draw significant air by the front of the equipment, because the mesh doors provide less resistance than the equipment in the cabinet. The focused air delivery, on the other hand, will deliver most of the difference between the under-floor air temperature and the ambient temperature directly to the equipment air in-takes.



Electronic Enclosure Air Distribution

Focused Blower and High Static Pressure Cabinet



High-powered fans either blowing air into the bottom of a cabinet or pulling air through from the top of the cabinet are not consistent with the principles discussed in this paper. For example, such fans will typically push or pull cooled air through both the front and back of the cabinet, thereby cooling exhaust air (return air), reducing the temperature differential between source air and return air and decreasing CRAC efficiency.

Data center equipment cooling does not need to be mysterious magic, but it often requires more than common sense, especially since so much of the action happens out of view below the raised floor tiles. The key points to remember are to only spend your cold air where it is really needed by your equipment, avoid mixing "used" return air with cooled source air, keep life simple and predictable by running all your air and under-floor cable in one direction and parallel to each other, and the name of the game is delivering effective cooling, not merely getting rid of hot air.

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