QuikChill Software for Efficient Chiller Upgrade Assessment

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ABSTRACT

Chiller upgrades, required by recent CFC legislation, have not occurred in most large U.S. facilities. Opportunities for compliance via efficient, correctly-sized chillers is significant, but there is little industry infrastructure encouraging downsizing and maximum efficiency, nor are changeouts approached as investments. Upgrade performance analysis is either too simplistic (missing integration and downsizing opportunities) or too difficult, detailed, and expensive. A niche exists for dedicated tools that can be used for both early screening and more detailed final design analysis, including downsizing, system integration, and staging.

QuikChill, a chiller upgrade analysis software tool, was developed by EPA's ENERGY STAR Buildings Program to address these issues. It performs economic and energy analyses of potential centrifugal chiller upgrades using minimal information, and performs more accurate calculations as the quality and detail of inputs are increased. QuikChill assesses the consolidation of existing chillers, integration/staging of new chillers, and refrigerant conversion retrofits. QuikChill was designed for facility managers and consulting engineers facing CFC phaseouts.

Rather than require time-consuming, detailed building shell and operational inputs, QuikChill estimates loads using DOE2-generated curves which plot the relationship between cooling load and outdoor temperature. Surprisingly, these curves reasonably predict annual cooling system operating requirements when used with local hourly temperatures and the peak load met by the existing system. Hourly temperature data is available for over 240 locations and users can easily supply peak information.

QuikChill's combination of simplified inputs, investment-orientation, and unique approach to hourly cooling load estimation help fill an analytical void for the post-CFC chiller industry.

Introduction

EPA's ENERGY STAR Buildings Partnership has, in recent years, picked up where Green Lights left off in helping Partners commit to significant investments in building energy efficiency. The suite of screening tools offered by the EPA allows key technology options to be assessed so that upgrade decisions can be made from an informed standpoint. Large Partners can participate more directly in decision making because they understand the options and what those options offer. Service providers often use these screening tools because they offer performance and economic analysis that was previously unavailable or only offered by more complex tools. QuikChill is one of EPA's ENERGY STAR Buildings screening tools.

QuikChill allows users to assess the potential energy and economic impact of modifying existing chillers to comply with the ban on CFC refrigerants, or of replacing chillers with units that are compliant. At the same time, users are able to investigate options for consolidating or staging chiller operation so that redundancy and partload operations are considered. Unlike tools that have traditionally been used to provide this decision support, QuikChill can perform this analysis without complex, time consuming data regarding the building shell (roof and wall construction, window type and area, etc.). This simplification allows the tool to be used for useful analyses right out of the box, since the very detailed building shell data is not needed.

EPA's policy is to make its analytical tools available both to ENERGY STAR Buildings Partners and anyone interested in saving energy at a profit. As a result, you can download QuikChill and several other EPA screening tools from the World Wide Web (*http://www/epa.gov/appdstar/appd/download.html*).

Approach to Building Load Analysis

The most difficult aspect of traditional building load and HVAC analysis is the data required to determine how much cooling or heating energy a building uses in the course of a year. Detailed analyses generally requires extensive information regarding the wall type, area, and insulation; window type, area, and orientation; occupant density and operating schedule; building volume and air changes per hour; etc. These details take time to assemble and input into a system, and offer, at best, the basis for a reasonable estimate of what is really happening in the building. Although there are analytical tools in the marketplace that, given this detailed input set, facilitate decision making regarding chiller upgrades, the effort required to make a basic go-no go decision is prohibitive. This is particularly true where competing energy-saving measures, such as lighting upgrades, have proven, easy-to-understand benefits.

QuikChill eliminates the need for detailed building data and allows users to focus on cooling system characteristics. This is accomplished by using a correlation of building load to hourly outdoor air temperature. Chiller load at actual peak operation is obtained using one of four methods, since users may have different kinds of operational data for their chillers (See Figure 1). This peak operating condition is assumed to correspond to the hottest hourly temperature event, and loads at lower temperatures are set using a load-to-temperature curve that is generated using DOE2 for a specific set of building attributes. In addition to significantly reducing the amount of data required of the user, this basic approach allows the following:

> The use of hourly temperature data makes QuikChill runs climate-specific. Over 200 sites are available and can be provided on one disk, if desired.
>
> Although a simplification of more traditional analyses, QuikChill is still an hourly tool, which allows time-of-day utility rates to be used in the tool.
>
> The user can control the operating schedule while retaining analytical accuracy.
>
> Future load reduction (e.g., peak load reductions associated with an anticipated lighting upgrade) can be entered as simple, at peak load reduction, allowing simple assessment of rightsizing scenarios for upgrade chillers.

The correlation between load and temperature, although initially viewed as counter-intuitive for internally loaded buildings, was verified using multiple DOE2 runs for different climates, building types, efficiencies, and climates. For these runs, building cooling load was accumulated associated with the outdoor temperature data for each hour. Although the slope of the correlation curve varies significantly with efficiency factors that involve outdoor temperature (e.g., insulation, shading coefficient, percent outdoor air intake), the relationship is very linear and with little spread for minimum and maximum load values at each temperature.

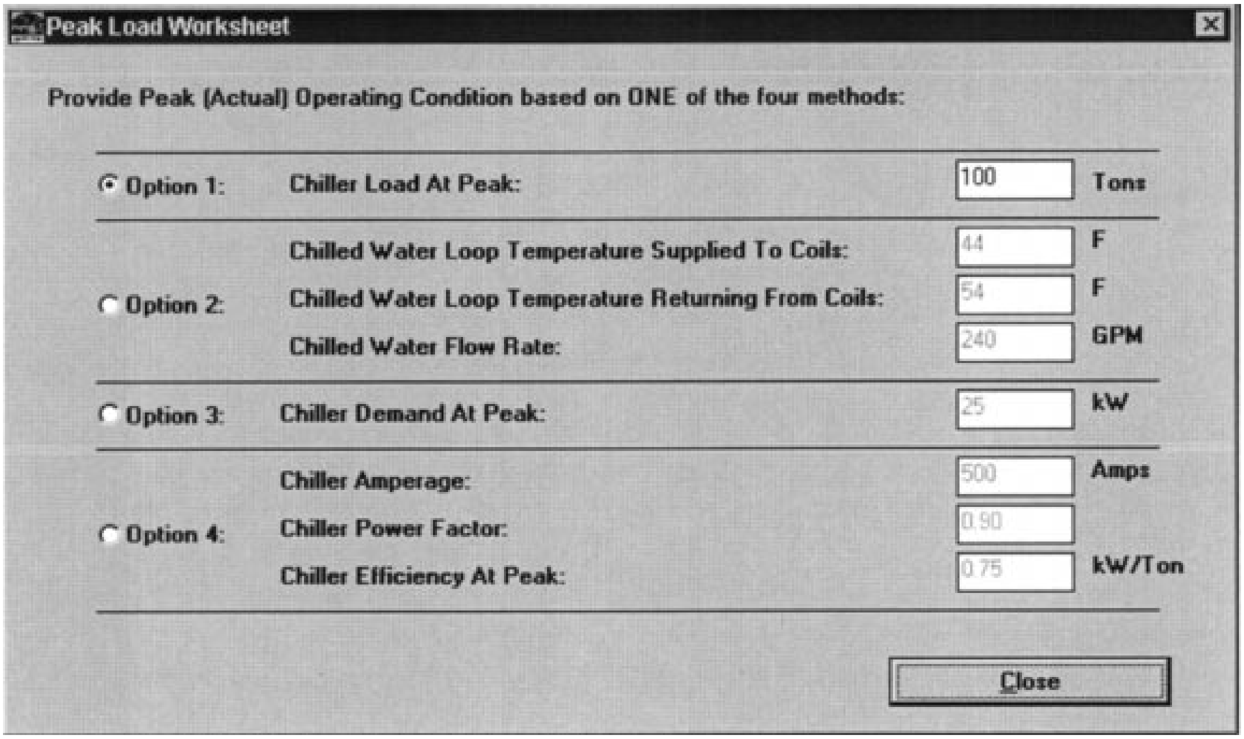

Figure 1 QuikChill's options for specifying chiller load at actual peak operation

Once it was verified that a load-to-temperature curve could be used to significantly reduce user input requirements, a library of curves was developed for use in QuikChill. These curves, of which there are now 16, are based on changes to the following variables:

Generic building type (office, education, hospital, retail)

High or low perimeter to core ratio (double loaded corridor

High or low building efficiency (pre-upgrade or post-upgrade)

Table 1 shows the data that are presented to the user for each of the four building types. This helps user view the curves and the data used to generate the curves in order to select the curve that most closely corresponds with their building. Users who make a reasonable curve selection will be able to analyze chiller upgrade potential by focusing on chiller inputs. Users who have become familiar with QuikChill's approach and who are comfortable with building attributes can create their own curves, which can be useful if a building falls between two options.

QuikChill's simplified approach is further justified by the fact that the building cooling load is used only to obtain a savings increment between the existing and upgrade cases. Absolute values associated with the operation and cost of either the existing or upgrade, where concerns about accuracy might be justified, are less important since the approach is comparative.

Table 1. Data presented by QuikChill for building parameters

Characteristics	Office 1	Office 2	Office 3	Office 4
Efficiency Category	Pre-Upgrade	Post-Upgrade	Pre-Upgrade	Post-Upgrade
Total Floor Area	338,688	338,688	158,400	158,400
Perimeter-Core Ratio	0.25	0.25	10	10
Exterior Length (East and West Exposure)	290	290	295	295
Exterior Length (North and South Exposures)	290	290	295	295
Number of Stories	4	4	3	3
Total Building Height	48	48	45	45
Window Wall Ratio (WWR)	5/12	5/12	6/15	6/15
Shading Coefficient	0.90	0.60	0.90	0.60
Site Shading	None	None	None	None
Wall R-Value	R-10	R-10	R-8	R-8
Roof R-Value	R-8	R-8	R-8	R-8
Lighting W/ft^2	3.0	1.5	3.0	1.5
Occupant Density	143	143	143	143
Outdoor Air Flow	5 cfm/ft^2	20 cfm/ft^2	5 cfm/ft^2	20 cfm/ft^2
Weekday Operating Hours	8 AM to 7 PM	8 AM to 7 PM	8 AM to 7 PM	8 AM to 7 PM
Weekend Hours	None	None	None	None
Economizer	None	None	None	None

Approach to Cooling Tower Analysis

The routines used to predict leaving cooling tower water temperature follow the Effectiveness-NTU (number of heat transfer units) method. Commonly taught in undergraduate studies, the Eff-NTU method provides closed form solutions to the problem of heat exchanger performance (Incropera & DeWitt 1996, 520-28.). Traditionally, Eff-NTU model is applied to heat transfer problems with temperature acting as the driving force. Cooling towers involve enthalpy transfer, which is a combination of both thermal and mass transfer.

The power of the Eff-NTU method is in the fact that the geometry of the problem is pre-solved for the engineer. Regardless of the driving forces, counter-flow, cross-flow and parallel-flow heat exchangers are each limited in their performance due to their geometric arrangements. In the case of parallel-flow for example, the Eff-NTU method demonstrates that two fluids with equal heat capacities can at best exchange only 50 percent of their heat. In the case of counter-flow, the Eff-NTU method demonstrates the superior performance available with this type of geometric arrangement. Where traditionally cooling tower evaluation requires the engineer to segment the tower into infinitesimally small segments and iteratively loop through solutions, the Eff-NTU method offers a simple closed form solution.

The limitation of the Eff-NTU method is its reliance of constant fluid properties. In its derivation, the Eff-NTU model assumes two fluids with constant specific heat and constant mass flow. This is an extremely safe assumption for the vast majority of heat exchanger problems involving fluids. For gases, specific heat may change significantly with temperature. In this case, it is possible to split the analysis into two or three segments and assume constant specific heat within each segment. With just a few segments, heat exchanger performance with gases experiencing large temperature changes can easily be handled by the Eff-NTU method.

Experience has demonstrated that typical cooling tower operating temperatures do not require the use of segments when applying the closed form solutions of Eff-NTU method. To predict the performance of cooling towers, the following substitutions are made in the Eff-NTU method.

Enthalpy (*h*) is substituted for temperature (*T*)

Mass flow (*m dot*) is substituted for *C* (heat rate capacity)

Where Eff-NTU is derived with temperature difference as the driving force, it is a simple matter to substitute enthalpy as the driving force. Where Eff-NTU is derived using heat rate capacity defined as mass flow times the specific heat, it is a simple matter to substitute mass flow of air. The Eff-NTU method is thus derived assuming heat exchange fluids experiencing temperature changes. Recognizing cooling towers' exchange enthalpy, the modifications to the Eff-NTU method merely result in the substitution of enthalpy as the driving force. As a reminder, the geometry of the heat exchanger is independent of the driving forces.

The one detail remaining to adapt Eff-NTU method for cooling tower performance is the conversion of water flow rate into an effective saturated air mass flow rate. The actual enthalpy exchange in a cooling tower takes place at the water-air boundary as both the entering air and entering water pass over and through the fill material. The entering air does not interact with the water directly, but rather with the saturated air film that exists just beyond the water's surface. Therefore, the water can be treated as a saturated air mass (100 percent humidity) at a temperature equal to the water. The numerical conversion from water flow rate into equivalent saturated air mass flow rate is defined below:

m dot equivalent = $q / (h_1 - h_2)$

where

m dot equivalent = equivalent saturated air mass flow rate

q = heat transfer of water

h_1, h_2 = enthalpy of saturated air at temperatures equal to water at conditions 1 and 2

All cooling towers are sold with a rated water mass flow and rated capacity. Thus if a cooling tower is designed to handle 50 tons of cooling with entering and leaving water temperatures of 95°F and 85°F, the equivalent saturated air mass flow rate is simple to determine. From that point forward, enthalpy (*h*) at any given temperature is substituted for temperature (*T*) and mass flow of air (*m dot*, or *m dot* equivalent) is substituted for heat rate capacity (*C*).

Pacific Gas and Electric (PG&E) recently reviewed the Eff-NTU method used in QuikChill for applicability in their CoolTools™ project (*http://www.pge.com/cooltools*). Over a water temperature range of 3°F to 20°F, 3°F to 20°F approach, 40°F to 80°F wet bulb, fan speed from 0 to 100 percent flow, and water temperature down to 15 percent flow, Eff-NTU proved accurate and robust. Ultimately, CoolTools adopted the DOE version 2.2 methodology to predict cooling tower performance because of its speed. Their comparison did independently verify the usefulness of Eff-NTU, since it calculated tower leaving temperature within 2°F of the nine actual towers tested (PG&E 1998).

Approach to Staged Chiller Operations

When multiple chillers are used to serve a single chilled water loop, staging of operation is necessary to assure that partload performance is minimize and that chillers are brought on and off load in a reasonable sequence. QuikChill allows the user to model a variety of staging approaches via a graphical interface that shows what chillers under various load conditions (See Figure 1). The fact that the staging graphic corresponds to the load-to-temperature graph assures that users understand the relationship between changing loads and changing chiller operation.

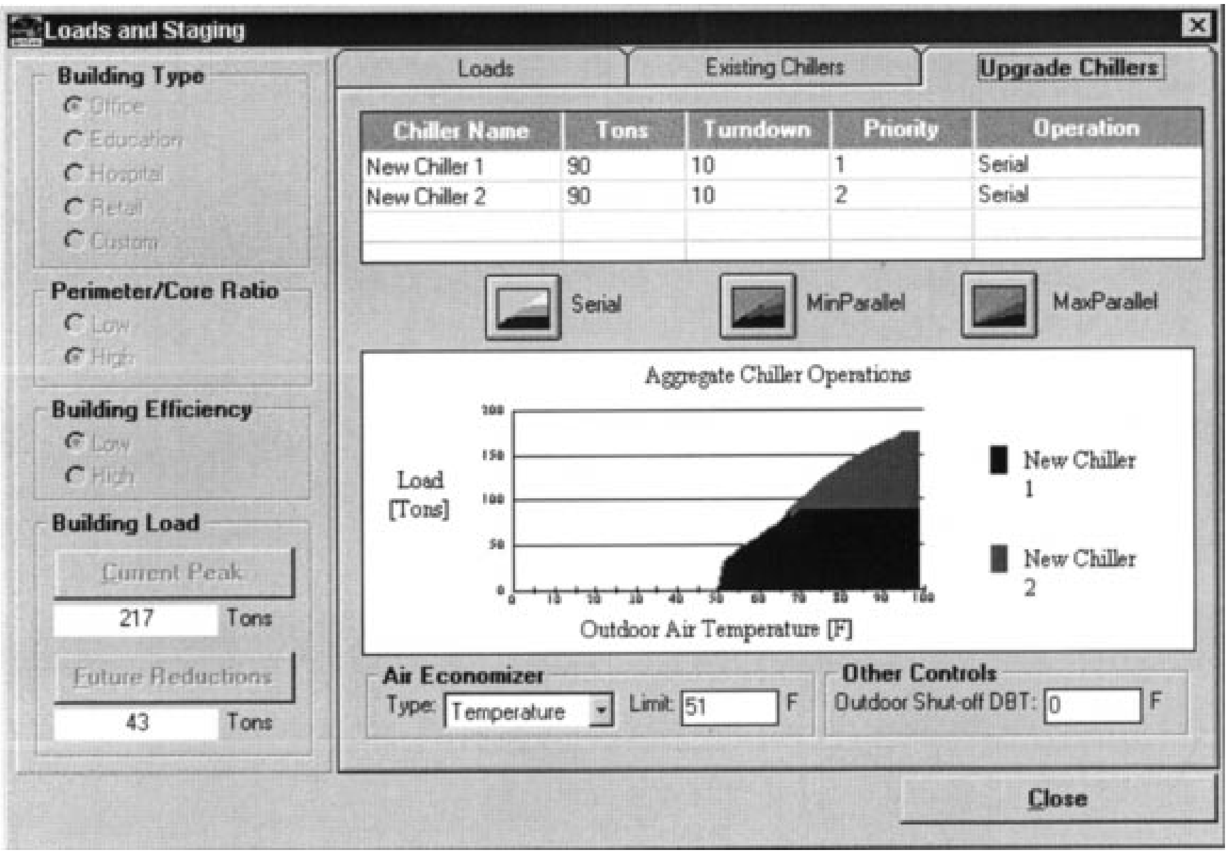

Figure 2. QuikChill options for staging approaches under various load conditions

Approach to the Cost Database

QuikChill includes an extensive database of chiller upgrade costs, which, despite inevitable job site variation, allows users to assess potential economics associated with chiller upgrades. This database was assembled in the following manner:

A number of actual chiller upgrade costs were collected for ENERGY STAR and other projects.

Means cost data was used to obtain estimated chiller upgrade costs for project similar to applications targeted by QuikChill.

All actual and Means cost and chiller size data were plotted and found to correlate well (R. J. Means 1997).

This approach allows the tools to provide cost estimates for a wide range of chiller sizes. Users can, of course, override the default costs if better costs are known.

Typical Applications

The following are descriptions of the most likely applications for QuikChill. For any given ENERGY STAR Partner, all of these approaches might be used in the course of their multi-year commitment to chiller upgrades:

Single chiller modification or replacement: Novice users would generally start by entering a single, simple chiller to assess the costs and benefits of modifying that chiller to use compliant refrigerants or replacing the chiller with a compliant, new model. This is the simplest use of the tool, and requires relatively little input data or user expertise.

Multi-chiller conversion or replacement: Large buildings that use water-cooled centrifugal chillers generally have more than one chiller serving a chilled water loop, and upgrade decisions are a bit more complicated (e.g., one chiller may be primarily a backup unit, so investments in efficiency are tough to justify). Users have a variety of options, and can choose which of their multiple chillers to modify, replace, or leave alone.

Multi-chiller strategic redesign: Many chiller upgrades in large commercial buildings involve either the consolidation of a bank of chillers that has been added to over time as needed changed, or the addition of chillers so that staging can be used to meet loads more efficiently. QuikChill can accommodate either scenario, since the existing and upgrade configurations are defined by the user and can be completely different. A large, old single unit can be analyzed against multiple, smaller units for redundancy and less part load operation. A confusing array of chillers added over a 20-year period can be analyzed against a pair of larger units. Putting this type of analytical capability in the hands of building engineers is one of QuikChill's key strengths.

Beyond these basic application scenarios lie some unique opportunities to take HVAC design to higher levels. For example, if a user can determine the most frequent outdoor air temperature occurrence for his climate (around 72°F in Washington, DC), he/she can use the tool to select a staged upgrade that allows most efficient operation at this temperature. A smaller unit could be brought in to handle loads that occur above this "temperature plateau." The result is a system that most efficiently meets loads across the year. This differs significantly from an industry approach that now designs to meet a peak temperature that only occurs several days per year.

Future Plans

Future enhancement for QuikChill will be driven, as with the other EPA tools, by budget and feedback from a variety of user groups. The screening tools have a unique role in supporting both Partner organizations and industry service providers. The needs of these two groups vary, so the challenge is to provide enhancements that do not benefit one group at the expense of the other. EPA is currently considering the following improvements to QuikChill:

Interface modification to allow more comparative analyses: QuikChill currently allows cooling tower attributes, chilled water reset, operating schedule, and building characteristics to be set once for both the existing and upgrade chiller run. The tool could be modified to allow any of these to be changed in the upgrade run, allowing a greater number of scenarios to be analyzed. For example, a user might use the tool to optimize cooling tower operation even without a chiller upgrade.

More educational help: QuikChill has an extensive, context specific help system that covers navigation through the tool and analytical approach. This could be expanded to include more detail regarding how chiller upgrades should be viewed as part of a staged approach to building upgrades (as promoted by the ENERGY STAR Buildings). More detail could also be provided regarding more advanced uses of the tool, such as analysis to find the best staging approach for multiple chillers.

Diagrammatic Interface: EPA is considering using a diagram of chiller system components as the interface for navigating through the tool. This would improve the educational benefits of the tool for novice users and could display data like flow rates and temperatures in a meaningful, high-level format.

More DOE2-generated building curves: The current library of building load-to-temperature curves includes 16 different options.

Greater selection of chiller performance curves: QuikChill contains a basic library of curves that allow calculations to reasonably address partload performance. This curve library could be expanded to include a wider range of options.

Move to air-cooled chillers: The basic analytical approach used in QuikChill applies well to other types of chillers, so air-cooled and packaged chillers are likely additions if capability is expanded.

Expand analytical capability: QuikChill could be expanded to include auxiliary pump and motor energy in addition to chiller energy.

Upgrade Cost Database: As with the other ENERGY STAR analytical tools, cost databases are periodically checked and improved as more and better information is obtained.

Conclusions

QuikChill fills an analytical niche at a critical time when chiller upgrades are essentially mandated for refrigerant compliance. EPA continues to show commercial building owners that these types of building infrastructure upgrades can be made profitable. QuikChill allows users to plan their chiller upgrades in a way that maximizes their ability to identify and ask for efficient, right-sized replacements. It also allows more savvy users to optimize their chiller upgrades for better performance. Because of EPA's partnering approach to energy savings and pollution prevention, QuikChill enhancements will increase this tool's decision-making capabilities.

References

Incropera, Frank P. and David P. DeWitt. 1996. *Fundamentals of Heat and Mass Transfer, Second Edition*. New York: John Wiley & Sons.

PG&E. March 1998. "Testing of cooling tower simulation algorithm candidates" (draft contract deliverable to the Pacific Gas and Electric CoolTools project). San Francisco: Pacific Gas and Electric.

R. S. Means Inc. (Melville J. Mossman, ed.). *Means Mechanical Cost Data 1997*. 1996. Kingston, Massachusetts: R. S. Means.