TRANE

ENGINEERS NEWSLETTER

providing insights for today's HVAC system designer

"Off-Design" Chiller Performance

What exactly do we mean by "off-design," anyway? Broadly interpreted, it's any set of operating parameters that differs from the single "design" performance rating for a chiller. Often, but certainly not always, this design point is an ARI-certifiable condition. ("ARI" refers to the Air Conditioning and Refrigeration Institute.) Some off-design conditions match ARI's specified IPLV or APLV part-load conditions. More often, they don't.

Note: *"IPLV" or "integrated part-load values" are based on chiller operation at standard ARI conditions and are typically used for ARI rating purposes. "APLV" or "application part-load values" are based on chiller operation at actual design conditions and are typically used in system design and specification. To make an educated chiller selection, the designer must know the prospective chiller's operating range and its efficiency at each point within that range.*

It is commonly acknowledged that HVAC systems spend most operating hours at conditions other than design, and they're expected to function properly at these conditions. Usually, this means that the various components of the HVAC system also encounter many hours of off-design operation. We expect them to perform efficiently and reliably at these conditions, too.

Operating Cost Estimations

In fact, all commonly accepted system-simulation/energy-consumption calculations follow the notion that off-design conditions constitute most operating hours. Only rarely do we see operating cost calculators use "equivalent full-load hours" as anything more than a very rough method of comparison.

At the opposite end of the spectrum are the system simulation software like TRACE® 600 and DOE-2. They represent the most sophisticated means of estimating operating costs. Such programs can do a credible job of constructing accurate building load profiles and simulating the operation of chillers and other equipment against those profiles. However, **real** system load profiles are difficult to obtain, even for existing buildings. Despite the precision of computerized calculations, there are still many ways to introduce measurable errors. **Accurate** simulations require care and effort.

> "Though bin-method estimates of operating costs commonly assume the "weather-dependency" of heating and cooling loads, this relationship is ambiguous for most commercial systems."

Between these extremes lie variations of the "bin method." This approach to estimating system operating costs segregates all operating hours into a finite number of temperature "bins." Bin-method calculations are typically based on the assumption that heating and cooling loads are "weather-dependent." However, the relationship between heating loads, cooling loads and weather is imprecise for most commercial systems. While basing operating cost estimates solely on weather temperature bins is useful for "back-of-a-napkin" analysis, its inherent flaws usually yield significant errors. Without the aid of load analysis software, bin-method estimates of system operating costs (at the risk of sounding patronizing) might be characterized as "better than nothing."

System Load Vs. Chiller Load

Despite valid load profiles, significant variations in energy consumption result from **assumptions** about the differences between **system** and **chiller** loads. Clearly, a simple, single-chiller system with little thermal inertia "sees" system loads directly as equipment (chiller) loads. Few commercial HVAC systems employ a single chiller—fewer still, a single compressor. The redundancy of multiple chillers is a recurring theme in HVAC system designs.

Since most multiple-chiller systems use chiller sequencing as a primary control strategy, individual chiller loads are totally different from system loads.

For Example … Consider a load profile defined in terms of weather temperature bins. Chart 1 displays 10 temperature bins which could easily typify hourly weather observations for Atlanta, Georgia. We know that a full year consists of 8,760 hours. Yet the time these 10 bins represent totals only 6,489 hours. In this case, the difference is the period when the temperature is below 50 F. Chart 1 also indicates the percentage of these 6,489 hours each bin represents. Clearly, the 21 hours above 94 F (i.e. ASHRAE's "1 percent design" for Atlanta) is less than one-half percent of 6,489 hours.

Simplistically, one might infer that a chiller in Atlanta spends only one-half percent of its operating hours at a design condition. At least three fundamental flaws in logic make this untrue:

1 Weather (outdoor air temperature) and loads are not proportional to each other.

2 Many of the 6,489 hours occur at night when the system may be inactive.

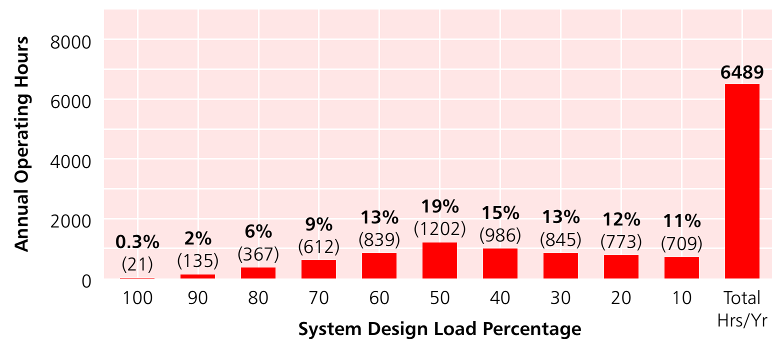
3 Multiple chillers greatly skew the load profile of any individual chiller.

Each of these factors influences the outcome. Together, they greatly complicate a theoretical study. For this discussion, we'll focus only on the impact of multiple chillers (Item 3).

Split The System Load Equally?

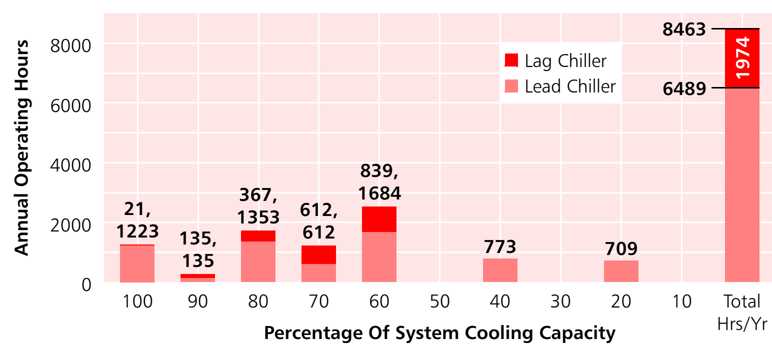
More often than not, designers split loads equally among multiple chillers. While this may not be the most efficient or least costly approach, it remains popular. Our example considers an 800-ton system that consists of two equally sized 400-ton chillers. Any system load greater than 400 tons requires operation of both chillers. Since most chillers are piped with parallel chilled water flow, both chillers "see" equal loads as long as they produce the same chilled water supply temperature.

Chart 1: System Load Profile



"Bin"	1	2	3	4	5	6	7	8	9	10	
Hi/Lo Temp, °F	99/ 95	94/ 90	89/ 85	84/ 80	79/ 75	74/ 70	69/ 65	64/ 60	59/ 55	54/ 50	Total
Oper Hrs/Yr	21	135	367	612	839	1202	986	845	773	709	6489
% Oper Hrs/Yr	0.3	2	6	9	13	19	15	13	12	11	100
% System Load	100	90	80	70	60	50	40	30	20	10	—

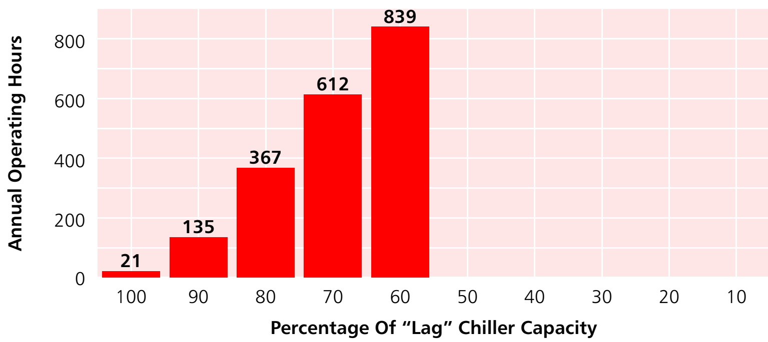
Chart 2: Load Profile For Two Equally Sized Chillers



"Bin"	1	2	3	4	5	6	7	8	9	10	
Hi/Lo Temp, °F	99/ 95	94/ 90	89/ 85	84/ 80	79/ 75	74/ 70	69/ 65	64/ 60	59/ 55	54/ 50	Total
Oper Hrs/Yr	21	135	367	612	839	1202	986	845	773	709	6489
% Oper Hrs/Yr	0.3	2	6	9	13	19	15	13	12	11	100
% System Load	100	90	80	70	60	50	40	30	20	10	—
% Clg Capacity:											
Lead Chiller	100	90	80	70	60	100	80	60	40	20	—
Lag Chiller	100	90	80	70	60	0	0	0	0	0	—

See Charts 3 and 4

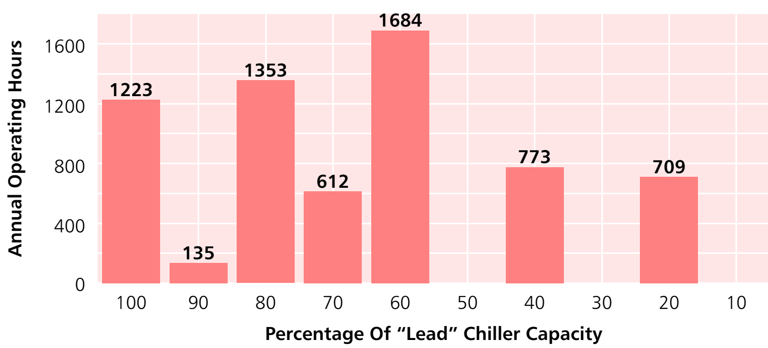
Chart 3: "Lag" Chiller Profile



"Bin"	1	2	3	4	5	6	7	8	9	10	
Hi/Lo Temp, °F	99/ 95	94/ 90	89/ 85	84/ 80	79/ 75	74/ 70	69/ 65	64/ 60	59/ 55	54/ 50	Total
Unit Capacity:											
Percentage	100	90	80	70	60	50	40	30	20	10	—
Tons	400	360	320	280	240	—	—	—	—	—	—
Operating Hrs:											
Per Year	21	135	367	612	839	0	0	0	0	0	1974
% Of Total	1	7	19	31	43	—	—	—	—	—	100

See Chart 2

Chart 4: "Lead" Chiller Profile



"Bin"	1	2	3	4	5	6	7	8	9	10	
Hi/Lo Temp, °F	99/ 95	94/ 90	89/ 85	84/ 80	79/ 75	74/ 70	69/ 65	64/ 60	59/ 55	54/ 50	Total
Unit Capacity:											
Percentage	100	90	80	70	60	50	40	30	20	10	—
Tons	400	360	320	280	240	—	160	—	80	—	
Operating Hrs:											
Per Year	1223	135	1353	612	1684	0	773	0	709	0	6489
% Of Total	19	2	21	9	26	—	12	—	11	—	100

See Chart 2

Therefore, loads are equally split during the 1,974 hours that the temperature exceeds 74 F. Chart 2 develops load profiles for each of the two chillers. One of the chillers, of course, does not operate during the 4,515 hours at or below 74 F. As a result, its load profile consists only of the 1,974 hours it operates. Chart 3 portrays the **lag** chiller's profile. Of the 1,974 operating hours, only 21 of them (1 percent) are spent at design load.

Refer to Chart 2 again. Notice that the **lead** chiller operates all 6,489 hours. In addition to the 21 hours when it shared design load conditions with the lag chiller, it runs 1,202 hours in the "74 F/ 70 F bin" at full capacity. However, ambient conditions potentially reduce condenser water temperature, permitting improved chiller efficiency. But this chiller must produce its full capacity or the lag machine will be called on to operate. Total full-capacity hours equal 21 + 1,202 or 1,223 hours. This represents over 19 percent of its total annual running time. Clearly, this is quite different from the one-half percent indicated by the top weather temperature bin.

Chart 4 further defines the lead chiller profile. If a designer has the flexibility to provide two different but equally sized chillers (i.e. one of higher efficiency than the other), it would make sense to avoid equalizing their run times by switching sequences. Why? Because one chiller spends 1,223 hours at design capacity and the other only 21 hours. On the other hand, if hours are equalized, both chillers operate at design for 612 hours, which represents 14 percent of the 4,232 hours each must run. (The value "4,232 hours" arises from 1,974 shared hours plus half of the 4,515 hours that reflect a control strategy which equalizes the run times of the two chillers.)

Note: *If the design goal is to balance the operating hours for both chillers, then both machines should be of identical efficiency.*

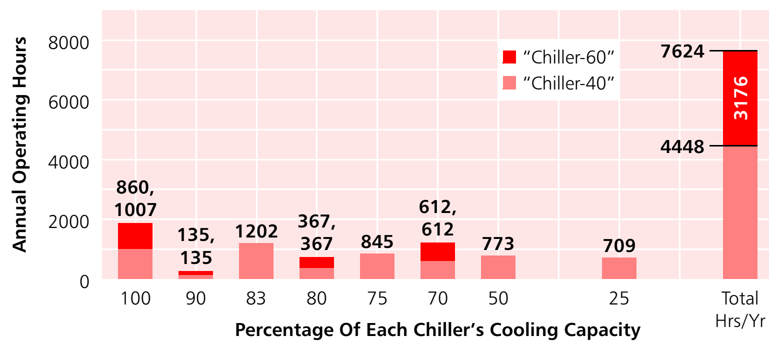
Or Split The System Load Unequally?

A strong case can be made for an uneven division of chiller capacity. For example, suppose that our 800-ton system consists of one 480-ton chiller and one 320-ton chiller. Such a design will cost less to install **and** operate.

Note: *This design concept was introduced in a 1989* ***Engineers Newsletter****, Vol. 18/No. 2, titled "Chiller Plant System Performance." Remarkably, only a few designers embrace this opportunity. But those who do seldom revert to the traditional practice of equally sizing all chillers.*

Let's look at the load profiles that result when we apply a 60/40 split in cooling capacity to our example system. Chart 5 is based on the same system load profile used in the preceding charts. Notice that both chillers must operate throughout the 1,135 hours associated with Bins 1 through 4 (i.e. a temperature range of 80 F to 99 F). Loads are proportional to chiller size during this period because both chillers encounter identical supply and return water temperatures.

Chart 5: Load Profile For A 60/40 Split In Chiller Capacity



"Bin"	1	2	3	4	5	6	7	8	9	10	
Hi/Lo Temp, °F	99/ 95	94/ 90	89/ 85	84/ 80	79/ 75	74/ 70	69/ 65	64/ 60	59/ 55	54/ 50	Total
Oper Hrs/Yr	21	135	367	612	839	1202	986	845	773	709	6489
% Oper Hrs/Yr	0.3	2	6	9	13	19	15	13	12	11	100
System Load:											
% Of Design	100	90	80	70	60	50	40	30	20	10	—
Tons	800	720	640	560	480	400	320	240	160	80	—
"Chiller-60":											
% Capacity	100	90	80	70	100	83	0	0	0	0	—
Tons	480	432	384	336	480	400	0	0	0	0	—
"Chiller-40":											
% Capacity	100	90	80	70	0	0	100	75	50	25	—
Tons	320	288	256	224	0	0	320	240	160	80	—

See Charts 6 and 7

Charts 6 and 7 show the profiles for "Chiller-60" and "Chiller-40," respectively. Beginning with a system load of 480 tons (Bin 5 in Chart 6), "Chiller-60" carries the load at 100 percent of its capacity. This adds 839 hours at the 100-percent capacity condition for a total of 860 hours, or 27 percent of its 3,175 total running hours. Surprisingly, this chiller does not operate at **any** load below 70 percent of its capacity (336 tons).

Chart 7 shows the profile for "Chiller-40," the smaller of the two machines. This chiller encounters 100-percent capacity demand in Bins 1 and 7 for a total of 1,007 hours, or nearly 23 percent of its 4,448 total operating hours. The striking feature of Charts 6 and 7 is the extremely large high-end loading. "Chiller-60" never operates below 70 percent and "Chiller-40" operates at less than half capacity for only 709 hours (16 percent of its annual operating time). These two profiles demonstrate that **full-load efficiency is important for *both* chillers,** and give the designer an opportunity to **concentrate on *chiller* efficiency to deliver *system* efficiency**. Notice, too, that the operating time of the two chillers is nearly equal without resorting to a sequence-changing control strategy based on operating hours.

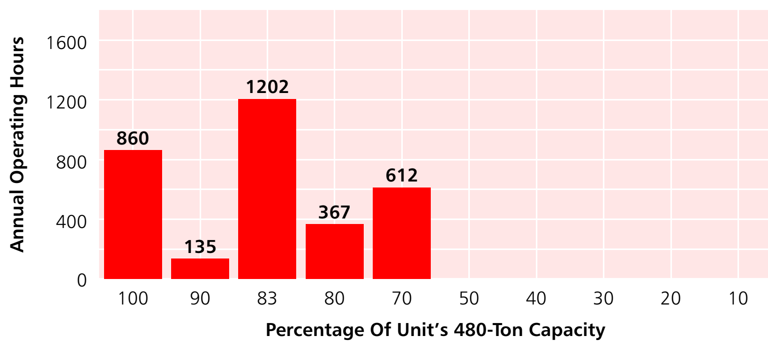
Significantly, there is little resemblance between the system load and the chiller loads in this example. In fact, they're not even remotely similar! Apparently, the "common sense" approach of inferring chiller loads from system loads is simply **false** wisdom.

What's The "Catch"?

It seems impossible for a load profile that encompasses only 30 percent of the total annual operating hours (6,489) at loads over 50 percent to produce individual chiller load profiles so markedly different. How can one of these chillers run at 70+ percent capacity throughout its entire annual operation while the other runs at 50+ capacity for most (84 percent) of its annual operation?

Why does a system that requires two equally sized chillers to run for a total of 8,463 hours need only 7,624 hours of operation when served by two **unequally sized** chillers? That's a difference of 840 hours annually, or

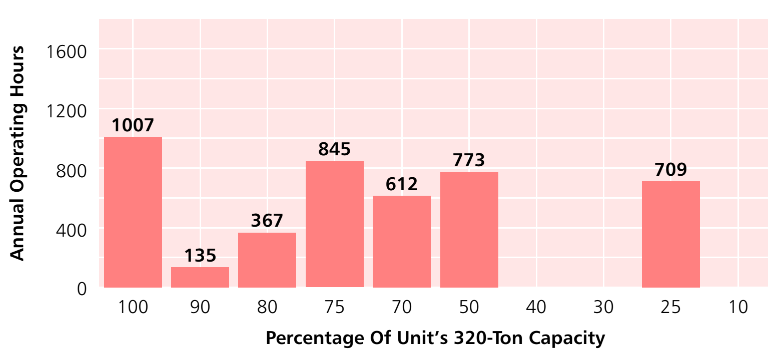
Chart 6: "Chiller-60" Profile



"Bin"	1	2	3	4	5	6	7	8	9	10	
Hi/Lo Temp, °F	99/ 95	94/ 90	89/ 85	84/ 80	79/ 75	74/ 70	69/ 65	64/ 60	59/ 55	54/ 50	Total
Unit Capacity:											
Percentage	100	90	83	80	70	50	40	30	20	10	—
Tons	480	432	400	384	336	—	—	—	—	—	—
Operating Hrs:											
Per Year	860	135	1202	367	612	0	0	0	0	0	3176
% Of Total	27	4	38	12	19	—	—	—	—	—	100

See Chart 5

Chart 7: "Chiller-40" Profile



"Bin"	1	2	3	4	5	6	7	8	9	10	
Hi/Lo Temp, °F	99/ 95	94/ 90	89/ 85	84/ 80	79/ 75	74/ 70	69/ 65	64/ 60	59/ 55	54/ 50	Total
Unit Capacity:											
Percentage	100	90	80	75	70	50	40	30	25	10	—
Tons	320	288	256	240	224	160	—	—	80	—	—
Operating Hrs:											
Per Year	1007	135	367	845	612	773	0	0	709	0	4448
% Of Total	23	3	8	19	14	17	—	—	16	—	100

See Chart 5

10 percent fewer running hours for the chillers and their auxiliary equipment. Clearly, the system operating costs associated with the uneven capacity split will be less.

Is mathematical trickery involved? **No!** This is simply an example of judicious chiller sizing to take advantage of the differences between **system load profiles** and **chiller load profiles**.

Summary

- Weather-versus-time system load profiles do not translate directly into individual chiller profiles.
- Thoughtful chilled water system design can extract higher operating efficiencies from ordinary equipment.
- Spectacular performance can be achieved without requiring design complexity, unwieldy control systems and other heroic measures. ■

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