TRANE

engineers newsletter

providing insights for today's hvac system designer

chilled water plants and…

Asymmetry as a Basis of Design

from the editor…
The Engineers Newsletter regularly features articles on chilled water plant design. For the most part, these articles examine the "science" of design: they offer practical advice for implementing control strategies and optimizing system performance. This issue promotes asymmetry as a "philosophy" of design. We hope it reminds you to look beyond the "safety of equals" and leads you to creative solutions that deliver better performance at a better cost.

asymmetry *(ay sim' i tree), n.* Lack of balance or symmetry.

symmetry *(sim' i tree), n.* …2A relationship of characteristic correspondence, equivalence, or identity among constituents of an entity or different entities. 3Beauty as a result of balance or harmonious arrangement.

from The American Heritage Dictionary of the English Language, Third Edition.

What does symmetry—or the lack of it—have to do with chilled water systems? Consider the complex process that transforms a client's requirements into a chilled water plant. To arrive at a final design, the design team must solve many problems. The nature or requirements of the application dictate some solutions; for example, the power source or method of heat rejection to use. Other solutions require detailed evaluations to determine "the best leaving chilled water temperature" or "the optimum cooling-tower flow rate." Still others, like plant capacity, are quantifications. Each solution contributes to the success of the final design.

One aspect of chilled water plant design that particularly leverages efficiency and operating cost is "partitioning." **Partitioning** is deciding how many chillers to use to produce the design capacity. A plant with a capacity of 3,000 tons could be comprised of two 1,500-ton chillers, three 1,000-ton chillers, or four 750-ton chillers. Even six 500-ton chillers are a possible solution.

Notice that all of the cited examples divide the total design capacity of the plant equally between the chillers. Partitioning a plant **symmetrically** is common design practice, and it does offer a number of advantages: it requires just one chiller selection; it simplifies system design, control and installation; and it allows any chiller to back up any other chiller. While symmetry reduces the complexity of plant design and installation, it also overlooks opportunities to improve efficiency, operating costs … even installed cost.

Selecting identical chillers limits the ability to optimize more than one design goal by establishing a single set of selection criteria. Employing an **asymmetrical** design—in this case, by selecting unlike chillers—provides an opportunity to satisfy multiple, often conflicting, design goals. The "swing-chiller" system (see inset, page 2) is a familiar example of an asymmetrical split in plant capacity. In this design, a large chiller provides daytime cooling and a small chiller satisfies evening and weekend requirements; both chillers operate together when peak cooling capacity is needed.

The following example illustrates another way to apply asymmetry: by unequally dividing hours of operation rather than tons of cooling. It relates the core decisions that shaped the final design for an actual 3,000-ton chilled water plant. More importantly, it illustrates how asymmetry affords greater design flexibility and can, in turn, lead to more efficient, cost-effective systems.

A Case in Point

The designer began by equally partitioning the plant's capacity among four 750-ton chillers. He did everything "by the book"; he even used energy simulation software to compare the respective life cycle costs of electrically driven and gas-powered chillers. Developing a cooling load profile for the system was paramount to that effort. (It was also of greater value than estimates of life cycle cost at this stage of the design process.) The system load profile revealed a peak load of 3,000 tons and 6.4 million ton-hours of cooling annually. If the chillers share the load equally, each 750-ton chiller must produce 1.6 million ton-hours of cooling annually; see Table 1.

Minimum-billing demand (ratchet) clauses can dramatically impact utility costs, as in this case. The local utility costs of $125 per kilowatt of demand, annually, and $0.05 per kilowatt-hour of consumption certainly figured into the prerequisites established by the design team. (Note: So-called "blended" electric cost data is not suitable for this type of analysis.) Among these prerequisites was a minimum performance standard of 0.58 kW per ton for electrical chillers.

With that in mind, the team initially considered a 750-ton, centrifugal chiller with full-load performance of 429 kW and an NPLV of 0.485 kW. (Defined by ARI Standard 550/590–1998, the NPLV rating is a "blended" estimate of stand-alone chiller performance based on weighted averages. Expect significant differences between ARI-rated performance and the actual performance of a specific chiller in a specific application.) Dividing the cooling load equally between all four chillers meant an annual, per-chiller operating expense of $38,800 for consumption plus $53,625 for demand, or $92,425. Without accounting for the cooling tower and pumps, the average cooling cost was $0.058 per ton-hour.

Table 1–An All-Electric Solution

Designation	Chiller Characteristics: Capacity	Chiller Characteristics: Power	Annual Operation, Per Chiller: Run Time	Annual Operation, Per Chiller: Cooling	Average Cooling Cost
Chillers 1–4	750 tons ea.	electricity	2,600 hr	1.6 million ton-hr	$0.058/ton-hr

The design team also explored the possibility of gas-powered cooling, hoping to take advantage of existing steam-producing boilers. For that alternative, the team evaluated a 750-ton absorption chiller with a COP of 1.21, which became 0.968 when combined with the 80-percent efficiency of the boilers. With gas consumption budgeted at $0.45 per therm, each absorption chiller would incur an annual operating cost of $89,256 for an average cost of $0.056 per ton-hour.

Table 2 summarizes the operating costs of these alternatives; the already negligible difference between them was even less when the cost of condenser pumps and cooling towers was included. From the standpoint of energy, there was no clear-cut winner; the all-electric-chiller solution was neither more nor less affordable than the all-absorption-chiller solution.

Asymmetrical Operation. Based on experience, the design team theorized that closer study of the annual load profile would reveal a "point of asymmetry" in the distribution of operating hours at various load conditions; in other words, significantly fewer hours would be logged above a certain capacity than below it. (See Figure 1 and Table 3.) If true, that distinction would let the team establish **different** selection criteria:

- Chillers selected to operate **below** the point of asymmetry would show an attractive payback for ultra-high efficiency.
- Chillers selected to operate only when the plant load was **above** the point of asymmetry would show marginal payback for efficiency, but might still be selected to reduce first cost or achieve other design goals.

The chiller-plant load profile revealed an annual cooling requirement of 6,385,000 ton-hours. But what would happen if the chillers were **not** operated equally? For example, there were 4,740 hours when the cooling load required the operation of at least one chiller. Conversely, only 990 hours required all four chillers. Starting the

"Swing-Chiller" Design

This popular design for chilled-water systems is usually achieved by unequally dividing the total plant capacity between the chillers. In a simple, two-chiller plant, for example, the designer may size one chiller to handle about two-thirds of the plant capacity. Usually, this represents the load condition at which most hours of plant operation will be spent.

By base loading the "large" chiller (see schematic at right), the initial premium paid for high-efficiency performance can be quickly recovered.

The "small" chiller acts as the swing chiller. It is used when plant demand exceeds the capacity of the "large," high-efficiency chiller. It's also used in lieu of the "large" chiller when cooling demand is low (e.g., at night and on weekends). Given the fact that the swing chiller is likely to operate at light loads for several hours at a time, it may require different selection criteria than the "large" chiller which seldom experiences loads below 50 percent.

Analysis software such as System Analyzer™, TRACE®, or DOE-2 is invaluable for modeling system and individual chiller load profiles, and for comparing various alternatives based on energy and economic performance.

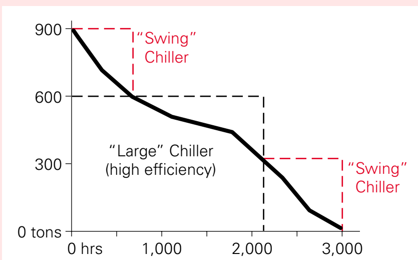


Table 2–Comparison of Energy Costs

		Local Utility Rate	Electric Chillers[a]	Absorption Chillers[b]
Electricity	consumption	$0.05/kWh	$38,800	—
	demand	$125/kW/yr	$53,625	—
Gas		$0.045/therm	—	$89,256
Total			$92,425	$89,256
Cooling cost[c]			$0.058/ton-hr	$0.056/ton-hr

[a] Rated full-load performance for the selected centrifugal chiller is 429 kW; part-load performance is 0.485 kW.
[b] The selected absorption chiller has a COP of 1.21; when the boiler efficiency (80 percent) is taken into account, its performance is 0.968.
[c] Cooling costs shown here exclude accessories.

chillers sequentially and without rotation yielded the run times and production capacities shown below:

Table 3

Chiller	Run Time	Cooling Production
1	4,740 hr	2,595,000 ton-hr
2	2,850 hr	1,852,000 ton-hr
3	1,890 hr	1,286,000 ton-hr
4	990 hr	652,000 ton-hr

While each chiller was subject to the same demand charge of $53,625, energy consumption differed radically. Consider Chiller 1. It would consume $62,856 of electricity to produce roughly 2.6 million ton-hours of cooling annually. When the demand charge of $53,625 was taken into account, the operative cost of cooling for Chiller 1 was $0.045 per ton-hour.

By virtue of substantial hours of operation, Chiller 1—and Chiller 2, for that matter—proved to be excellent candidates for reselection at a higher efficiency. (The cost-add for better performance can be justified with lower energy costs.) The new selection was a 750-ton, centrifugal chiller with full-load performance of 383 kW and an NPLV of 0.412 kW per ton. An energy analysis confirmed that the price tag to reduce the average operating cost by $0.019 per ton-hour (from $0.058 to $0.039) was a sound investment.

By injecting asymmetry into a symmetrical plant design, the design team reduced the cost of operating Chiller 1 by 30 percent!

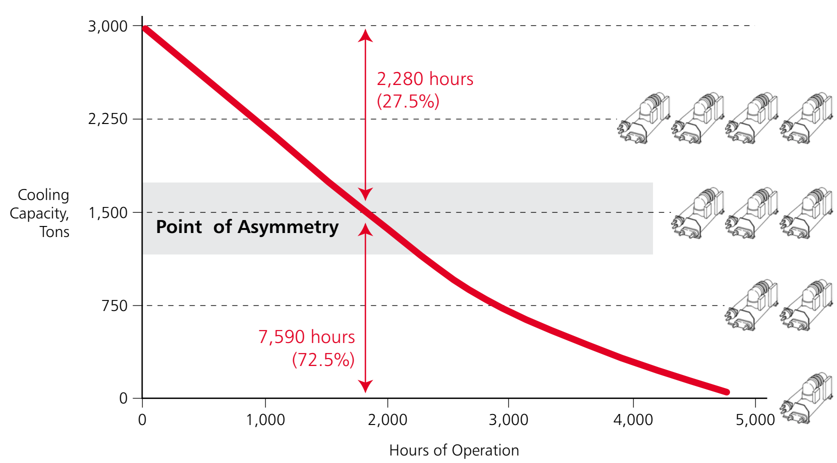
Hybrid Opportunity. What about Chiller 3 and Chiller 4? Chiller 4 is required only 990 hours each year, yet bears the same demand charge. Producing only 652,000 ton-hours, its average cooling cost is $0.131 per ton-hour. Chiller 3 "clocks in" at $0.070 per ton-hour. (NPLV was not used in this calculation because Chiller 3 and Chiller 4 operate only at conditions when cool condenser water is unlikely.)

Recall the absorption chiller considered earlier? Its average cooling cost of $0.056 made gas-powered cooling an excellent candidate for Chiller 3 and Chiller 4. (See Table 4, page 4.) Why? While demand charges were only 47 percent of the cost of operating Chiller 1, they represented more than 74 percent of the operating cost for Chiller 4.

The decision to use absorption chillers raised two issues: **first cost** and **performance**. In this example, performance was considered irrelevant because Chiller 3 and Chiller 4 account for less than one-third of the plant's chilled water production. But the matter of cost remained. To address that concern, the designer arranged the chillers in **series**, with the absorption machines **upstream** of the centrifugal chillers. The absorption chiller selection could then be based on a warmer leaving chilled-water temperature, i.e., 50°F rather than 42°F. This design (Figure 2, page 4) substantially reduced the cost of the absorption chillers and greatly improved the COP. In the end, it also proved to be an irresistible option. But the design team didn't settle on that combination without first entertaining other ideas for Chiller 3 and Chiller 4.

A gas-engine-driven generator was among the alternatives considered in lieu of absorption chillers. In that scenario, Chiller 3 and Chiller 4 were electric centrifugal chillers, but each chiller received power from a gas-engine-driven generator during on-peak

Figure 1–Annual Load Profile



A publication of
The Trane Company
Worldwide Applied Systems Group
La Crosse, WI 54601-7599

Table 4–A Hybrid Solution[a]

Designation	Chiller Characteristics: Capacity	Chiller Characteristics: Power	Annual Operation, Per Chiller: Run Time	Annual Operation, Per Chiller: Cooling	Average Cooling Cost
Chiller 1	750 tons	electricity	4,740 hr	2.6 million ton-hr	$0.039/ton-hr
Chiller 2	750 tons	electricity	2,850 hr	1.8 million ton-hr	$0.049/ton-hr
Chiller 3	750 tons	gas	1,890 hr	1.3 million ton-hr	$0.056/ton-hr
Chiller 4	750 tons	gas	990 hr	652 thousand ton-hr	$0.056/ton-hr

[a] Chiller 3 and Chiller 4 are absorption chillers powered by 125-psig steam from a gas-fired boiler. If electric centrifugal chillers were used instead, the average cooling cost would be $0.070 and $0.131 per ton-hour, respectively.

times. Adding a gas-engine generator meant a substantial capital investment. Leasing was deemed a more attractive option since the engine-generator package might only be required five or six months of the year. (Leasing and temporary siting also solve certain space problems.)

Another issue was the added maintenance expense engines incur (for example, a major overhaul is required every 20,000 hours); however, running hours in this application were low, i.e., less than 700 hours annually.

Note: While Chiller 3 and Chiller 4 run 1,890 and 990 hours, respectively, only 700 of those hours were likely to occur on-peak and impact demand charges. During other periods, it was still less expensive to operate these two chillers with purchased power. The flexibility to run Chiller 3 and Chiller 4 from gas or purchased electricity was very valuable; so was the ability to provide emergency cooling in case of a power outage.

The design team considered thermal storage before eventually choosing a plant design that combined absorption and electrical chillers. Ice storage can be attractive for small chilled water systems, especially when paired with air-cooled chillers. ("Small" describes a building not large enough to require more than two chillers.) The capital cost and space requirement of ice storage is more readily managed when ice capacity is limited to less than half of design cooling capacity.

The "Moral" of This Story

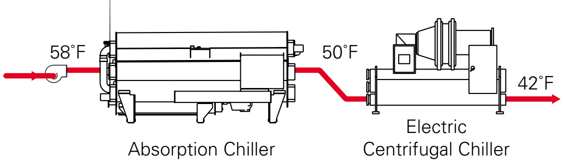
Gas-powered chillers, absorption chillers, or ice—located upstream of electrical chillers—are all examples of what is termed a combination or "hybrid" chilled water plant. The success of these plants is predicated on the principle of asymmetrical design, where one set of chillers tackles the problem of overall plant efficiency, while a second set of cooling devices is assigned the task of minimizing demand charges. Series chiller arrangements and low-flow designs are also critical ingredients to the success of hybrid applications.

A Postscript. Utility rates influenced the decision to use a hybrid plant design, once asymmetry helped establish two distinct design goals. Consider the effect of a deregulated utility market in which electricity that might cost less than $0.02 per kilowatt-hour at times of low demand skyrockets to $1 or more during on-peak periods. What could be more appropriate for an asymmetrical utility rate structure than an asymmetrical plant design? ■

By Don Eppelheimer, applications engineer, and Brenda Bradley, information designer, The Trane Company.

To comment on this article, send a note to The Trane Company, Engineers Newsletter Editor, 3600 Pammel Creek Road, La Crosse, WI 54601, or via e-mail from www.trane.com. Check the electronic bookstore for informative Trane publications on chilled water plants and other commercial HVAC systems. Back issues of recent Engineers Newsletters are available on our Web site, too.

Figure 2–Series Arrangement Improves Absorption-Chiller Performance



Leaving Water Temperature	Capacity	COP
40°F	0.88	1.19
44°F	1.00	1.24
50°F	1.12	1.29

Printed on recycled paper as part of The Trane Company's recycling program.