Engineering White Paper

USING FOUR-STEP TECHNOLOGY TO OPTIMIZE DATA CENTER COOLING EFFICIENCY

SUMMARY

Data center cooling systems are sized for a full-load operating point that exists infrequently. This is necessary to ensure the system has the capacity to handle these conditions when they do exist; however, it creates the challenge of providing efficient operation at less than one-hundred percent load.

Compressor unloading has proven to be an effective approach to ensure efficiency at reduced capacities. Unloading works by shutting off the flow of refrigerant to some cylinders within the system, minimizing the need to cycle compressors on and off to control capacity. This can result in significant energy savings at lower capacities and increases system reliability by eliminating the wear and stress on the electrical system, motor and cylinder that occurs during startup.

In the two-compressor Liebert Deluxe System, unloading, managed by a sophisticated control system, enables four “steps” of capacity control:

1. Step One - one compressor partly loaded (38% capacity).
2. Step Two - two compressors partly loaded (76% capacity)
3. Step Three - one compressor at full capacity, one partly loaded (88% capacity)
4. Step Four - both compressors at full capacity (100% capacity)

This four-step approach provides greater operating flexibility and enhanced reliability of data center cooling systems and should be considered for any application where the workload of the protected equipment or ambient temperatures fluctuate frequently.

Sizing for Efficiency and Scalability

Load calculations for cooling systems are based on both design ambient temperatures and the projected equipment load.

However, according to the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE), design weather conditions occur less than 5% of the time each year. And, when you consider the fact that not all protected equipment is going to be running at full load all of the time, it becomes clear that precision cooling systems will necessarily run at less than full load most of the time in most applications.

This creates the challenge of balancing capacity and efficiency. General building HVAC designers can make some compromises in comfort to size systems closer to typical operating conditions. In effect, sacrificing some comfort at design weather conditions to provide greater efficiency the other 95% of the year. However, the data center environment is less forgiving.

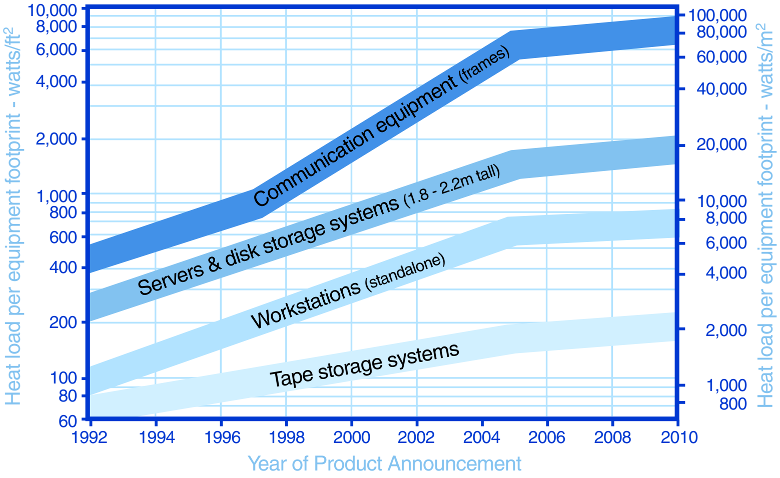


Figure 1. Rising heat densities will increase the cooling capacity requirements in many data centers.

Where people can wear lighter clothing or make other changes to accommodate less-than-ideal building conditions, computer systems must be maintained within a narrow range of temperatures to ensure reliable operation. In addition, the controlled environment requires continuous, year-round cooling instead of the seasonal and intermittent requirements of building systems. This means data center systems must provide cooling across a much wider range of ambient temperatures.

So, one of the key challenges that must be addressed when designing data center cooling is ensuring protection of critical systems at varying ambient temperature and load extremes, while ensuring energy-efficient operation under typical conditions.

This issue is further complicated by the dynamic nature of the data center. Building heat loads are fairly static over time, while the controlled environment is not. On a daily basis it will vary based on the workload of protected equipment. In the long run, the load will most likely increase as new higher-density equipment is introduced.

According to the Uptime Institute, a research institute supported by companies seeking to achieve the highest levels of availability for their computer systems, power densities increased 300% from 1992 to 2002. The Institute's study found that "in each subsequent year the annual change gets larger," and projected continued increases at least through the end of this decade (see Figure 1).

. . .a short sighted approach that does not build enough capacity into a cooling system at the front end can jeopardize protected equipment in the short term and limit data center growth in the long term.

The Meta Group explored this same trend in a 2001 report, which concluded:

> Driven primarily by rapidly increasing rack-mounted servers (being added at 45 percent to 55 percent annual rates) and storage, power-hungry hardware threatens many current data-center design specifications . . .In fact, the 2004 400-watts-per-square-foot requirement will again double by 2008, so designers must work this into longer-range facilities plans so that space can be fully used, as opposed to 40 percent to 50 percent utilization because of insufficient power and cooling.

Clearly, a short sighted approach that does not build enough capacity into a cooling system at the front end can jeopardize protected equipment in the short term and limit data center growth in the long term. Consequently, precision air conditioners must be able to operate efficiently at a wide range of loads and the key to accomplishing that is compressor unloading.

Understanding Four-Step Technology

Compressor unloading removes the load from a cylinder, or group of cylinders, to adjust capacity without turning off the cylinders. When integrated with the proper controls, unloading becomes the basis for a cooling system that combines flexibility, efficiency and scalability.

The unloader utilizes a spring-loaded piston that shuts off, or allows, the flow of gas into the cylinder. When the compressor is loaded, the unloader takes a small amount of discharge gas from the other cylinders and uses it to compress the valve, allowing suction gas to get into the cylinder. When the cylinder is unloaded, the valve closes, causing refrigerant to bypass the cylinder during the upstroke. The cylinder piston continues to go up and down, but with the flow of refrigerant blocked, there is no compression work (see Figure 2).

Liebert has utilized this technology, in conjunction with sophisticated microprocessor controls, to create a “Four-Step” precision cooling system that provides efficient operation at a wide range of operating conditions.

This system achieves four steps of capacity control using compressor unloading in a two-compressor Deluxe System/3. Because unloading essentially changes the compressor operating point, it enables the cooling system to operate more efficiently at lower capacities. For example, a system operating with two compressors partly loaded will consume approximately 50% of the energy of a fully loaded system, but will deliver 76% capacity because the condenser and evaporator are sized for full load.

Following are the four-steps of a two compressor system with unloaders on each compressor:

1. Step One - one compressor partly loaded (38% capacity).
2. Step Two - two compressors partly loaded (76% capacity)
3. Step Three - one compressor at full capacity, one partly loaded (88% capacity)
4. Step Four - both compressors at full capacity (100% capacity)

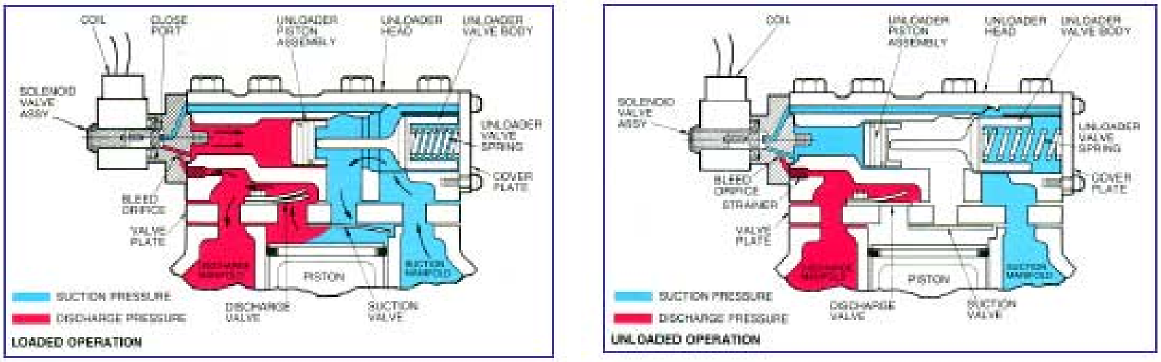


Figure 2. Loaded versus unloaded operation.

This approach to capacity control significantly reduces energy costs at lower capacities and reduces stress on internal components, while providing the required capacity for extreme conditions or data center growth.

Four-Step Technology and Energy Efficiency

Four-Step systems deliver savings at partial loads due to the way they adjust to capacity. Figure 3 shows energy usage versus capacity for each of the four steps of system operation. When the system is operating at 38% capacity, it is utilizing only 25% of the energy used at 100% capacity. At Step 2, capacity and energy use are both doubled, enabling the system to operate at 76% capacity with 50% energy usage. At Step 3, capacity increases to 88% and energy use is at 75%.

How does the system achieve these efficiencies? The key is the compressor operating point, which changes with unloading. When the compressor is unloaded, its mass flow rate is cut by half. This means the evaporator and condenser in a given circuit are now oversized compared to the unloaded compressor. An oversized evaporator results in a higher suction temperature, while an oversized condenser results in a lower condensing temperature. Figure 4 shows how the operating point changes when the compressor unloads.

Figure 5 shows how the EER (energy efficiency ratio) changes in response to

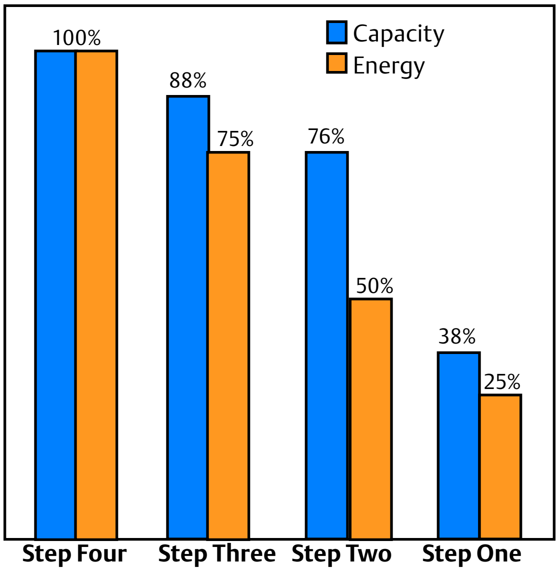


Figure 3. Operating capacity versus energy consumption for the four stages of operation.

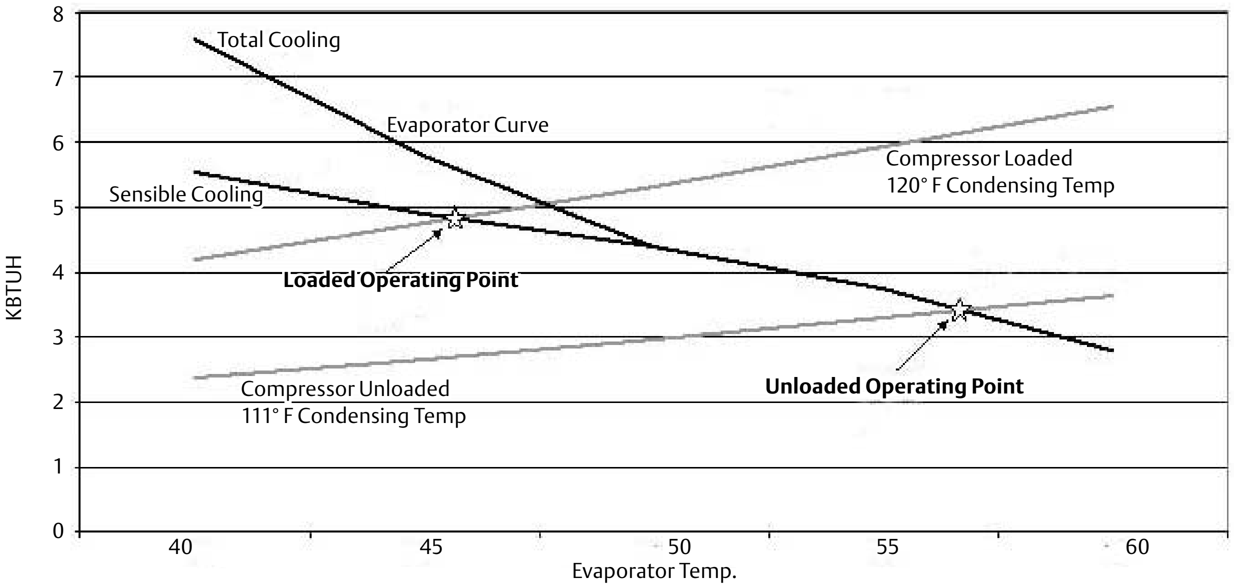


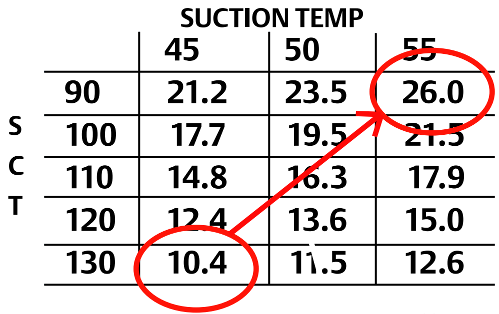
Figure 4. Four-step system balance diagram shows how the operating point changes as a result of compressor unloading.

In addition to energy improvements, unloading increases compressor reliability by minimizing compressor starting and stopping.

the changes in operating point. Note that the condensing temperature is reduced, and the evaporator temperature increases enabling the compressor to operate more efficiently

Unloading and Dehumidification

A four-step approach to compressor unloading also offers advantages when humidifying at part load. As each compressor unloads, the latent capacity is reduced, increasing the net humidification capacity. The evaporator coils in the unloaded compressor dry up, so moisture is not being removed when it doesn't need to be. For example, the system is most likely to operate with both compressors unloaded during the winter months. This is also the time when humidification is most needed. When both compressors are unloaded the system is providing only sensible cooling, eliminating the need for re-humidification.



		SUCTION TEMP		
		45	50	55
SCT	90	21.2	23.5	26.0
	100	17.7	19.5	21.5
	110	14.8	16.3	17.9
	120	12.4	13.6	15.0
	130	10.4	11.5	12.6

Figure 5. Improvement in energy efficiency ratio resulting from change in operating point.

Four-Step Technology and Reliability

In addition to energy improvements, unloading increases compressor reliability by minimizing compressor starting and stopping. As with any motor-based system, the greatest stress on cooling system components occurs during startup. In fact, the inrush current is four to five times higher during startup than during normal operations. This increases the stress on the entire electrical system. In addition, during startup there is almost no oil pressure in the cylinder. The oil pump feeds oil into the bearings at startup and it takes about a second for oil to get to the bearings. As a result, the stress on bearings is at its greatest during startup. By controlling capacity in a way that minimizes compressor starting and stopping, unloading minimizes the wear on internal components and enhances reliability.

Calculating the Economic Impact of Four-Step Technology

When considering four-step technology it is important to evaluate the costs of this approach over the life of the system versus the lifecycle costs of alternate approaches. A lifecycle cost analysis provides a proven methodology for accomplishing this.

Lifecycle cost analysis takes into account operating and maintenance costs, as well as initial costs. For a detailed discussion of lifecycle cost analysis methodology and considerations, see the Liebert white paper: *Lifecycle Costing for Data Centers.*

For the purposes of this paper, we'll consider a fairly simple analysis that compares a Liebert Four-Step Deluxe System to a two-step Deluxe System. The two-step system does not use unloaders; it achieves two-steps of capacity control by shutting down one of the systems two compressors. Although maintenance costs could be impacted by the increased starting and stopping of the compressors in the two-step system; for the purpose of this paper only the two most significant variables will be considered: initial costs and energy costs. To keep the analysis somewhat conservative, the analysis will utilize a 10-year lifecycle for the cooling system, rather than the 15-year lifecycle, which is more typical for a cooling system.

Initial costs.
Initial costs include the cost to acquire and install the two competing technologies. Unloaders add approximately $1500 to the initial cost of the system.

Energy Costs:
To calculate energy costs over the ten-year life of the project, assumptions must be made about operating conditions, geographic location, and expected energy costs. For the purpose of this comparison, two U.S. cities have been selected with significant variation in seasonal ambient temperatures, creating different operating conditions for the precision cooling systems in those locations (Figure 6).

	Chicago, IL	**Atlanta, GA**
Operating hours less than 34°F ambient	8,142 hours	544 hours
Operating hours at 35°F to 59°F ambient	3,199 hours	3,086 hours
Operating hours at 60°F to 79°F ambient	2,751 hours	3,930 hours
Operating hours above 80°F ambient	618 hours	1,200 hours

Figure 6. Operating conditions used for cost analysis.

In both cases, there is significant opportunity for the compressor to run at a lower condensing temperature than design-day conditions.

This information can then be used to calculate unloader operation at different temperatures. The worksheet at the end of this paper focuses on Atlanta, showing compressor kw adjusted for ambient and part-load conditions.

With unloading, total energy costs for this system round out to $3,548.00 annually. Without unloading, the compressor operates at higher capacities more frequently, resulting in annual energy costs of $4,281.

The presence of unloaders results in an annual energy savings of $733 per year. Performing a similar calculation for Chicago, shows energy savings of $686 annually.

	2-step	4-step	Savings
Atlanta, GA	$4,281	$3,548	$733
Chicago, IL	$3,587	$2,901	$686

To determine life-cycle costs determine the present value of the energy costs, plus the present value of 4-step system. The example below uses a 5% discount rate over the ten-year analysis period. The present value calculation shows a savings of 13.7% for Chicago, and 12.6% for Atlanta.

Conclusion

Data center cooling systems must operate efficiently at a wide range of operating conditions to accommodate variations in ambient temperature, changes in the load and growth of the data center. Unloading providing a practical, economically attractive approach to increasing cooling system efficiency at partial loads. Applied to both compressors in a Liebert Deluxe System 2, unloading provides four steps of capacity control. Because unloading change the operating point of the compressor, the Liebert Four Step system actually achieves higher efficiencies at partial loads, while also enhancing system reliability by minimizing compressor starting and stopping.

	Chicago		**Atlanta**	
	DH125A	DH125AU	DH125A	DH125AU
Initial Cost	$0	$1,500	$0	$1,500
Compressor Energy Cost	$3,587	$2,901	$4,281	$3,548
Discount rate	5.0%	5.0%	5.0%	5.0%
Years	10	10	10	10
PV	$27,698	$22,401	$33,055	$27,397
Total PV	$27,698	$23,901	$33,055	$28,897
% Savings	**-13.7%**		**-12.6%**	

Figure 7. Summary lifecycle cost analysis showing the saving achieved by four-step operation in different ambient temperature conditions.

Energy Costs Work Sheet for Atlanta

FOUR-STEP OPERATION

Atlanta, GA	**<80°F amb**	**80-84°F**	**85-89°F**	**90°F+**
Sensible Load	87,500	87,500	87,500	87,500
Step 1 capacity	43,300	42,200	41,200	40,100
Step 1 kw	2.1	2.3	2.4	2.5
% Step 1 operation	0.0%	0.0%	0.0%	0.0%
Step 2 capacity	86,500	84,400	82,300	80,200
Step 2 kw	4.2	4.5	4.8	5.1
% Step 2 operation	92.7%	78.1%	63.6%	50.2%
Step 3 capacity	100,200	98,400	102,900	94,800
Step 3 kw	6.4	6.7	7.1	7.4
% Step 3 operation	7.3%	21.9%	36.4%	49.8%
Step 4 capacity	113,800	112,400	123,500	109,400
Step 4 kw	8.5	8.9	9.3	9.7
% Step 4 operation	0.0%	0.0%	0.0%	0.0%
Total Compressor kw	4.4	5.0	5.6	6.2
Hours/yr	7,560	636	386	178
Kwhr	32,966	3,168	2,176	1,112
Total kwhr	39,422			
Rate ($/kw)	$0.09			
Total energy cost	$3,548			
TWO-STEP OPERATION				
Compressor1 kw	3.8	4.5	4.7	4.8
% Step 1 operation	100.0%	100.0%	100.0%	100.0%
Compressor2 kw	3.8	4.5	4.7	4.8
% Step 2 operation	37.4%	44.7%	47.2%	49.9%
Total Compressor kw	5.2	6.5	6.9	7.2
Hours/yr	7,560	636	386	178
Kwhr	39,472	4,141	2,671	1,281
Total kwhr	47,565			
Rate ($/kw)	$0.09			
Total energy cost	$4,281			

Liebert Corporation

1050 Dearborn Drive
P.O. Box 29186
Columbus, Ohio 43229
800.877.9222 (U.S. & Canada Only)
614.888.0246 (Outside U.S.)
Fax: 614.841.6022
www.liebert.com

Printed in U.S.A. 2003