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PG&E's "CoolTools™" Project:
A Toolkit to Improve Evaluation and Operation of Chilled Water Plants

A Report of the CoolTools™ Project

CoolToolsô Report #CT-007 - Sept. 1997

http://www.hvacexchange.com/cooltools

For more information about this technical document, contact:

Marlene Vogelsang
PG&E Energy Center
851 Howard Street
San Francisco, CA 94103
Internet MXV6@pge.com

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September 1997

Abstract: Chilled water plant owners, engineers, purchasing agents and plant operators are making critical design, control and purchasing decisions in an information vacuum. Seemingly simple decisions such as choosing a replacement for an existing chiller or selection of a temperature set point for the condenser water control can have a significant impact on the cost of running the plant, yet consistent unbiased methods for making these choices are not readily available. This paper describes PG&E's "CoolTools™" project, a collaborative effort to provide an integrated set of project planning, implementation and design documents with simulation tools that can be easily calibrated to the specific characteristics of the facility and equipment. This project grew from years of experience assisting customers and design professionals who were motivated to improve plant efficiency but were hampered by lack of tools. It has the participation of industry research organizations, manufacturers, customers, design professionals, federal and state agencies and energy efficiency advocates.

CoolTools™ Project. This technical document is part of a broader set of products developed by PG&E's CoolTools Project. CoolTools™ is a market transformation project developing, disseminating, and promoting an integrated set of tools, guidelines, and services for the design and operation of optimized chilled water plants. CoolTools™ products inform owners, design professionals, and operators about methods to achieve the most cost-effective and efficient equipment selection, system design, and operating scenario for new construction and retrofit applications. Products are Internet-based and intended for broad public use.

Editor and Project Manager:

Kenneth L. Gillespie, Jr.
Pacific Energy Center
851 Howard Street
San Francisco, CA 94103

Authors:

Mark Hydeman, PG&E Pacific Energy Center
Ken Gillespie, Pacific Gas & Electric
Ron Cammerud, Paradigm Consulting

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Legal Notice

Table of Contents

Introduction

Huge opportunities exist to improve the efficiency of existing chilled water plants (Howe, 1995; Haberl et. al., 1996). Furthermore, with the phase-out of certain refrigerants, the next few years offer a unique window of opportunity to improve existing plant performance as plant owners replace or retrofit existing equipment (Smit, 1996; ARI, 1996; Randazzo, 1996; Fryer, 1995). In California, PG&E estimates that a conservative effort could yield a yearly saving of 20 MW of demand and 30 GWh/yr of energy savings from careful equipment selection alone.

However, experience and the trade literature clearly indicate that optimization of plant design and operation is a complicated matter for which there are few tools and many disparate opinions. Analysis of design and purchasing options is rarely performed. When it is performed, it seldom captures the dynamics of the individual pieces of equipment, the system interactions and the variations in load and weather. Between the prevalent practice of purchasing the cheapest alternative and informed life-cycle cost analysis based on calibrated or customized analysis there is a vast chasm (Figure 1).

The "CoolTools™" project is predicated on the hypothesis that we can empower decision makers to look at complex system interactions by introducing low-cost, accurate and easy to use central plant simulation tools. We are proceeding with the knowledge that many individuals are willing to forego more stringent accuracy to get quick results, and that the route to detailed analysis will involve several steps. This project intends to provide those stepping stones.

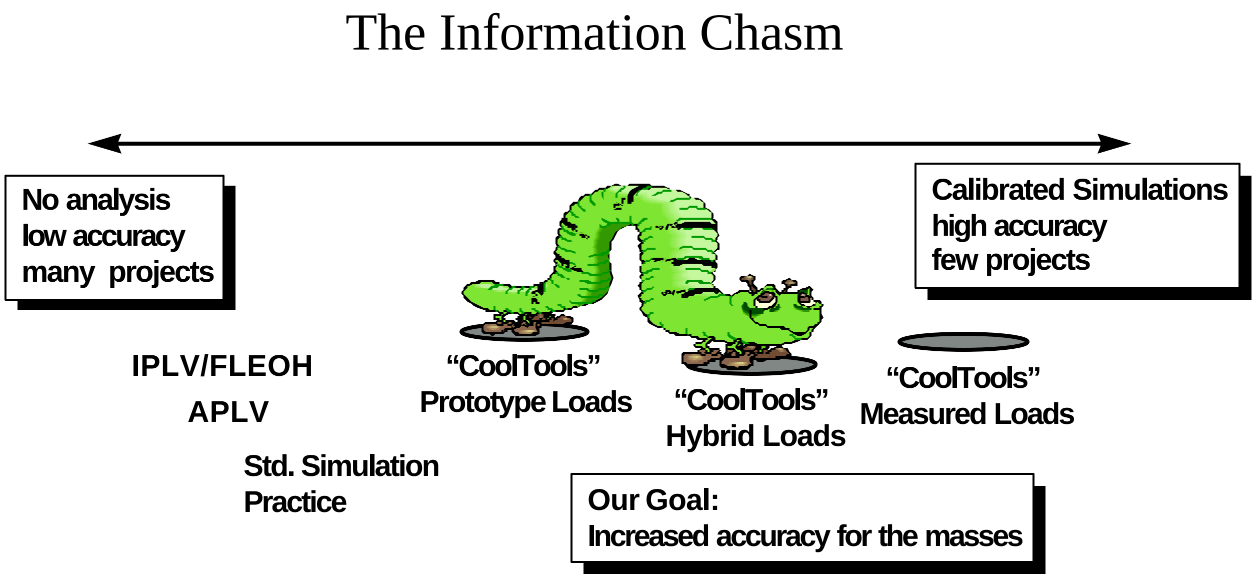

Figure 1: The Information Chasm. *This graphic depicts the breach between standard practice and calibrated simulation. The "CoolTools™" approach is to support a range of evaluation methods across the chasm.*

Background

This project is built upon a foundation of project experience at PG&E. At its inception, we consolidated the relevant data, techniques, guides and tools that had been developed for customer service, demonstration projects and rebate programs. In addition, several members of the project team brought resources from their participation in development of codes and standards.

The initial project resources include:

- Consultations with customers, plant managers and engineers.
- Data and experience in instrumenting over a dozen chilled water plants.
- Creation of monitoring guidelines for chilled water plants (PG&E, 1995).
- Participation in the development of Title 24 (CEC, 1995), ASHRAE/IES Standard 90.1 (ASHRAE, 1989; ASHRAE, 1996), ASHRAE Guideline 1 (ASHRAE, 1996), ASHRAE Guideline 14P: Measurement of Energy & Demand Savings, and ASHRAE Standard 150P: Method of Testing the Performance of Cool Storage Systems.
- Participation in the development of simulation tools and interfaces including VisualDOE, Comply 24, Energy Pro and PowerDOE.
- Market research which defines characteristics of buildings in PG&E's service territory that utilize chilled water systems.
- Central plant simulation techniques developed in support of customized rebate programs.
- Development of several hundred calibrated electric chiller curves for simulation analysis.
- Development and field testing of performance based equipment specifications and life-cycle cost based bid evaluations.

  Team project experience includes detailed evaluation of over 30,000 tons of installed capacity representing a range of occupancies. The analysis, performed in spreadsheets and automated database applications, considered alternative equipment, alternative tower sizes, equipment staging and condenser set point optimization. In three manufacturing projects, these techniques yielded 2MW of demand savings and 10 GWh/yr of energy savings. One project goal is to automate these analysis techniques and provide them to the public.

  For many years, project staff have provided assistance to customers and design professionals faced with purchasing and design decisions. Common questions include:

- Which of these alternative chillers has the lowest life-cycle cost for my facility?
- How much will I save if I retrofit this chiller with a variable speed drive?

- Should I consider a variable speed drive for this cooling tower?
- How much will I save if I put in a larger motor on my cooling tower?
- What set point should I use for my cooling tower controls? Should I reset by wet-bulb temperature?
- How much money will I save if I design the system with a lower flow rate on the condenser water loop?
- What are the benefits of designing my chilled water system to a lower flow rate (higher temperature rise) on the evaporator side?
- What is the operating efficiency of my existing chiller? How many hours does it operate at each load condition?
- How do I determine the performance of my chilled water plant? How can I improve its performance?

These questions run the gamut from scoping studies to detailed analysis. On the surface, they appear simple. In fact, the answer to each depends on complex interactions of several factors:

- Performance of the plant equipment (pumps, chillers and towers) with changes in load, flow, weather, controls, and water temperatures.
- Variation of load profile and coincident outside ambient dry- and wet-bulb temperatures from hour to hour.
- How well the available performance data represent the actual performance of equipment.
- A myriad of other issues including: the appropriateness of the original design for current and proposed future operating conditions, calibration of control sensors; implementation of control logic; installation of equipment; system maintenance; and changes made by the operating personnel.

The "CoolTools™" project is developing elements to address each of these factors. Project elements are depicted in Figure 2. This paper elaborates on a representative portion of these elements: the software tools, guides, web-site, and collaborations.

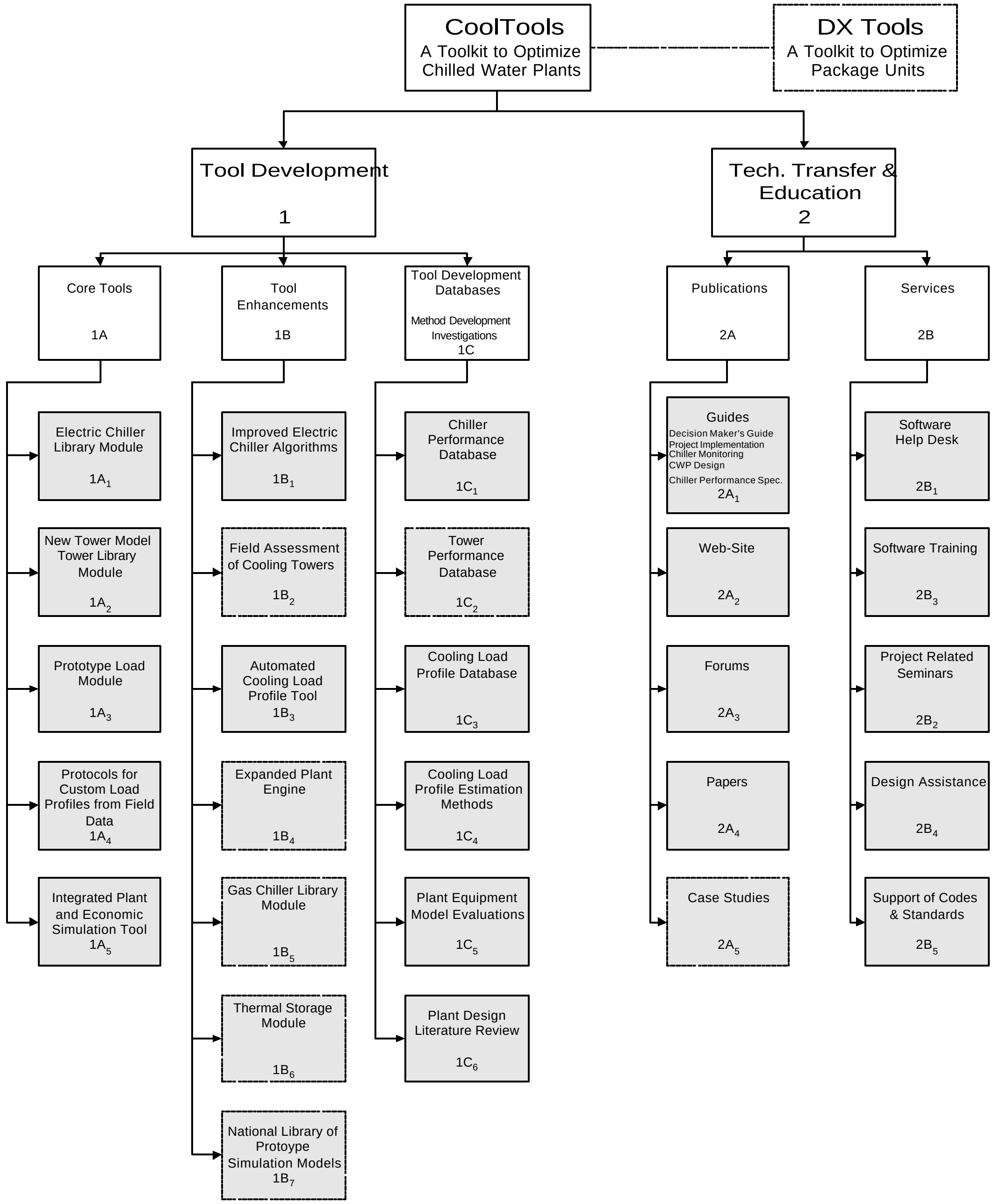

Figure 2: Elements of the "CoolTools™" Project. *This chart depicts the deliverables of the "CoolTools™" project. Each of these elements will be described in detail on our web-site. The boxes with dashed lines are deliverables that are not presently under contract.*

Discussion

Our first product creates customized chiller models from either field-measured or manufacturer's performance data. Over the past 10 years, manufacturers have uniformly stopped publishing chiller performance data in their catalogs. Performance data is developed in selection programs which are certified in accordance with ARI standards (ARI, 1992). Access to the selection programs is limited to field sales representatives. Neither customers nor design professionals can access these programs directly.

In 1993, "CoolTools™" project staff worked with manufacturers and ARI to develop representative default chiller models in support of ASHRAE/IES Standard 90.1R (ASHRAE, 1996). The analysis techniques were the foundation of the chiller routines included in the "CoolTools™" Library Module. Subsequent data sets were acquired as part of utility rebate programs. In all, approximately three dozen field data sets and 77 data sets of manufacturer's data have been acquired and archived over a four year period.

Although ASHRAE Standard 90.1R utilized the DOE2 (ver 2.1e) curve format, other chiller models were tested by the project team. 45 data sets were subsequently tested on the Gordon and Ng model utilized in ASHRAE Research Project 827 (Brandemuehl et. al., 1996) and a generic regression model developed at LBNL (Sezgan et. al., 1996). With these data sets and models the predicted power root mean squared (rms) error was least in the DOE2 format as indicated in Table 1.

Table 1: RMS Power Prediction Error of Alternative Chiller Models.

	DOE2e	Gordon & Ng	Sezgen et. al.
Minimum	0.7%	1.6%	1.1%
Maximum	4.2%	37.0%	17.3%
Median	1.6%	4.1%	6.0%
Average	1.8%	5.1%	6.9%

Note: Developed from 45 sets of manufacturer's data representing a full range of electric compression chiller products. Source: PG&E.

The automated Library Module produces custom chiller models in DOE2 (ver 2.1e) format from either field-measured or manufacturer's performance data. The performance curves are produced in one of two ways: with rich data sets which can be differentiated by full- and part-load operation the curves are directly derived utilizing standard linear regression techniques; from incomplete data sets or where the data represents a mixture of full- and part-load conditions the curves are developed by scaling an existing curve from the library to best fit the data.[1]

[1] These techniques and the conditions of their use are described in another paper in this forum (Eley et. al., 1997).

In both cases the user can view the total rms predicted power error of the data set and the percent power deviation for each of the input data (Figure 3).

Curve:	WCCentC7
RMS Error:	2.2%

Engineering Units			**DOE 2 Units**		
Capacity	745.7	tons	DOE2 SIZE	8.949	MMBH
Power	385.7	kW	DOE2EIR	0.147	EIR

	A	B	C	D	E	F
CAPFT	-1.96879031	0.06572961	-0.00055230	0.04579468	-0.00052560	0.00023956
EIRFT	-0.06089429	0.00944508	0.00000732	0.01773596	-0.00000110	-0.00022178
EIRFPLR	0.14146237	0.30281842	0.55404037			

Manufacturer's Data				**Curve Data**					
CHWS	**CWS**	**Q**	**P**	**CAPFT**	**EIRFT**	**PLR**	**EIRFPLR**	**Power**	**%kWError**
°F	**°F**	**tons**	**kW**					**kW**	
42	74	800	399	1.07	0.97	1.00	1.00	399.00	0.0%
42	70.5	600	260	1.14	0.94	0.70	0.63	259.89	0.0%
42	67	400	168	1.20	0.91	0.45	0.39	162.87	-3.1%
42	63.5	200	95	1.25	0.88	0.22	0.23	98.11	3.3%

Figure 3: Sample Chiller Curve Fit Data Report. *This figure indicates the kind of information that is provided by the Library Module. For each of the data points entered, the program reports the predicted power and the percent error in predicting the power. For all of the data entered a total rms error is reported.*

The scaling routines are limited to chillers of the same condenser class (air- or water-cooled) and compressor mechanism (centrifugal, screw, scroll or reciprocating). In addition the user may chose to filter the available curves by refrigerant and/or unloading mechanism.

The routines to produce a new curve directly from a data set are presently implemented in an automated MSExcel spreadsheet that can be downloaded from PG&E's web-site. This site also contains a paper describing the underlying algorithms.[2] An automated Library Module is under development that will provide both functions.

The structure of our software modules is depicted in Figure 4. The Library Module will initially contain routines for electric chillers, cooling towers and load. It will be distributed as a stand-alone tool which can be called from other 3rd party interfaces. We plan to integrate this tool with the "CoolTools™" Integrated Plant Simulation Tool (Eley et. al., 1997), VisualDOE, COMCheck-Plus[3], Energy Pro[4]

[2] This information and the downloadable tool is presently located at the following URL, "http://www.pge.com/pec/tooltoc/chillint.html." In the very near future this information will migrate to the project web-site at "http://www.pge.com/cooltools."

[3] This program is in development by RER of San Diego under contract to Battel Pacific Northwest Labs and with the support energy commissions from several states. It is windows interface that performs energy code compliance from a description of the building and a description of the compliance rule set. It is presently in beta testing.

[4] This program developed by Gabel-Dodd/EnergySoft is an energy code compliance program with a hard-coded rule set. It is presently available for compliance with

and PowerDOE. On request, we will provide detailed I/O specifications to other 3rd party vendors.

The Library Module may be expanded to include gas-fired equipment and low-temperature machines for thermal energy storage. These projects are not part of the present phase of work.

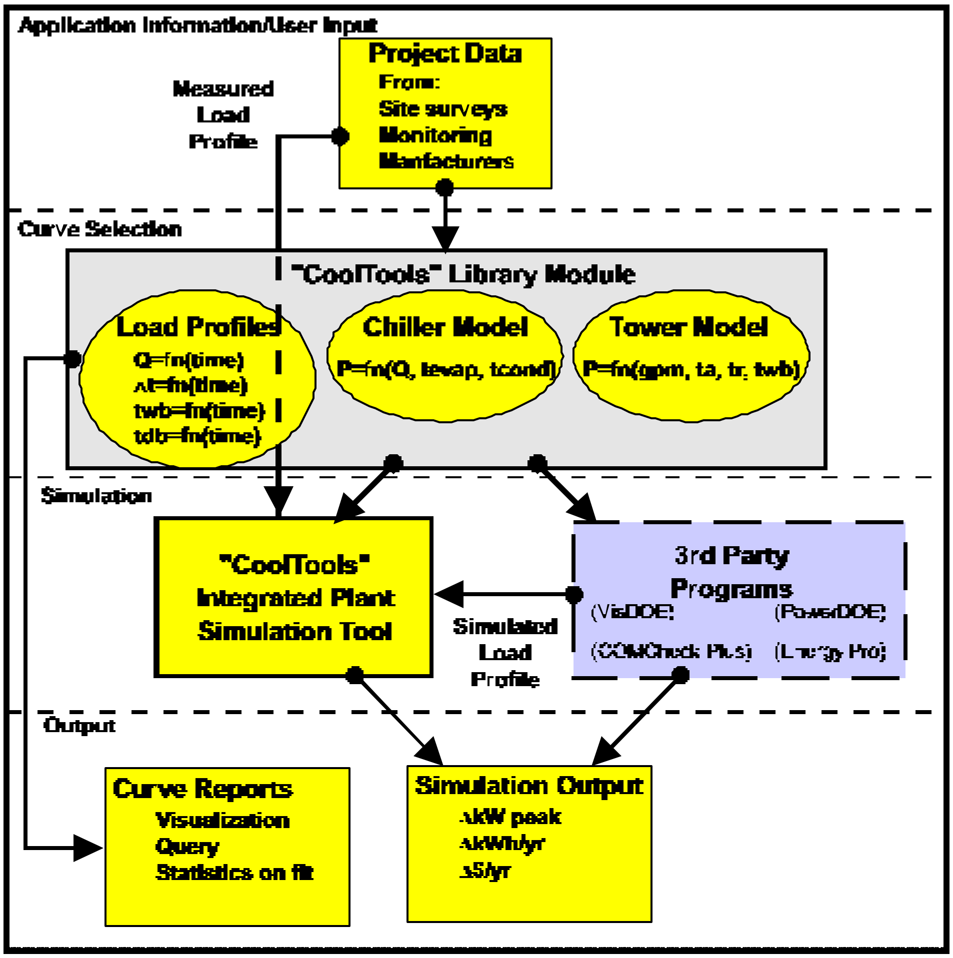

Figure 4: Structure of the "CoolTools™" Software Tools. *This chart depicts how the project software tools interrelate with each other and 3rd party vendors. The Library Module program includes the user interface, curve generation routines and the curve report routines (visualization, query tools and statistics of fit). Both the Integrated Plant Simulation Tool and 3rd party programs include a user interface, simulation engine and simulation output routines.*

The Integrated Plant Simulation Tool can utilize load data from the Library Module, imported from measured data or imported a 3rd party program. The import routines are described later in this paper.

California's Title 24 (CEC, 1995). A compliance version for Canadian Provences based on ASHRAE/IES Standard 90.1-1989 (ASHRAE, 1989) is under development.

Cooling Tower Model

A parallel effort to develop a customized cooling tower tool is presently under way. As for chillers, the tower tool will allow the user to develop a custom tower model from either field-measured or manufacturer's performance data. Error analysis of the curve fits will be presented similar to those in the electric chiller routines (Figure 3).

Unlike the chiller industry, manufacturer's performance data for cooling towers is readily available. At least two of the major manufacturers, Marley and BAC, have computerized selection programs that provide performance data for their packaged towers. Copies of these programs are readily accessible from local sales representatives.

Cooling tower tool development will be phased as follows:

1. Selection of a model.
2. Development of a tool to create a model from manufacturer's or long-term monitored data.
3. If necessary, implementation of the new model in DOE2 (ver 2.1e).
4. Development and testing of techniques to create a model from short-term monitored and/or field survey data.
5. Automation of the techniques from phase 4.

Phases 1. and 2. are presently under contract. Phase 1 will compare existing tower models including those in DOE2 (versions 2.1d, 2.1e and 2.2), the Merkle model (Lebrun et. al., 1995), and others which are uncovered in an open literature search. Each model will be evaluated for accuracy over a range of conditions, speed of calculation, ease of use, the ability to implement it inside of DOE2 (ver 2.1e) and other criteria. In phase 2, the model selected will be implemented in an automated tool.

If this work uncovers a model preferred to the one presently in use in DOE2 (ver 2.1e), a separate contract will be written to update that model. This is significant, not only because it strengthens Integrated Plant Simulation Tool, it also improves the accuracy of 3rd party tools which use the DOE2 (ver 2.1e) engine.

Phase 4 and 5 will develop a tool for modeling of existing towers through short term field monitored and/or site-survey data. This work will build on a body of utility industry experience in developing cooling tower models for power plant analysis.

Load Profiles

With equipment models in hand, the evaluator still needs a representative cooling load profile with coincident weather data to make an informed decision. The need for representative load profiles are universally recognized. However, the method for development of them is hotly debated. "CoolTools™" supports utilization of three classes of load profiles. As depicted in Figure 1 and described below, these methods represent a range of accuracy and effort:

Prototype simulations. This approach is typically applied in development of utility rebate programs and codes. Of the three, it is the least accurate but quickest method for developing results.

Hybrid approaches using statistical or mathematical techniques. These techniques utilize a mixture of data sources including but not limited to: short term measurements, simulations, site survey data and billing data. They are the subject of many technical papers and are showcased in the Great Energy Predictor Shootouts (Haberl et. al., 1996; Kreider et. al., 1994). They represent a balance of accuracy and effort.

Measured profiles (retrofit) or customized simulations (retrofit or new construction). This approach is the most accurate but requires planning, technical expertise, specialized equipment, budget and time allotments that are beyond the means of many projects.

The "CoolTools™" project supports analysis of both new and retrofit chilled water plants. For new construction there are typically two methods available for the prediction of load: customized simulations and use of prototypes. As previously described, customized simulations have the potential for the greatest accuracy, but they are costly to develop and subject to error on the part of the modeler. Prototype simulations offer quick and relatively inexpensive analysis, but sacrifice accuracy. In either case, the results will only be an estimate of the actual operation.

For retrofit plants, a range of analysis methods are available. Customized and prototype simulations are available and subject to the same issues as described for new construction. With retrofit projects however, monitoring may be employed. Long term monitoring ,if carefully performed, can offer an accurate load and weather profile. However, long term monitoring is both expensive and subject to both equipment and user errors. Monitoring may also be used to calibrate simulations or to train statistical models or neural networks. These and other hybrid techniques appear to offer a balance between cost, effort and accuracy.

Prototype simulations. The "CoolTools" project is developing a library of 800 preprocessed simulated profiles that represent prototypical projects in the climates of California. These models represent a range of occupancies, climates, mechanical systems and operating hours. Each profile can be scaled to match a proscribed peak tonnage. Multiple profiles can be blended through an automated interface based on a combined peak tonnage and a percentage contribution from each of the profiles selected.

Measured profiles (retrofit) or customized simulations (retrofit or new construction). In addition to the library of prototype simulated profiles, the

Integrated Plant Simulation Tool (Eley et. al., 1997) can import hourly files text files from either simulated or measured sources. These files contain hourly cooling loads and coincident outdoor dry- and wet-bulb temperatures.
The prototype simulation and import features are part of the Integrated Plant Simulation Tool. An existing chilled water plant monitoring guide (PG&E, 1995) is under revision to assist individuals in the development of hourly load profiles from field monitored data.

Hybrid approaches using statistical or mathematical techniques. A parallel project is under contract to develop an automated tool that falls in the hybrid category. The goal of this contract is to develop specifications for an automated tool. Due to the complexity of the problem, this project is split into three phases:

Phase one will provide a systematic assessment of candidate methodologies. This phase includes identification and evaluation of past work, development of selection criteria and selection of an approach.

Phase two sets the ground work for the design of a prototype tool. This includes an initial functional design of the tool, details of the site survey required to provide tool input and development of a work plan for phase three.

Phase three includes the development and testing of a prototype tool. At the end of this phase the contractor will produce a specification for an automated tool.
To assist this project, a database containing load profiles from a variety of sources is being developed. This includes nearly two dozen measured sites, the 800 prototype simulations and 150 simulations which were calibrated to building meter data. This test bed will be used to tune the prototype models and to test the algorithms for extrapolation, scaling and/or blending of profiles.

Integrated Plant Simulation Tool

The equipment models and load profile will be integrated in a single stand-alone plant simulation tool. The first version of this simulation tool will be based on the VisualDOE program which utilizes a DOE2 (ver 2.1e) engine. A detailed description of this tool is the subject of another paper in the CoolSense Forum (Eley et. al., 1997) however an overview will be provided here.

This tool will have the following functions:

- Create a load profile from the prototype library, field measured data, import from a 3rd party program or the hybrid loads tool in the Library Module.
- Develop equipment models from the Library Module.
- Perform analysis of alternatives using a fully functional VisualDOE plant and economics interface.
- Analyze alternative designs using a scenario wizard.

A post-processor module will be included to assist in the analysis of simulations. This module will produce a report on the operating characteristics of individual chillers (see Table 2). This report will detail the most frequent operating conditions for each chiller in the simulation, and the corresponding chiller's performance at those conditions. This report can be used as a basis for performance based bids. It presents a site-specific weighting of full- and part-load operating conditions for an individual machine.

Table 2: Report on Simulated Chiller Duty

Col A Chilled Water Temp. (°F)	Col B Condensor Water Temp. (°F)	Col C Capacity (tons)	Col D Power (kW)	Col E Runtime (hrs/yr)	Col F Cooling (ton-hrs/yr)	Col G Energy (kWh/yr)
44	85	745	515	104	77,480	53,551
44	82.5	671	444	260	174,330	115,502
44	80	596	382	884	526,864	338,053
44	77.5	522	328	1,092	569,478	358,127
44	75	447	280	1,144	511,368	320,027
44	72.5	373	237	780	290,550	184,801
45	70	298	199	624	185,952	123,914
45	67.5	224	165	208	46,488	34,369
45	65	149	136	104	15,496	14,110
				Totals==>	**2,398,006**	**1,542,454**
				Average Efficiency ==>	**0.643**	

Note: *A post processor for the Integrated Plant Simulation Tool will provide statistics on each chiller's most prevalent operating conditions. These reports can be used to develop performance specifications for bid alternatives.*

A second post processor function will assist in the analysis of condenser water controls. These functions will utilize the hourly reports of alternative runs that stage the condenser water set-point throughout its allowable range. The resulting data will be used to develop the plant energy usage of a theoretical optimal controller, identify the single set point for a fixed temperature control that minimizes total plant energy usage and provide analysis of several dual-set point and reset control schemes. As illustrated in Figure 5, the optimal condenser water control is extremely difficult to develop.

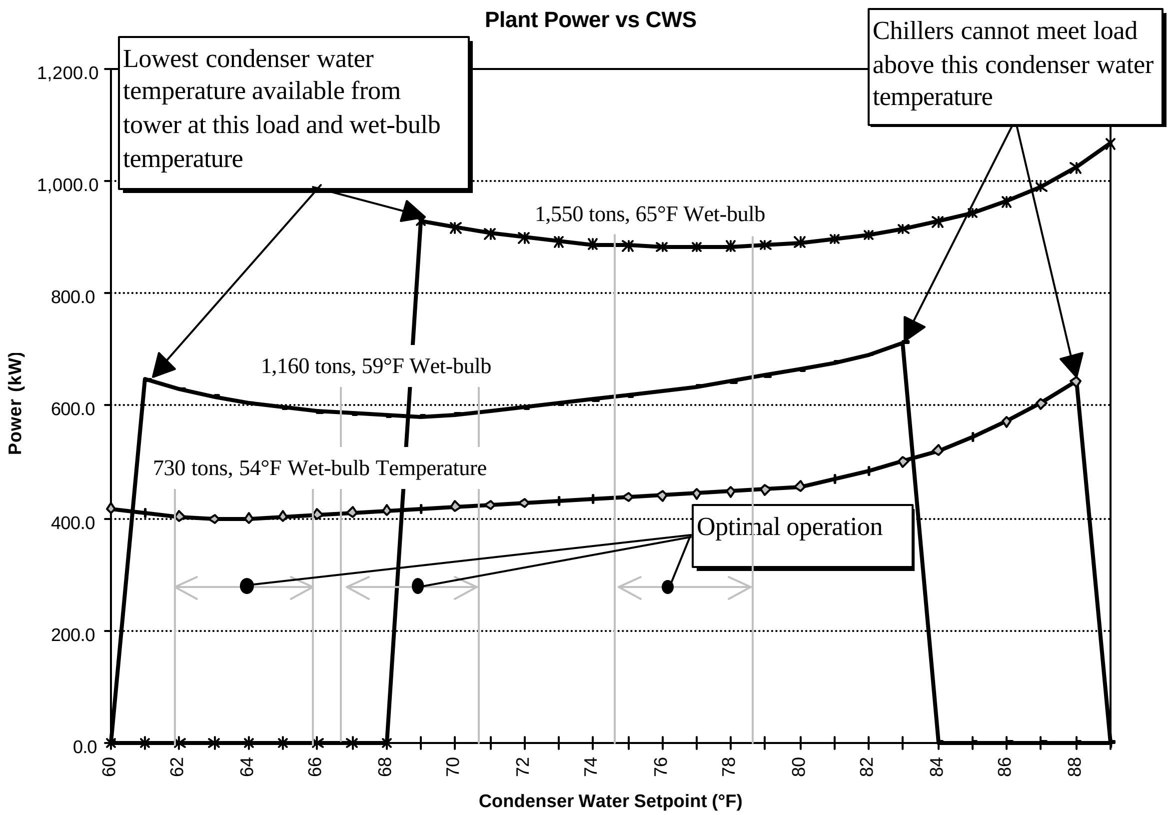

Figure 5: Chilled Water Plant Power as a Function of Condenser Water Set Point. *This chart depicts the variation of chilled water plant power (pumps, chillers and tower fan) as a function of the condenser water set point. The three lines represent 3 different load conditions for the plant (out of 8760). As shown, each of these load conditions has a different optimal condenser water operating point.*

Guides

As is well documented in the literature on thermal storage and commissioning, project success is not solely a function of proper design. The efficiency of a chilled water plant is affected by design and purchasing decisions, implementation of controls and O&M practices. Each player and decision can hamper efforts to optimize the plant performance. In recognition of this, the project is providing a number of guides to support the needs of each player and the decision process involved.

The first phase of this project includes the following guides:

Decision Maker's Guide is intended for the executive decision maker in the owner's organization. It should also be useful to design engineers, design-build firms, energy service companies, and other consultants seeking to market their services to owners. It will summarize the key concepts and strategic recommendations, and will offer a bottom-line rationale for changing the way chilled water plants are procured and operated.

Project Implementation Plan will be targeted at a technical-administrative audience, such as facility managers and project managers in the owner's organization. The project implementation plan:

- Describes the formula for success by outlining the roles of each player and details the related elements of the toolkit
- Details how to facilitate the successful design, installation, and operation of chilled water plant systems.
- Provides guidance in the overall process of implementing a project, from concept definition through installation, verification, performance testing, and operation.
- Points out the important issues that need to be considered and questions that need to be asked, and will provide guidance in resolving those issues and questions.

It will not attempt to provide all of the detailed information needed to plan, design, construct and commission an optimized chilled water plant, but it will assist the user in finding that information.

Chilled Water Plant Design Guide will be targeted to a technical design audience. It will detail design issues many of which are introduced in the Project Implementation Plan. Issues include selection of coils, applications of various piping distribution systems, design and applications of controls, etc.

Chilled Water Plant Performance Specification Guide will be targeted to equipment specifiers including engineers and facility purchasing agents. It will detail methods to request and analyze performance data of submitted equipment. Topics include, zero tolerance performance specifications, applications of witness tests, performance tables for bid alternates, etc.

Chilled Water Plant Monitoring Protocols are geared to a technical audience with experience in data collection and simulation. As previously discussed an existing chilled water plant monitoring guide (PG&E, 1995) is under revision.

Web-Site

With the exception of the Integrated Plant Simulation Tool, all elements of this project will be distributed through the web-site at "www.pge.com/cooltools." It is our intention to utilize the site to facilitate distribution and review of products. Document drafts will be posted with a scheduled review period. Threaded discussion sessions will be maintained to facilitate review. Finished documents will be available for download in adobe acrobat and rich text (rtf) or MS Word format. Most of the documents will be converted to web-pages to allow for the incorporation of plug-ins and linkages.

Software tools will also be posted on the web-site. The site will be used to facilitate the distribution of updates.

Collaborations

This project relies heavily on collaborations. The project is funded with public goods money. This money is intended to transform markets through development of public domain tools and support (Eto et. al., 1996). A measure of our success is the use of our products by other organizations.

Our collaboration efforts are in the following areas:

- Support for 3rd Party Software Vendors. This includes incorporation of the Library Module in COMCheck-Plus, Energy Pro, PowerDOE and others.
- Support of development of codes and standards. This includes on-going support of California's Title 24, ASHRAE/IES Standard 90.1R, ASHRAE GPC1, ASHRAE GPC14P, FEMP, and DOE's IEMVP. An example of this work is an on-going review of California's Alternative Calculation Manual (ACM) at the request of the California Energy Commission. Prior to our involvement, they were unwilling to provide credit for off peak performance of chillers. At present they are considering utilizing the specifications of public domain tools provided by this project as an acceptable means for generating chiller curves.
- Institutional support at meetings and forums including ASHRAE, CoolSense, ACEEE and others. The project has already developed four papers and co-sponsored this forum. Another half dozen papers are already in the works.

Summary

This is an on going effort that is intended to span a three year period. In the first six months of operation we have gained considerable progress towards producing our first phase of software tools, the web site and guides which will conclude early next year.

A significant deliverable of the first six months is a project description of this complex effort and the blessing and guidance from our focus groups representing building owners, facility managers and design professionals. Each group expressed the belief and anticipation that the goals and products of this project will provide significant benefit to the market place.

We are in the process of forming an advisory board with representation from DOE, EPRI, GRI, CEC, manufacturers, owners, and the design and energy services communities. Individual members of a project advisory committee, yet to be convened, have been selected and engaged in discussions which have indicated their support for the project's future. To a member they have been excited about becoming part of this project and quick to see its benefit to other efforts.

Most individual scopes of work for the first phase have been completed and almost all of the necessary contracts are let.

We are actively seeking reviewers for the "CoolTools™" products. If you are interested contact us by email (klg2@pge.com) or phone (Ken Gillespie @ 415-973-7514).

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