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Prepared for Pacific Gas and Electric Company by CTG Energetics, Inc. for the statewide Energy Design Resources program (www.energydesignresources.com).

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PART 1: Underfloor Air Distribution and Thermal Displacement Ventilation

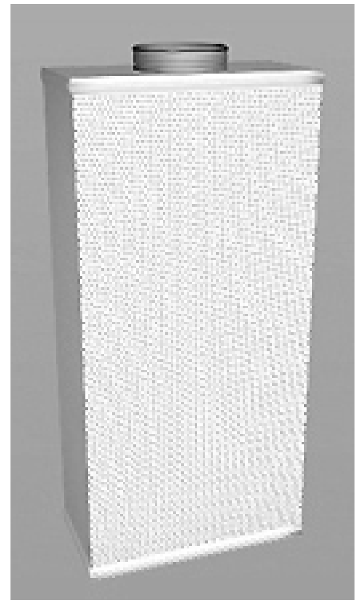
Underfloor air distribution (UFAD) and thermal displacement ventilation (TDV) have become increasingly common in commercial new construction because they are energy-efficient, enhance indoor air quality, and increase flexibility for space reconfiguration. However, conflicting opinions exist concerning the benefits of UFAD and TDV. This often leads to inappropriate analysis and unrealistic customer expectations. There are many different notions regarding the energy efficiency of UFAD and TDV systems, with some people claiming that these systems save little or no energy, while others suggest that they can cut HVAC energy usage by fifty percent or more. To help the energy modeler evaluate the energy benefits of UFAD and TDV, this simulation guidebook identifies the key characteristics that distinguish UFAD and TDV systems from traditional overhead systems and presents a logical, engineering-based method for analyzing UFAD and TDV with DOE-2-based simulation programs.

What are Underfloor Air Distribution and Thermal Displacement Ventilation?

This simulation guidebook is concerned with methods for analyzing air distribution systems that deliver cooling and heating air at floor level instead of from the ceiling. An example of such a system is underfloor air distribution (UFAD), where conditioned air is delivered at a moderate velocity (650 to 800 feet-per-minute) via a 10” to 16” plenum space underneath an access floor system (Figure 1a). Another example is a Thermal Displacement Ventilation (TDV) system that delivers supply air horizontally at low velocity (50 to 100 feet-per-minute) from wall-mounted diffusers without using an underfloor plenum (Figure 1b).

Figure 1:
(a) A typical underfloor air distribution system consists of a raised access floor, a 10" to 16" underfloor plenum, and air delivery diffusers. (b) A thermal displacement ventilation system delivers low velocity air at floor level. An access floor is not usually employed for such a system.

Diffuser for Underfloor Air Distribution System[1] (1a-left) versus Diffuser for Thermal Displacement System[2] (1b-right)



While there are differences in the performance characteristics between UFAD and TDV systems, the modeling methodology described in this simulation guidebook applies to both. Energy modelers must exercise judgment to adjust the methods to suit either system. Guidelines are provided throughout this guidebook that can be applied to account for differences between the two systems.

What differentiates UFAD and TDV systems from overhead distribution systems?

Traditional space conditioning systems supply heated or cooled air from diffusers mounted in a suspended ceiling grid. The design assumption made is that supply air completely mixes with the air in the room, and as a result, all of the air within the conditioned space reaches a homogeneous temperature (Figure 2).

Designers go to great effort to select diffusers that promote this mixing effect so that cold air does not "dump" onto the occupants below. In an overhead mixing system, cold supply air mixes with hot air that accumulates near the ceiling as a result of heat generated

[1] Source: Tate Access Floors
[2] Source: Halton Group

by people, lights, and equipment. While an overhead mixing system concept can provide good occupant comfort, it wastes energy by providing comfortable conditions from the floor all the way to the ceiling. It would be more efficient to limit the distribution of heated or cooled air only to the lower volume (for example, up to seven feet above the floor) of the room where the occupants are located.

Overhead Air Delivery Provides Homogeneous Temperature Distribution[3]

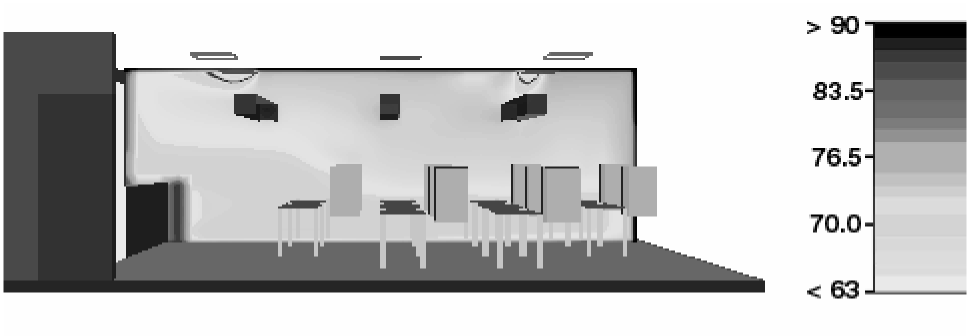


Figure 2: Traditional overhead air distribution systems are designed to completely mix supply air with room air. The goal is to provide a uniform temperature distribution from floor to ceiling.

Thermal Displacement Ventilation Encourages Stratification[4]

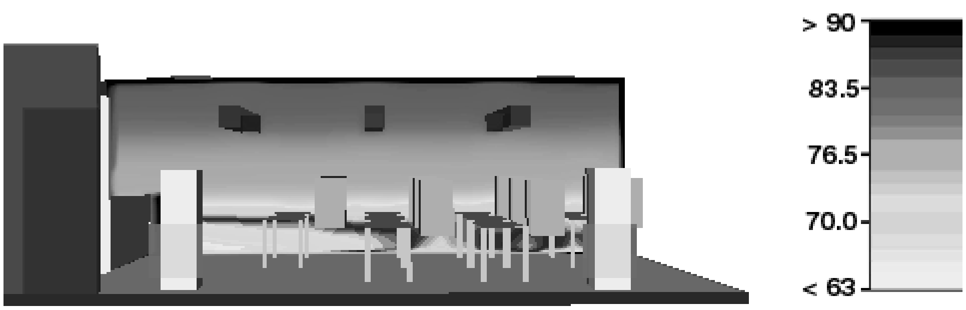


Figure 3: By delivering cool air at floor level and drawing warmer air from the ceiling, TDV encourages thermal stratification.

Barriers to Modeling UFAD and TDV in DOE-2

Uniform temperatures are assumed throughout the entire conditioned space

Most simulation programs based on DOE-2.1e or DOE-2.2 (such as eQUEST and EnergyPro) determine space cooling loads as a summation of all heat losses and heat gains within a space, without regard to how the loads are influenced by airflow patterns and the buoyancy of warm air. Stated another way, most simulation programs are not aware that hot air rises, and therefore assume a uniform temperature throughout the conditioned volume.

[3] Source: CTG Energetics, Inc.
[4] Source: CTG Energetics, Inc.

For example, consider the following internal load calculation:

People (sensible + latent)	
30 occupants x 500 Btu/hr-person	15,000 Btu/hr
Lights	
900 SF x 1.5 W/SF x 3.413 Btu/hr-W	4,608 Btu/hr
Equipment	
900 SF x 1.0 W/SF x 3.413 Btu/hr-W	3,072 Btu/hr
TOTAL	22,680 Btu/hr

Most simulation programs calculate the required cooling capacity to meet these internal loads as the sum of the loads. The fact that hot air rises (producing warmer temperatures near the ceiling and cooler temperatures near the floor) is not accounted for. For overhead mixing-type air distribution this approach is satisfactory because overhead diffusers are selected and placed to promote mixing of supply air and room air. The flow of supply air from the ceiling pushes the hot air near the ceiling down to the level of occupants.

Calculation of cooling loads isn't available

> The effect of thermal stratification is that cooling loads are reduced relative to those of overhead delivery systems, but most simulation programs do not reflect this change.

When conditioned air is delivered at floor level at low velocity, it does not significantly mix with the hot ceiling air. Accordingly, floor-supplied air is not as disruptive to thermal stratification as overhead delivery (Figure 3). This is advantageous because the hot ceiling air can be drawn directly into the return air system and exhausted from the space instead of neutralized by mixing with cold air. The effect of thermal stratification is that cooling loads are reduced relative to those of overhead delivery systems, but most simulation programs do not reflect this change. Referring to the previous load calculation example, a UFAD system would reduce the cooling load resulting from internal heat gains by nearly 50 percent. More complex and time-consuming analysis methods, such as computational fluid dynamics (CFD), must be employed if one wishes to calculate cooling loads that account for thermal stratification. In most cases it is not practical to perform CFD analysis, and such analysis cannot be submitted to show Title 24 compliance.

Thermal Displacement Ventilation and Underfloor Air Distribution Modeling

The strategy for modeling TDV and UFAD systems is to move a portion of the heat gain from people, lights and equipment from the conditioned space to an unconditioned plenum space. While project-specific information about how much of each internal load should be apportioned to the plenum is highly desirable, such data is infrequently available. Table 1 provides reasonable estimates for both UFAD and TDV systems. Figure 4 and Figure 5 show how lighting and receptacle loads would be redistributed in a typical underfloor air system. A similar approach would be employed for occupant heat gain.

Internal Load Distribution Values for Typical Underfloor Air and Thermal Displacement Ventilation Encourages Systems[5]

Table 1

Load Component	Percent Load to Space: Underfloor Air Distribution	Percent Load to Space: Thernal Displacement Ventilation	Percent Load to Plenum: Underfloor Air Distribution	Percent Load to Plenum: Thernal Displacement Ventilation
People	75%	67%	25%	33%
Lights	67%	50%	33%	50%
Equipment	67%	50%	33%	50%

Source: CTG Energetics, Inc.

Room Cross Section with Loads in Space[6]

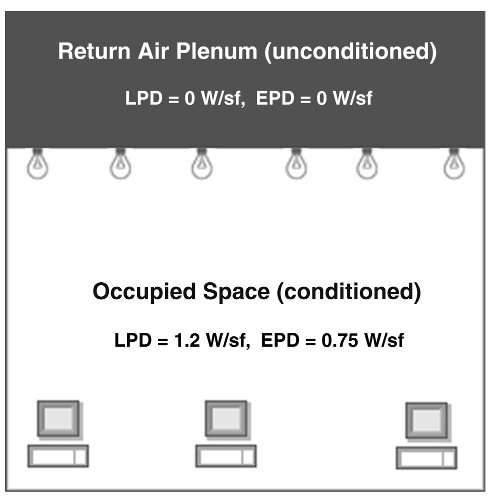
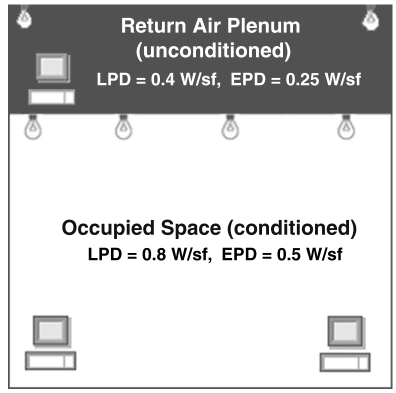


Figure 4: Cross-section view of typical room showing conditioned and unconditioned spaces, with typical lighting power density (LPD) and equipment power density (EPD). The total internal heat gain from these sources is 1.95 W/ft2.

5 Source: CTG Energetics, Inc.
6 Source: CTG Energetics, Inc.

Room Cross Section with Loads in Plenum[7]

Figure 5: To simulate the reduced heat gain from lighting and receptacle loads, much of the load is reassigned to the unconditioned return air plenum. The effect is that cooling loads in the conditioned space are reduced while the return air temperature is increased. The total gain from lights and receptacles is unchanged; however, it has been apportioned differently between conditioned and unconditioned space.



Modeling Issues

There are a number of issues that must be considered when modeling thermal displacement or underfloor air distribution systems. These issues include:

- System Selection
- Supply Air Temperature
- Dehumidification
- Air Volume
- Static Pressure
- Economizer Controls
- Building Skin Loads
- Perimeter Systems

7 Source: CTG Energetics, Inc.

System Selection

The energy modeler must take care to choose the appropriate HVAC system type from those available within the simulation program. The exact system choice should reflect whether the system operates in constant or variable-volume fashion, the source of heating and cooling, and the way that outside air ventilation is managed. The following are examples of potential system selections:

Example #1: Access Floor System with Manually Adjustable Diffusers. This sort of system, which may include a large number of round, manually adjustable “swirl” diffusers (approximately one diffuser per 75 to 100 ft^2 of conditioned area), has become increasingly common in office buildings. Because occupants have some control over the airflow in their workspace - but cannot completely shut off the air supply - the system operates essentially as a variable-air-volume system with a high minimum airflow rate. Such systems are most commonly employed as part of a chilled water cooling system. In the DOE-2 simulation environment, such a system could be modeled using system type VAVS (variable-air-volume, with chilled water cooling). The minimum airflow rate (MIN-CFM-RATIO) would be set high to reflect the diversity of loads in the conditioned space and also the limited turndown offered to occupants. It is common for turndown ratios to be 70 to 80 percent of full flow, though modeling assumptions should be verified with the HVAC engineer. In many cases, a 100% outside-air-economizer cycle will be employed and the specific program inputs should reflect the fact that the cooling requirements can be met using warmer air than with overhead systems (i.e. 64°F to 67°F).

Example #2: Access Floor System with Thermostatically Controlled VAV Zone Terminals. This system is similar in some respects to Example #1, but the large number of “swirl” diffusers is replaced with a reduced number of thermostatically-controlled VAV terminals located in the underfloor plenum. Zoning for such systems is often comparable to overhead systems in terms of the average area per zone. Such systems usually offer higher turndown than the manual “swirl” diffusers and are automatically controlled based on space temperature. As a result, the minimum airflow ratio (MIN-CFM-RATIO) will frequently be lower with this air distribution strategy. Reviewing the zone schedule prepared by the mechanical engineer should provide information about the minimum airflow for each VAV terminal. Without such data, it is reasonable to assume a minimum airflow ratio of 50 percent until more detailed information is available.

Example #3: Thermal Displacement System with Constant Volume Delivery. This system design is most frequently used in classrooms or other assembly areas. A common configuration for thermal displacement systems consists of four-pipe fan coil units for each zone (or classroom), with a central air-handling unit distributing outside air to each unit. The fan coil units deliver constant volume supply air horizontally at low velocities from wall-mounted diffusers. The system can be modeled in DOE-2 using system type FPFC (four-pipe fan coil). The energy model system inputs should reflect the supply air temperature and volume design conditions associated with TDV, and fan energy inputs for each fan coil should account for the contributions from the central outside air supply unit.

The energy modeler must take care to choose the appropriate HVAC system type from those available within the simulation program.

Supply Air Temperature

Since TDV and UFAD generally introduce conditioned air in close proximity to the building occupants, the air is delivered at a temperature only slightly (5ºF to 10ºF) below space temperature set points. This corresponds to a 64ºF to 67ºF supply air temperature set point (MIN-SUPPLY-T or COOL-SET-T) as opposed to a 55ºF set point for traditional mixing systems.

Dehumidification

Due to the elevated supply air temperature associated with TDV and UFAD, the mechanical designer must give close attention to humidity control for these systems. With the exception of cool, dry climates, cooling coils provide inadequate removal of latent load when cooling to only 64ºF or 67ºF. Consequently, most TDV and UFAD designs need to implement supplemental humidity control features to avoid the decreased comfort and indoor air quality associated with high space humidity conditions. In a common TDV or UFAD humidity control scheme, the chilled water coil cools a mixture of outside air and return air down to 55ºF, and this conditioned air is then mixed with the remainder of the return air to increase the temperature back up to the supply air temperature set point. Although the limitations of DOE-2 prevent the accurate modeling of this humidity control scheme, energy modelers should keep in mind that this form of humidity control will achieve less energy savings than projected by a DOE-2 model with a high supply-air temperature set point.

With the exception of cool, dry climates, cooling coils provide inadequate removal of latent load when cooling to only 64ºF or 67ºF.

Air Volume

Design supply airflow calculations for the space must account for both the elevated supply air temperature and the redistribution of a portion of the occupant, plug and lighting loads from the space to the return air. Ignoring the high supply-air temperature for TDV and UFAD systems will result in an underestimation of supply air volume, and neglecting to redistribute a portion of the space loads to the plenum will result in supply air-flow rates that are up to two times greater than the amount required to condition the space. Typically, supply air flows for a true TDV system exceed those of a corresponding overhead mixing system by only five to twenty percent.[8] Supply air flow rates for UFAD systems range from twenty-five percent less to fifteen percent more than traditional overhead systems.[9]

Static Pressure

In most UFAD systems, the underfloor plenum serves as the primary source of air distribution. Consequently, UFAD systems generally use far less ductwork than corresponding overhead systems, resulting in reduced static pressure at the supply fans when compared against standard overhead systems. However, due to the wide variance in UFAD

[8] "Underfloor Air Distribution and Access Floors." Energy Design Resources Design Brief.

[9] Webster, Tom, Bauman, Fred, and Reese, Jim. "Underfloor Air Distribution: Thermal Stratification." ASHRAE Journal. May 2002. Vol. 44, No. 5, Pg. 34.

design, energy analysts should confirm estimated values for static pressure with the mechanical designer prior to modeling savings associated with reduced fan static pressure. The fan energy savings linked to lower fan static pressures will generally not be reflected in Title-24, since the standard case changes with the proposed case for inputs related to fan power.

Economizer Controls

TDV and UFAD systems can often take advantage of increased hours of economizer operation due to the higher temperature of air delivered to the space. In most California climate zones, raising the supply air temperature from 55ºF to 65ºF can extend economizer operation by 2,000-2,500 hours per year.[10] However, the humidity control requirements in many of these climates will limit the hours of additional economizer operation, resulting in reduced free cooling benefits. In climate zones that require additional dehumidification, the economizer operation must be integrated with the humidity control to maintain proper humidity conditions. This requires differential enthalpy-based economizer operation to ensure that the humidity of the outside air remains lower than that of the return air. In DOE-2, differential enthalpy control is modeled using the ENTHALPY keyword for OA-CONTROL at the system level.

In most California climate zones, raising the supply air temperature from 55ºF to 65ºF can extend economizer operation by 2,000-2,500 hours per year.

Building Skin Loads

If return grilles are located directly above the windows in perimeter spaces served by UFAD or TDV systems, a significant portion of the convective cooling load associated with the building skin can be funneled directly into the return air plenum.[11] A precise energy model for UFAD and TDV systems can account for the energy savings associated with this phenomenon by reapportioning some of the glazing and exterior walls in the occupied space to the adjacent plenum. However, this methodology may result in the loss of legitimate automated daylighting control savings in DOE-2-based programs. Furthermore, this modeling approach has not yet been approved for demonstrating UFAD system savings in 2005 Title-24.

Perimeter Systems

Perimeter system approaches vary widely for both UFAD and TDV systems. In some cases, perimeter underfloor air plenums for UFAD systems are separated from interior underfloor air plenums with dividers; in another approach, underfloor ductwork provides perimeter spaces with a separate source of supply air, and sometimes perimeter spaces are entirely served by overhead systems. Baseboard heating can also be provided as the primary heating source for perimeter zones served by TDV or UFAD systems. The Underfloor Air Distribution Design Guide (ASHRAE, 2003) provides a good overview of

10 "The Case for TDV in California Schools." California Energy Commission's Public Interest Energy Research (PIER) Program. http://www.archenergy.com/ieq-k12/thermal_displacement/thermal_displace_background.htm

11 Bauman, Fred S. and Daly, Alan. Underfloor Air Distribution (UFAD) Design Guide. Atlanta: ASHRAE, 2003.

the range of perimeter system designs commonly applied in conjunction with underfloor air distribution. Energy analysts should use their judgment to select the type of space heating and zone terminal units in DOE-2 that most closely represent the perimeter system design for their project.

Modeling Methodology

In native DOE-2 (the BDL input file),[12] energy modelers can apply the modeling strategies described above for TDV and UFAD. However, strict alternative calculation methods (ACMs) published by the CEC for the 2001 Title-24 standards have prevented the simple application of TDV and UFAD modeling strategies to the Title-24 compliance modules of EnergyPro and eQUEST. The ACMs defined for 2005 Title-24 standards do permit software developers to offer an optional system type for Underfloor Air Distribution (UFAD), which will make accommodations for the user to assign a percentage of the occupant, lighting and plug loads to the return air plenum.[6] The following step-by-step TDV modeling methodologies for DOE-2, EnergyPro and eQUEST assume that a UFAD system has not yet been implemented.

Common Simulation Software

This guidebook uses research generated from the following energy simulation software packages: EnergyPro v. 3.142, eQUEST v. 3.44 with DOE2.2 release 42k6, and DOE-2.1e release 134.

Keep in mind that this software is constantly updated. Review the documentation of later releases for any changes to software inputs or keywords that might impact the modeling methodology discussed in this simulation guidebook.

Modeling TDV and UFAD in DOE-2.1e

In native DOE-2.1e, energy analysts can define TDV or UFAD systems using the following process:

Step 1. Define at least one (but no more than three)[7] return air plenum(s) for each system. In cases where the building design defines a return air plenum, model the plenum as drawn in the plans. If no return air plenum is defined in the plans, add a plenum with a height of three feet, and an area equal to the building area served by the system.

Step 2. For each space served by a TDV or UFAD system, multiply the number of occupants, the lighting power density, and the equipment power density by the Percent Load to Space factor for each load defined in Table 1. If occupant density is defined using the AREA/PERSON keyword, divide the AREA/PERSON by the Percent Load to Space factor for people. Input the revised occupant, lighting, and equipment data in each space.

Step 3. Input the lighting, equipment and occupant schedules defined for the occupied spaces into the return air plenum(s).

12 This simulation guidebook refers to "Native DOE-2" as the BDL (or plain text) DOE-2 input file. This is contrasted against a graphical user interface program such as EnergyPro, VisualDOE, or eQUEST.

13 "NonResidential ACM Manual." October 2003 Draft Language, Commission Proposed Standards. California Energy Commission.

14 DOE-2.1e does not allow more than three plenums per zone.

Step 4. Calculate the AREA/PERSON, lighting power densities, and equipment power densities using equations 1, 2, & 3 shown in Figure 6.

Step 5. Insert the values calculated in step four above for plenum area per person, equipment power density, and lighting power density into the plenum using DOE-2 keywords AREA/PERSON, EQUIPMENT-W/SQFT, and LIGHTING-W/SQFT respectively.

Step 6. Select the DOE-2 system type in accordance with the system selection instructions above. Set the return air path (RETURN-AIR-PATH) to plenum (PLENUM-ZONES).

Step 7. For variable volume systems, set the MIN-CFM-RATIO for each zone in accordance with the system selection instructions above; if the supply fan design includes a variable speed drive, be sure to set the FAN-CONTROL equal to FAN-EIR-FPLR, and the FAN-EIR-FPLR equal to ANY-FAN-W/VSD.

Step 8. Set the keyword for cooling supply air temperature (MIN-SUPPLY-T or COOL-SET-T) as defined in the design (generally 64-67 °F).

Step 9. Model the system economizer controls as designed. In most California climate zones, a differential enthalpy economizer should be used (OA-CONTROL = ENTHALPY).

Equations Used in Modeling UFAD and TVD

$$\text{AREA/PERSON}_{Pln} = \frac{\left[\text{AREA}_{Pln} \times \sum_{spaces} \frac{\text{AREA/PERSON}_{space}}{\text{AREA}_{space}}\right]}{\left[\%\text{ Load to Plenum}\right]_{People}} \qquad (1)$$

$$\text{E - W}_{Pln} = \frac{\left[\sum_{spaces} \text{E - W}_{space} \times \text{AREA}_{space}\right] \times \left[\%\text{ Load to Plenum}\right]_{Equip}}{\text{AREA}_{Pln}} \qquad (2)$$

$$\text{LIGHTING -W/SQFT}_{Pln} = \frac{\left[\sum_{spaces} \text{LIGHTING} - \text{W/SQFT}_{space} \times \text{AREA}_{space}\right] \times \left[\%\text{ Load to Plenum}\right]_{Lights}}{\text{AREA}_{Pln}} \qquad (3)$$

Figure 6: These equations calculate Area per Person, Lighting Power Density, and Equipment Power Density for Underfloor Air Distribution system energy modeling.

Pln = Return air plenum serving the selected spaces

AREA/PERSON = Area per person

Equip = Equipment

E-W = Equipment watts per square foot

Lighting-W/SQFT = Lighting watts per square foot

% Load to Plenum is the percentage defined in Table 1.

DOE-2.1e Sample Text for an Access Floor System with Manually Adjustable Diffusers

Figure 7: The system that corresponds to this sample text serves three spaces and is modeled with a return air plenum to simulate the impacts of underfloor air distribution. One third of the lighting and equipment loads and one quarter of the occupant load is redistributed to the plenum. The system operates with a variable speed fan and a differential enthalpy economizer and supplies air at an elevated supply air temperature. The minimum air flow to the space is assumed to be 75%.

```
$ SAMPLE SPACE-DEFINITION - OFFICE WITH UNDERFLOOR AIR CONDITIONING:
$ E. Office $
ZONE-1 = SPACE
    ZONE-TYPE  = CONDITIONED
    PEOPLE-SCHEDULE   = SCHED-26
    LIGHTING-SCHEDULE = SCHED-25
    EQUIP-SCHEDULE   = SCHED-24
    INF-SCHEDULE       = SCHED-23
    AREA/PERSON      = 133         $ AREA/PERSON = 100/75% = 133
                                   $ where 75% = Percent to space factor
    PEOPLE-HG-SENS  = 250
    PEOPLE-HG-LAT     = 200
    LIGHTING-W/SQFT  = 0.871     $ LIGHTING-W/SQFT = 1.3 * 67% = 0.871
                                   $ where 66% = Percent to space factor
    EQUIPMENT-W/SQFT = 1.0       $ EQUIPMENT-W/SQFT = 1.5 * 67% = 1.0
                                   $ where 66% = Percent to space factor
    EQUIP-SENSIBLE  = 1.0
    EQUIP-LATENT      = 0.0
    INF-METHOD        = AIR-CHANGE
    AIR-CHANGES/HR   = 0.2027
    AREA             = 1710
    VOLUME         = 17100
..

$ SAMPLE ZONE-DEFINITION - OFFICE WITH UNDERFLOOR AIR CONDITIONING,
UFAD DIFFUSERS WITH VSD ON FANS
ZONE-1 = ZONE
    ZONE-TYPE        = CONDITIONED
    DESIGN-HEAT-T      = 70.0
    DESIGN-COOL-T     = 74.0
    THROTTLING-RANGE =   4.0
    HEAT-TEMP-SCH      = SCHED-20
    COOL-TEMP-SCH     = SCHED-19
    OA-CFM-PER                 = 15
    SIZING-OPTION     = ADJUST-LOADS
    INDUCED-AIR-ZONE  = ZONE-1
    TERMINAL-TYPE     = SVAV
    MIN-CFM-RATIO      = 0.75                  $ MINIMUM CFM SET TO 75%
..
```

```
$ SAMPLE PLENUM SPACE DEFINITION - OFFICE WITH UNDERFLOOR AIR
 CONDITIONING
(SERVES THREE SPACES LIKE THE E. OFFICE SPACE ABOVE)
$ Plenum Zone - Space $
PlnZone = SPACE
      ZONE-TYPE   = PLENUM
       PEOPLE-SCHEDULE  = SCHED-26         $Same schedule defined for space occ
      LIGHTING-SCHEDULE= SCHED-25          $Same schedule defined for space ltg
      EQUIP-SCHEDULE    = SCHED-24         $Same schedule defined for space
                                             equip
      AREA/PERSON       = 400              $ AREA/PERSON = 100/25% = 400
                                           $ where 25% = Percent to plenum factor
      PEOPLE-HG-SENS    = 250
      PEOPLE-HG-LAT     = 200
0.429LIGHTING-W/SQFT  = 0.429              $ LIGHTING-W/SQFT = 1.3 * 33% =
                                           $ where 33% = Percent to space factor
      EQUIPMENT-W/SQFT = 0.5      $ EQUIPMENT-
                                  $ where 33% = Percent to space factor
      EQUIP-SENSIBLE    = 1.0
      EQUIP-LATENT      = 0.0
      AREA              = 5130
      VOLUME              = 15390
..

$SAMPLE PLENUM ZONE DEFINITION - OFFICE WITH UNDERFLOOR AIR CONDITIONING
(SERVES THREE SPACES LIKE THE E. OFFICE SPACE ABOVE)
PlnZone = Zone
      ZONE-TYPE = PLENUM
..

$ SAMPLE SYSTEM DEFINITION - OFFICE WITH UNDERFLOOR AIR CONDITIONING
SYSTEM-1 = SYSTEM
      SYSTEM-TYPE            =  VAVS
      ZONE-NAMES   = (
                        ZONE-1,
                        ZONE-2,
                        ZONE-3,
      )
      PLENUM-NAMES = (
PLNZONE,)
      RETURN-AIR-PATH       =  PLENUM-ZONES
      FAN-SCHEDULE          =  SCHED-18
      OA-CONTROL             =  ENTHALPY               $Differential enthalpy economizer
```

```
ECONO-LOCKOUT          =  NO
      MAX-OA-FRACTION        =  1.0
      FAN-CONTROL            =  FAN-EIR-FPLR
      FAN-EIR-FPLR           =  ANY-FAN-W/VSD          $Variable Speed Fan Controls
      MIN-FAN-RATIO          =  0.30
      SUPPLY-CFM             =  5000
      SUPPLY-KW              =  0.001
      SUPPLY-DELTA-T         =  2.79
      DUCT-AIR-LOSS          =  0.00
      COOL-CONTROL           =  RESET
      COOL-RESET-SCH         =  COLD-DECK-RESET
      COOLING-CAPACITY       =  153000
      COOL-SH-CAP            =  122400
      MIN-SUPPLY-T           =  65          $ ELEVATED SUPPLY AIR TEMPERATURE
..
```

Modeling TDV and UFAD in eQUEST

If eQUEST users are not using the Title-24 compliance module, they can define TDV and UFAD systems using the following process:

Step 1. If the building design includes a return air plenum, model the plenum in the Building Footprint screen of the eQUEST wizard by selecting floor-to-floor height and floor-to-ceiling height as shown in the plans. If no return air plenum is defined in the plans, a plenum must be defined in the eQUEST detailed edit interface. The plenum should have a height of three feet, and an area equal to the building area served by the system.

Step 2. From the **Occupied Loads by Activity Area** screen of the eQUEST wizard, multiply the installed lighting power density and the equipment power density for each occupancy type by the **Percent Load to Space** factor for each load defined in Table 1. Input the revised lighting and equipment data in each space.

Step 3. From the **HVAC System Definitions** screen, select the system type as outlined in the system selection guidelines above.

Step 4. From the **HVAC Zones: Temperatures and Air Flows** screen, set the supply air temperature as defined in the plans. For VAV systems, define the VAV minimum flow for both core and perimeter spaces, as described in the system selection guidelines.

Step 5. Switch to **Detailed Edit Mode** by selecting **File / Mode / Detailed Edit Mode.**

Step 6. From the Internal Loads module, select the Spreadsheet tab, and then select Occupancy. Divide the AREA/PERSON for each space by the Percent Load to Space factor for people defined in Table 1. Input the revised data in each space. In the return air plenum space, select the occupancy schedule to be the same as the occupied spaces.

Use equation 1 to calculate the AREA/PERSON for the plenum.

Step 7. Again from the **Spreadsheet** tab, select **Lighting**. In the return air plenum, select the same lighting schedule as is defined for the occupied spaces. Use equation 3 to calculate the lighting power density for the plenum. Repeat this process for **Equipment**, using equation 2 to calculate the plenum equipment power density.

Sample eQuest Input Screen

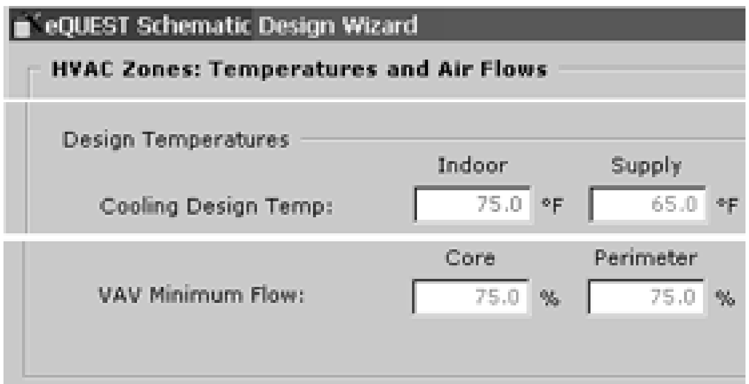


FIGURE 8:
eQUEST ZONE TEMPERATURE AND AIR FLOW SELECTIONS FOR AN ACCESS FLOOR SYSTEMS WITH MANUALLY ADJUSTABLE DIFFUSERS.

Defining TDV or UFAD for Title-24 Comparisons

When using the Title-24 compliance module, eQUEST users must define TDV or UFAD inputs using a slightly more complex process:

Step 1. Complete steps 1, 3, and 4 described above for the eQUEST non-compliance TDV and UFAD modeling process.

Step 2. Run the Title-24 simulation using the **Perform Compliance Analysis** option.

Step 3. Load the DOE-2 input file for the Title-24 proposed case (titled [FileName]- T24 Proposed Building.inp) into eQUEST by selecting **File / Open / Files of Type / DOE-2.2 BDL Input Files,** and then selecting the appropriate file.

Step 4. From the **Internal Loads** module, select the **Spreadsheet** tab, and then select **Occupancy**. Divide the AREA/PERSON for each space by the **Percent Load to Space** factor for people defined in **Table 1.** Input the revised data in each space. In the return air plenum space, select the occupancy schedule to be the same as the occupied spaces. Use equation 1 to calculate the AREA/PERSON for the plenum.

Step 5. Again from the **Spreadsheet** tab, select **Lighting.** Multiply the installed lighting power density for each space by the **Percent Load to Space** factor for defined in **Table 1**. Input the revised lighting power density in each space. In the return air plenum, select the same lighting schedule as is defined for the occupied spaces. Use equation 3 to calculate the lighting power density for the plenum.

Step 6. Repeat the process above for **Equipment** using the equipment power densities, equipment schedules, and calculating the plenum equipment power density with equation 2.

Step 7. Rerun the energy model to obtain a revised Title-24 proposed case. The Title-24 standard case should remain the same. As an error-checking routine, the energy modeler should confirm that the lighting and equipment energy usage for the original Title-24 proposed case is equal to those shown in the revised Title-24 proposed case.

Modeling TDV and UFAD in EnergyPro

An energy modeler can simulate TDV or UFAD with EnergyPro by:

- Inputting system inputs directly in EnergyPro;
- Using the EnergyPro Win/DOE module to generate a DOE-2 input file, and
- Revising the lighting, equipment, and occupant inputs directly in DOE-2. This step is explained below.

Revising the Lighting, Equipment, and Occupant Inputs Directly in DOE-2

Step 1. Define at least one but no more than three return air plenums for each system. In cases where the building design defines a return air plenum, model the plenum as drawn in the plans. If no return air plenum is defined in the plans, add a plenum with a height of three feet, and an area equal to the building area served by the system.

Step 2. Select the DOE-2 system type as outlined in the system selection instructions above. Set the cooling supply air temperature in the cooling tab for each system. Model the economizer type as designed (often differential enthalpy for TDV systems). For each system, confirm that any variable speed fans are appropriately defined under the **Fans** tab.

Step 3. For variable volume systems, select a zonal system from the mechanical tab for each zone, with minimum air flow set in accordance with the system selection guidelines.

Step 4. From the File menu, select **Calc Manager / Options / Win/DOE**. Confirm that Delete DOE files after run is unchecked.

Step 5. To generate the DOE-2 files, select **Calc Manager / Calculate**.

Step 6. From your EnergyPro Win/DOE directory, open the Title-24 proposed input file titled [FileName]-Proposed.doe (where filename is the name you entered for the project in EnergyPro).

Step 7. Complete steps 2-5 for Modeling TDV in DOE-2 as outlined above.

Step 8. Create a text file in your Win/DOE directory using the following syntax: doe21e

“[FileName]-Proposed.doe” [EnergyProWeatherPath]\[WeatherFile]. [FileName] represents the name of your project, [EnergyProWeatherPath] represents the path to the EnergyPro weather directory, and [WeatherFile] represents the name of the weather file used for your project. For example, the text file for a project titled Office and located in Sacramento, CA (climate zone 12) would contain the text doe21e “office-Proposed.doe” C:\EP3\Weather\CZ12RV2.WY2, assuming that the EnergyPro directory was located in C:\EP3.

Step 9. Change the extension of the text file to .bat to create a batch file that can run your project in MS DOS. (To run the simulation, navigate to the .bat file using either Windows Explorer or My Computer, and double-click on the .bat file)

Step 10. As an error-checking routine, the energy modeler should confirm that the lighting and equipment energy usage for the original Title-24 proposed case are equal to those shown in the revised Title-24 proposed case.

PART 2: Energy Efficient Chillers

Advances in heat transfer surface technology, digital control, and variable frequency drives have resulted in chillers that are much more efficient at part load and low lift conditions than those available ten years ago. For example, many chillers equipped with Variable Frequency Drives (VSDs) perform up to three times better at 30-50% load when chilled water supply temperature is raised and entering condenser water temperature is lowered. At present, VSDs are only available on centrifugal chillers.

To achieve any savings, condenser water temperature must be lowered on centrifugal chillers with VSDs. This is due to the fact that these chillers operate with both inlet vanes and VSDs to achieve both capacity reduction and to keep out of surge. If the entering condenser water temperature is kept high (high chiller lift), the capacity control is entirely with the inlet vanes, and the chiller will be less efficient than the same chiller without a VSD due to the drive losses.

DOE-2-based simulation programs have the capability to accurately model the chiller performance if the programmer specifies appropriate performance curves. However, this approach is often overlooked by building simulation programmers, who opt to use default chiller performance curves rather than develop curves calibrated for the specific chillers under investigation. This significantly limits the effectiveness of the energy model as a tool for chiller selection and optimization. By developing chiller performance curves to match the performance of the specific chillers being modeled, energy modelers can accurately reflect the product capabilities of each chiller, and avoid the over or underestimation of savings that commonly occurs with default curves.

Accordingly, this simulation guidebook addresses the following topics to present strategies for modeling customized chiller curves in DOE-2-based simulation programs:

- Chiller curves used to define chiller performance data in DOE-2;
- Two methods for developing chiller curves and implementing them into the DOE-2 model, and

COMMON SIMULATION SOFTWARE

This guidebook uses research generated from the following energy simulation software packages:

EnergyPro v. 3.142, eQUEST v. 3.44 with DOE2.2 release 42k6, and DOE-2.1e release 134.

Keep in mind that this software is constantly updated. Review the documentation of later releases for any changes to software inputs or keywords that might impact the modeling methodology discussed in this simulation guidebook.

- Manufacturer's data necessary to generate chiller curves.

Figure 9:

Equations for Energy Input Ratio as a Function of Part-Load Ratio[15]

$$CAPFT = a_1 + b_1 \times t_{chws} + c_1 \times t_{chws}^2 + d_1 \times t_{cws/oat} + e_1 \times t_{cws/oat}^2 + f_1 \times t_{chws} \times t_{cws/oat} \qquad (4)$$

$$EIRFT = a_2 + b_2 \times t_{chws} + c_2 \times t_{chws}^2 + d_2 \times t_{cws/oat} + e_2 \times t_{cws/oat}^2 + f_2 \times t_{chws} \times t_{cws/oat} \qquad (5)$$

$$EIRFPLR = a_3 + b_3 \times PLR + c_3 \times PLR^2 \qquad (6)$$

$$PLR \equiv \frac{Q}{Q_{ref} \times CAPFT(t_{chws}, t_{cws/oat})} \qquad (7)$$

$$P = P_{ref} \times CAPFT(t_{chws}, t_{cws/oat}) \times EIRFT(t_{chws}, t_{cws/oat}) \times EIRFPLR(Q, t_{chws}, t_{cws/oat}) \qquad (8)$$

t_{chws} = the chilled water supply temperature (°F)

$t_{cws/oat}$ = the condenser water supply temperature (°F) for water-cooled equipment and the outdoor air dry-bulb temperature (°F) for air-cooled equipment

Q = the capacity (tons)

Q_{ref} = the capacity (tons) at the reference evaporator and condenser temperatures where the curves come to unity

PLR = a function representing the part-load operating ratio of the chiller

a_i, b_i, c_i, d_i, e_i, and f_i are regression coefficients

P = the power (kW)

P_{ref} = the power (kW) at the reference evaporator and condenser temperatures where the curves come to unity

How Chiller Performance is Specified in DOE-2

DOE-2-based simulation programs give users several options for creating calibrated models of chillers. (A handy reference on this subject is provided in the ASHRAE Symposium Paper, "Tools and Techniques to Calibrate Electric Chiller Component Models."[16]) These programs use the following three chiller curves to define the impact of varying chilled water

15 Source: ASHRAE

16 Hydeman, M; K Gillespie. "Tools and Techniques to Calibrate Electric Chiller Component Models." ASHRAE. Atlanta GA. AC-02-9-01. January 2002.

temperature, condenser temperature, and load on chiller performance and capacity:

- CAPFT - Capacity as a Function of Temperature. This curve adjusts the available capacity of the chiller as a function of evaporator and condenser temperatures (or lift).
- EIRFT - Energy Input Ratio as a Function of Temperature. This curve adjusts the efficiency of the chiller as a function of evaporator and condenser temperatures (or lift).
- EIRFPLR - Energy Input Ratio as a Function of Part-Load Ratio. This curve adjusts the efficiency of the chiller as a function of part-load operation.

The format of these curves is shown in Figure 9. Using Equations (4) to (7), the power under any conditions of load and temperature can be found from equation 8 (see Figure 9). Each of these curves is described below:

CAPFT- Chiller Capacity as a Function of Temperature

This curve defines how chiller cooling capacity changes with different refrigerant lift conditions. The curve can be directly calculated in the DOE-2 program by entering an array of data points that each contains three numbers: the chilled water supply temperature, the condenser temperature, and the corresponding value of CAPFT. For example, the data point (44, 85, 1.0) for a water-cooled chiller translates as, "...when the chiller is producing 44 degree F chilled water and the entering condenser water temperature is 85 degrees F, the chiller provides 100% of its rated capacity." This would make sense to many mechanical engineers because 44 and 85 correspond to the ARI rating conditions under which chiller capacity and integrated part load value (IPLV) are calculated. All data for the CAPFT curve assumes the chiller is operating at 100% of motor load.

CAPFT is defined from equation 7 above at the point where the "part-load ratio" (PLR) is unity. This is shown in equation 9:

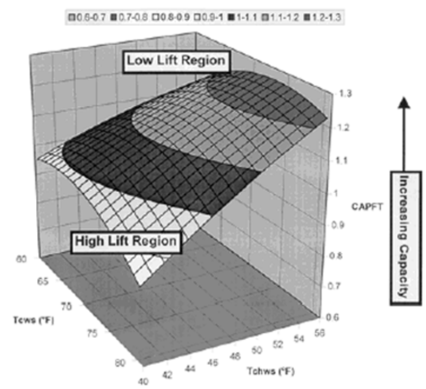
$$CAPFT = \frac{Q}{Q_{ref}} \quad (9)$$

EIRFT- Energy Input Ratio as a Function of Temperature

This curve defines how chiller efficiency changes with different refrigerant lift conditions. The curve can be directly calculated in the DOE-2 program by entering an array of data points that each contains three numbers: the chilled water supply temperature, the condenser temperature, and the EIRFT. For example, the data point (44, 85, 1.0) translates as, "...when the chiller is producing 44 degree F chilled water and the entering condenser water temperature is 85 degrees F, the chiller operates at its nominal full-load efficiency." All data for the CAPFT curve assumes the chiller is operating at 100% of motor load. EIRFT is defined from equation 8 above at the point where the "energy input ratio as a function of part-load ratio" (EIRFPLR) is unity. This is shown in equation 10:

$$EIRFT = \frac{P/Q}{P_{ref}/Q_{ref}} \quad (10)$$

CAPFT Curve[17] **EIRFT Curve[18]**



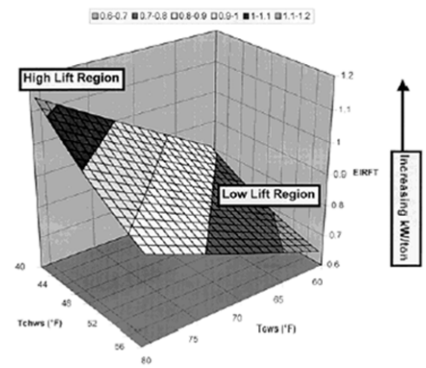


Figure 10 (left): *CAPFT- Capacity as a Function of Temperature.* This curve adjusts the available capacity of the chiller as a function of evaporator and condenser temperatures (or lift).

Figure 11 (top right): *EIRFT- Energy Input Ratio as a Function of Temperature.* This curve adjusts the efficiency of the chiller as a function of evaporator and condenser temperatures (or lift).

EIRFPLR- Energy Input Ratio as a Function of Part Load Ratio

This curve defines how the efficiency of a particular chiller varies with the amount of cooling that the chiller is providing. The curve can be directly calculated in the DOE-2 program by entering an array of data points that each contains two numbers: the part load ratio (PLR) and the EIRFPLR. For example, the datapoint (1.0, 1.0) translates as, "...when the chiller is at 100% of its load it is at 100% of its power draw at the current lift conditions." All data for the EIRFPLR is relative to the current lift conditions. The PLR is calculated from equation 7 above. It is important to note that this is not the ratio of the current capacity to the rated capacity of the chiller, but is the ratio of current chiller capacity to available chiller capacity at the current lift conditions (determined by the CAPFT equation).

EIRFPLR is defined from equation 8 above at the current lift conditions. This is shown in equation 11:

$$EIRFPLR = \frac{P}{P_{ref} \times CAPFT \times EIRFT} \tag{11}$$

Note that the CAPFT and EIRFT curves are defined in terms of a reference condition (Q_{ref} and P_{ref}). The default DOE-2 curves are all normalized to the ARI reference conditions of 44°F chilled water supply temperature and 85°F condenser water supply temperature. For user-defined curves, the reference can be chosen at any point (though the design condition is typically selected). However, it is critical that the DOE-2 keywords Size and EIR (energy input ratio) be selected at this reference point.[19] Failure to do this will usually result in incorrect chiller comparisons as well as incorrect peak kW estimates. The following formulas define Size and EIR.

[17] Source: ASHRAE
[18] Source: ASHRAE
[19] Winkelmann, F.C., Birdsall, B.E., Buhl, W.F., Ellington, K.L., Erdem, A.E, Hirsch, JJ, Gates, S. "DOE-2 BDL Summary, Version 2.1E." November, 1993.

- *Size - Nominal Rated Output Capacity.* This input for nominal chiller capacity, expressed in units of one million Btu's per hour (Mbtu/hr), is used to normalize the CAPFT curve.

$$SIZE = Q_{ref}\,[in\ tons] \times \frac{0.012\ MBtu/hr}{ton} \qquad (12)$$

  Most DOE-2.1e user interfaces such as EnergyPro or VisualDOE allow the user to input nominal chiller capacity in units of tons.

- *ELEC-INPUT-RATIO, or EIR- Electric Input to Nominal Capacity Ratio.* This input is used to define the efficiency of the chiller at the reference conditions. The EIR is calculated as follows:

$$EIR = \frac{1}{COP} = \left(\frac{P_{ref}[kW]}{Q_{ref}[tons]}\right) \times \frac{3413\left[\frac{Btuh}{kW}\right]}{12000\left[\frac{Btuh}{ton}\right]} \qquad (13)$$

  This data is generally entered in unit of kW/ton in DOE-2.1e- based programs such as EnergyPro and VisualDOE.

DOE-2.1e Sample Text for Chiller Inputs

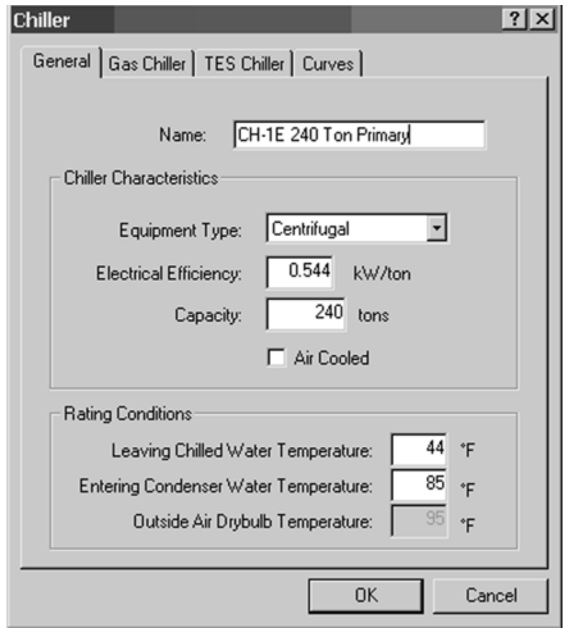
Figure 12

```
INPUT PLANT  ..
CHWPlnt = PLANT-ASSIGNMENT ..
$ ******************************************************************** $
$                     General Chiller Inputs                             $
$ ******************************************************************** $
$ electric centrifugal chiller #1
  CHILLER1 = PLANT-EQUIPMENT
    TYPE = OPEN-CENT-CHLR         $ Selections available are described in
                                  $ DOE-2.1e BDL summary, Page 50 (Nov 1993)
    SIZE = 2.393                  $ SIZE = Capacity * 0.012 MBTU/hr / ton
                                $   where capacity is expressed in units
                                $   of tons
    INSTALLED-NUMBER = 1
    MAX-NUMBER-AVAILABLE = 1
..
$ part load ratio for electric centrifugal chiller #1
  PART-LOAD-RATIO
    TYPE = OPEN-CENT-CHLR
    ELEC-INPUT-RATIO = 0.199 $ EIR = kW/ton * 3413 Btu/kW / 12,000 Btu/ton
                             $ EIR should be defined using the same
                             $ conditions for CHWT & CWT as SIZE
    MIN-RATIO = .1
```

```
$ ********************************************************************** $
$                     End General Chiller Inputs                         $
$ ********************************************************************** $
$ CONTINUE PLANT INPUTS BELOW (NOT SHOWN) ...
```

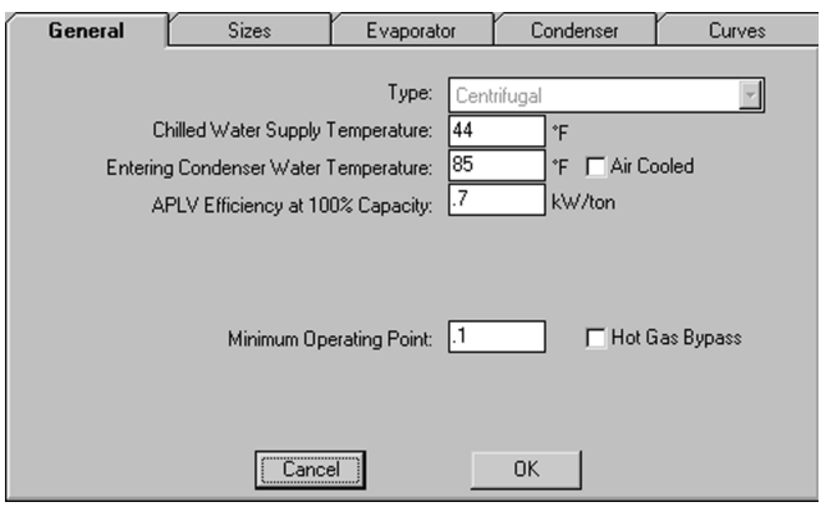
Energy Pro 3.1 General Chiller Inputs

Figure 13



VisualDOE General Chiller Inputs

Figure 14



The DOE-2.2 inputs used for normalizing the curve fit data are similar to the inputs described above for DOE-2.1e-based simulation programs; however, the keyword for SIZE has been modified to CAPACITY, representing the nominal capacity of the chiller. In later versions of eQuest. the reference point selected should generally correspond to the most common operating condition (which is typically not at ARI-rated conditions).

Improved Models for Variable Speed Chillers in DOE-2.2

DOE-2.2 offers an improved model for variable-speed-driven chillers that includes temperature terms in the EIRFPLR equations. This model was based on research reported in the ASHRAE Symposium paper, “Development and Testing of a Reformulated Regression Based Electric Chiller Model.”[20] The research reported in this paper demonstrates the accuracy of the DOE-2 model in predicting the performance of all electric chiller types over a wide range of operating conditions. The two main shortcomings of the original DOE-2 (2.1E) model are the part-load efficiency of variable speed driven chillers over a range of temperatures, and the performance of these models where the condenser water flow varies through the chiller. The variable speed model has been improved in DOE-2.2; however, the variable flow condenser water performance[21] was not fixed.

The format of the revised EIRFPLR curve for variable speed chillers in DOE-2 is shown in Figure 15.

Improved Equations for Energy Input Ratio as a function of Part-Load Ratio (EIRF-PLR)

Figure 15

$$EIRFPLR = a_3 + b_3 \times PLR + c_3 \times PLR^2 + d_3 \times dT + e_3 \times dT^2 + f_3 \times PLR \times dT \quad (14)$$

PLR is defined in equation 7 above

$$dT = t_{cws/oat} - t_{chws} \quad (15)$$

a_3, b_3, c_3, d_3, e_3, and f_3 are regression coefficients

The variable speed chiller EIRFPLR curve can be calculated in DOE-2.2 by entering an array of data points that each contains three numbers: the part load ratio (PLR), the difference between the entering condenser water temperature and the leaving chilled water temperature (dT), and the EIRFPLR (defined in Equation 11 above). For example, the

[20] Hydeman, M.; N. Webb; P. Sreedharan; S. Blanc. “Development and Testing of a Reformulated Regression Based Electric Chiller Model.” ASHRAE, Atlanta GA. HI-02-18-02.2002.

[21] Hydeman,Mark. Personal Interview. 20 Apr. 2004.

data point (1.0, 41, 1.0) translates as, "...when the chiller is at 100% of its load, and there is a 41-degree temperature difference between the condenser temperature and the leaving chilled water temperature, the chiller is at 100% of its power draw at the current lift conditions."

Data Required for Specifying Chiller Performance Curves in DOE-2

To develop curves that accurately model chiller operation, the energy modeler needs access to at least twenty to thirty records of data which fully cover the range of conditions that will be simulated.[22] The required data consists of one subset of full-load data and a second subset of part-load data. The modeler is cautioned to ensure that the data covers the full range of conditions under which the chiller will be modeled.

During the simulation, if the chiller is subjected to conditions outside of the range of tuning data, very unpredictable and inaccurate results can occur.

With the exception of cool, dry climates, cooling coils provide inadequate removal of latent load when cooling to only 64ºF or 67ºF.

Full-load data used for defining the CAPFT and EIRFT curves must represent the entire range of condenser and chilled water supply temperatures that will be evaluated by the energy model. For water-cooled chillers, condenser temperature is defined as the entering condenser water temperature; for air-cooled chillers, the condenser temperature is defined as the outside air drybulb temperature. To generate the full-load curves, there must be at least six full-load data points, with at least two different values for both chilled water and condenser temperatures, and the data points must include both the minimum and maximum chilled water and condenser temperature values that will be evaluated by the model. The information required for each full-load data point includes chiller capacity, input power, chilled water temperature, and condenser temperature. Although the energy modeler can generate full-load curves with as little as six data points, a significantly greater number of distinct full-load data points (i.e., 10 to 20 points) should be used to avoid skewed or inaccurate results.

Part-load data used for defining the EIRFPLR curve must represent the complete range of chiller unloading that will be analyzed within the energy model. At least three distinct data points are required in order to develop the EIRFPLR curve, but a significantly larger number of points (i.e., 6 to 10 points) should be used to improve the accuracy of the chiller curve. In DOE-2.2, at least six distinct points are required when defining the EIRFPLR curve for VSDs, and additional data should be included whenever possible. For each data point defined in any EIRFPLR curve, the minimum amount of information needed from the

22 Hydeman, Mark, and Gillespie, Kenneth L. Jr., pp.3.

chiller sales representative includes chiller capacity, input power, and condenser and evaporator temperatures. Additionally, each part-load data point must have a corresponding full-load data point with matching evaporator and temperatures.

Obtaining Data Required for Chiller Performance Curves

Collecting the data necessary to develop these three performance curves is a lot of work, and getting the data requires a major time commitment from the chiller sales representative. Manufacturer's sales personnel have the software needed to calculate each of the data points required. However, developing a full set of data (twenty to forty points) can take up to an hour per chiller to develop. In general, a sales representative will provide the detailed data required to generate chiller curves if a potential sale is likely and the request for information is coming directly from the customer. This means that the customization of chiller curves must often take place late in the construction documents phase, or during bids for project construction. When requesting data from the manufacturer, there are two important issues to consider:

- The manufacturer will typically confuse "full-load" and "rated load" conditions. It is not uncommon for a manufacturer to provide a spreadsheet full of data where all of the data is at the same design capacity. It takes less time to do this than to make sure that the unloading mechanism (e.g., inlet vanes, slide valve, VSD...) is fully open at a given set of temperatures for each set of data. If the full load capacity does not vary with temperature, the energy modeler is forced to use the default DOE-2 EIRFT and CAPFT curves, and then develop a custom curve for the EIRFPLR.

- The manufacturer's data includes "tolerance" on the capacity and efficiency as allowed by ARI Standard 550/590. This tolerance is low at full load (~5%) but gets very high at part load. Experience with "0 tolerance" performance-based chiller bids shows that the manufacturers typically inflate their efficiency by the full ARI tolerance.

Condenser Water Temperature Assumptions

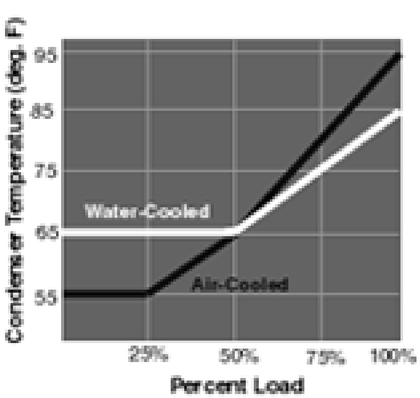


Figure 16:
This graph shows the condenser water temperatures used when implementing ARI Standard 550/590-1998 test procedures.

ARI Standard Tolerances as a function of Full Load[23]

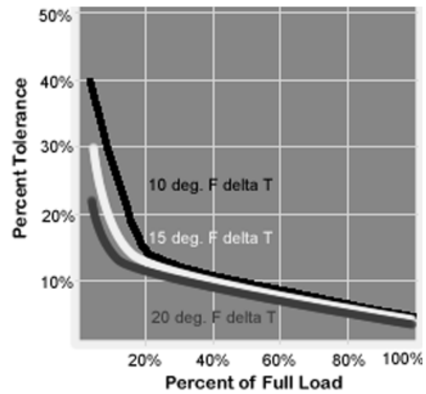


Figure 17: The ARI Standard allows this tolerance to be applied on capacity, EER, COP kW/ton, and heat balance.

Methods for Creating Custom DOE-2 Chiller Models

Generally speaking, there are three methods for developing calibrated DOE-2 chiller models. These are presented in the order from least to most accurate:

Method 1. Scale the capacity (SIZE) and efficiency (EIR) only, and use the default CAPFT, EIRFT and EIRFPLR curves. Method 1 should be avoided, as it is the least accurate.

Method 2. Scale the capacity (SIZE) and efficiency (EIR) and create a custom EIRFPLR curve. (This method retains the DOE-2 default CAPFT and EIRFT curves). Care must be taken to adjust the reference capacity and efficiency to the CAPFT and EIRFT curve reference of 44°F chilled water supply and 85°F condenser water supply temperatures. Energy modelers are often forced to use this method where there is limited performance data available or where the manufacturer has provided "full load" data all at a single design capacity. Method 2 is also the best that can be done with field-measured data that cannot be separated into full and part-load bins, and can provide surprisingly accurate results.

A variation of Method 2 is described in the paper, "Tools and Techniques to Calibrate Electric Chiller Component Models," but it requires a database of chiller performance curves. This database can be accessed on the Internet at http://www.hvacexchange.com/ cooltools/CAP. However, the data should be used with caution, as it is easy to select a reference curve that was not calibrated to the full range of temperatures used to simulate chiller operation (e.g., the energy modeler is in danger of extrapolating performance beyond the tuning data).

Method 3. Scale the capacity (SIZE) and efficiency (EIR) and create custom CAPFT,

[23] Source: Taylor Engineering

EIRFT and EIRFPLR curves. This is the preferred method for developing calibrated DOE-2 chiller models.

Manufacturer's Data Request Form

Chiller Data Sheet

Project:				
Manufacturer:				
Condenser Flow		GPM		ft. hd.
Evaporator Flow		GPM		ft. hd.
Minimum Capacities:	without Hot-Gas Bypass			tons
	with Hot-Gas Bypass			tons

Part Load (mfg data)

CHWS (°F)	CWS (°F)	Percent Loading	Capacity (tons) *	kw*
	85	100%		
	82.5	90%		
	80	80%		
	77.5	70%		
	75	60%		
	72.5	50%		
	70	40%		
	67.5	30%		
	65	20%		
	62.5	10%		

Full Load (mfg data)

CHWS (°F)	CWS (°F)	Capacity (tons) *	kw*
42	85		
42	80		
42	65		
43	85		
43	80		
43	65		
45	85		
45	80		
45	65		
46	85		
46	80		
46	65		

Note: CHWS and CWS temperatures are only shown for illustrative purposes. They do not need to be set at these values. The designer should select temperatures which will best represent how the chiller will be operated.

* Note to Chiller Manufacture's Rep., Please allow your program to size (don't input capacity and kW into your program)

Figure 18:

The data request form shown provides a simple means for requesting chiller curve input data from chiller manufacturers. A more substantial manufacturer's data request form is available at http://www.hvacexchange.com/cooltools/CAP/. You may access it by clicking the "Excel spreadsheets for site surveys and manufacturer's data requests" link.

Methods for Including Chiller Data in DOE-2 Performance Curves

DOE-2 offers two methods for creating chiller curves: the DATA method and the COEFFICIENT method. In the DATA method, the programmer defines each data point directly in DOE-2. In the COEFFICIENT method, the programmer calculates the regression coefficients for each curve based on the available data, and inputs these regression coefficients into the model. VisualDOE and eQUEST support both methods for defining chiller curves, while the current version of EnergyPro supports only the COEFFICIENT method. The COEFFICIENT method is much more time-consuming than the DATA method, yet produces the same results. Therefore, the most time-efficient method for modeling custom chiller curves for EnergyPro projects may be to generate a DOE-2 input file from EnergyPro, modify the input file with the custom chiller curves, and run the input file directly in DOE-2.

Calculating the CAPFT Curve in DOE-2

The CAPFT curve requires three pieces of data per point: the CAPFT, the chilled water supply temperature, and the condenser temperature. Each CAPFT point is calculated as follows:

$$CAPFT_i = \frac{Q_i}{Q_{ref}} \quad (16)$$

Where:

Q_i = chiller capacity at specified temperature conditions

Q_{ref} = reference capacity, which can be selected based on either the design capacity or the ARI-rated capacity of the chiller, but must be equal to the nominal capacity defined for the chiller in DOE-2.

To define CAPFT curves using the DATA method in DOE-2.1e, the energy modeler should group together the corresponding chilled water temperature, condenser temperature, and $CAPFT_i$ for each point by enclosing these three values into a single set of parentheses. The first point in the curve must be normalized to 1.0, and must correspond to the conditions at which the CAPACITY and EIR are specified. A sample DOE-2.1e CAPFT curve is shown in Figure 20.

In DOE-2.2, curves are defined by grouping all the data for a given input parameter into a single array. For example, in the CAPFT curve, the chilled water leaving temperatures are listed in the "INDEPENDENT-1" array, the condenser temperatures are listed in the "INDEPENDENT-2" array, and the calculated values for CAPFTi are listed in the "DEPENDENT" array. The sample DOE-2.1e CAPFT curve shown in Figure 20 below would be defined in DOE-2.2 as shown in Figure 21.

eQuest Chiller Curve- DATA Method

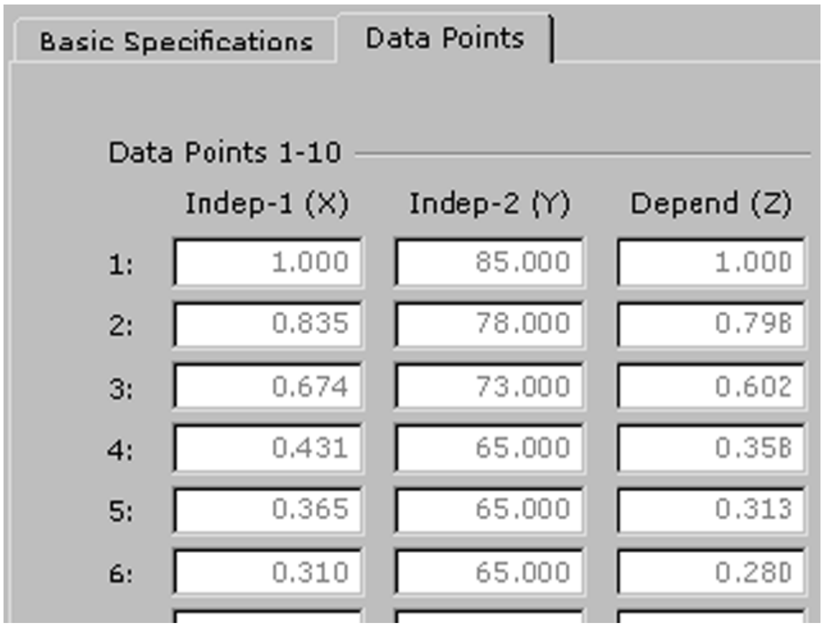


Figure 19: The screen shot shows how to define a chiller curve in eQuest using the Data Method.

DOE-2.1e CAPFT Curve- DATA Method

```
$*******************************************************$
$            DOE-2.1e CAPFT Curve - DATA Method          $
$*******************************************************$
$ Insert curve under PLANT-ASSIGNMENT in the PLANT portion of
$ the DOE-2 input file
TYP-CAPPFT  = CURVE-FIT
TYPE = BI-QUADRATIC
DATA
$ (CHWSi, CWSi, CAPFTi)
DATA (44,85,1.000)        (42,85,0.981)(40,85,0.946)  (38,85,0.911)
                          (42,75,1.035)(40,75,1.035)  (38,75,0.989)
     (50,65,1.035)        (42,65,1.035)(40,65,1.035)  (38,65,1.035)
$****************************************************************$
$     END DOE-2.1e CAPFT Curve - DATA Method     $
$****************************************************************$
```

Figure 20

DOE-2.2 CAPFT Curve- DATA Method

Figure 21

```
$*******************************************************$
$           DOE-2.2 CAPFT Curve - DATA Method           $
$*******************************************************$
$ Insert curves after the last input for SPACE
    "TYP-CAPFT" = CURVE-FIT
    TYPE            = BI-QUADRATIC-T
    INPUT-TYPE        = DATA
    INDEPENDENT-1     =
        (44,42,40,38,42,40,38,50,42,40,38)
        $Independent-1 defines chilled water leaving temperature
    INDEPENDENT-2     =
        (85,85,85,85,75,75,75,65,65,65,65)
        $Independent-2 defines condenser water entering temperature
    DEPENDENT         =
        ( 1.000,0.981,0.946,0.911,1.035,1.035,0.989,
          1.035,1.035,1.035,1.035)
    $Dependent defines calculated values for CAPFTi
    ..
$********************************************************$
$         END DOE-2.2 CAPFT Curve - DATA Method          $
$********************************************************$
```

In the COEFFICIENT method, the inputs for chilled water supply temperature, entering condenser water temperature, and CAPFT are folded into an input matrix which can be solved for the six regression coefficients in equation 4 using the least squares linear regression routine.[13] The matrix for the CAPFT curve appears as follows:

$$\begin{bmatrix} CAPFT_1 & t_{chws,1} & t_{chws,1}^2 & t_{cws/oat,1} & t_{cws/oat,1}^2 & t_{chws,1} \times t_{cws/oat,1} \\ CAPFT_2 & t_{chws,2} & t_{chws,2}^2 & t_{cws/oat,2} & t_{cws/oat,2}^2 & t_{chws,2} \times t_{cws/oat,2} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ CAPFT_n & t_{chws,n} & t_{chws,n}^2 & t_{cws/oat,n} & t_{cws/oat,n}^2 & t_{chws,n} \times t_{cws/oat,n} \end{bmatrix} \quad (17)$$

Where:

t_{chws} = the chilled water supply temperature (°F)

$t_{cws/oat}$ = the condenser water supply temperature (°F) for water-cooled equipment and the outdoor air dry-bulb temperature (°F) for air-cooled equipment

A typical CAPFT curve in DOE-2.1e using the COEFFICIENT method would be defined as shown in Figure 22.

DOE-2.1e CAPFT Curve- COEFFICIENTS Method

Figure 22

```
$**************************************************************$
$ DOE-2.1e CAPFT Curve - COEFFICIENTS Method   $
$**************************************************************$

$ Insert curve under PLANT-ASSIGNMENT in the PLANT portion of
$ the DOE-2 input file
TYP-CAPFT = CURVE-FIT
TYPE = BI-QUADRATIC
$ COEF = (a2, b2, c2)
   COEF=( -0.38924542, -0.02195141, -0.00027343
    0.04974775, -0.00053441, 0.00067295)
..
$*******************************************************************$
$ END DOE-2.1e CAPFT Curve - COEFFICIENTS Method  $
$*******************************************************************$
```

Calculating the EIRFT Curve in DOE-2

The EIRFT curve is similar to the CAPFT curve, but replaces the "CAPFT" term with a term for "EIRFT". Similarly to the CAPFT curve, the first point in the EIRFT curve must be normalized to 1.0, and must correspond to the conditions at which the CAPACITY and EIR are specified. When implemented correctly, this curve should show the best chiller performance at low lift conditions and the worst performance at high lift conditions. Each EIRFT point is calculated as follows:

$$EIRFT_i = \frac{P_i \times Q_{ref}}{P_{ref} \times Q_i} \qquad (18)$$

where:

Q_i and Q_{ref} are defined in equation 16, and

P_i = chiller input power at specified temperature conditions

P_{ref} = reference input power which can be selected based on either the design capacity or the ARI-rated capacity of the chiller; but must use the same conditions as Q_{ref}.

Using the DATA method, the EIRFT curves can be defined in DOE-2.1e or DOE-2.2 by implementing the same format as that shown for the CAPFT curves in Figures 20 and 21 respectively. In each case, the $EIRFT_i$ terms should replace the $CAPFT_i$ terms.

The EIRFT curve can also be defined in DOE-2 using the COEFFICIENT method. The coefficients should be calculated by folding values for chilled water supply temperature, entering condenser water temperature, and EIRFT into an input matrix, and solving for the six curve coefficients in equation 5 using the least squares linear regression routine.[14]

The matrix for the EIRFT curve appears as follows:

$$\begin{bmatrix} EIRFT_1 & t_{chws,1} & t_{chws,1}^2 & t_{cws/oat,1} & t_{cws/oat,1}^2 & t_{chws,1} \times t_{cws/oat,1} \\ EIRFT_2 & t_{chws,2} & t_{chws,2}^2 & t_{cws/oat,2} & t_{cws/oat,2}^2 & t_{chws,2} \times t_{cws/oat,2} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ EIRFT_n & t_{chws,n} & t_{chws,n}^2 & t_{cws/oat,n} & t_{cws/oat,n}^2 & t_{chws,n} \times t_{cws/oat,n} \end{bmatrix} \quad (19)$$

where:

t_{chws} = the chilled water supply temperature (°F)

$t_{cws/oat}$ = the condenser water supply temperature (°F) for water-cooled equipment and the outdoor air dry-bulb temperature (°F) for air-cooled equipment.

The DOE-2.1e formatting for the EIRFT coefficient method is similar to that shown Figure 22.

Calculating the EIRFPLR Curve in DOE-2

For the EIRFPLR curve, the following pieces of information are required for each data point: the CAPFT at the current evaporator and condenser temperatures; the EIRFT at the current evaporator and condenser temperatures; the part-load ratio (PLR), and the ratio of power for part-load to power for full-load (EIRFPLR) at the given lift conditions. As with the EIRFT and CAPFT curves, the first point defined for this curve should also be normalized to 1.0, and should correspond to the conditions at which the CAPACITY and EIR are specified. The PLR is defined as the ratio of the present capacity over the full-load capacity at the given lift conditions. For each data point, the chilled water and condenser temperatures for the part-load point should be equal to the temperatures used for the corresponding reference full-load point.

$$PLR_i = \frac{Q_i}{Q_{ref} \times CAPFT} \quad (20)$$

where:

Q_i = part-load capacity

Q_{ref} = full-load capacity at the same evaporator and condenser temperatures

CAPFT is the capacity as a function of temperature curve evaluated at the current temperature conditions.

The EIRFPLR for each point is calculated as follows:

$$EIRFPLR_i = \frac{P_i}{P_{ref} \times CAPFT \times EIRFT} \tag{21}$$

where:

P_i = part-load input power

P_{ref} = full-load input power at the same evaporator and condenser temperature, for the given part-load capacity

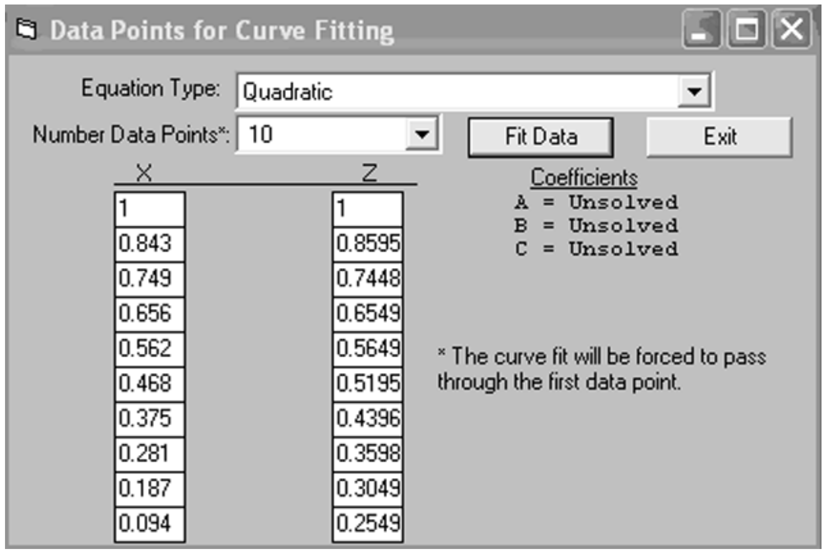
$CAPFT_i$ is the capacity as a function of temperature curve evaluated at the current temperature conditions.

$EIRFT_i$ is the energy-efficiency ratio as a function of temperature curve evaluated at the current temperature conditions.

Consider a sample point of data with a part-load capacity of 797 tons, power consumption of 355 kW, entering condenser water temperature of 75ºF, and chilled water supply temperature of 44ºF. The reference full-load data point, having the same condenser and evaporator temperature, has a capacity of 1,150 tons power consumption of 698 kW. The ARI-rated full-load capacity is 1,200 tons, with a power consumption of 708 kW. ARI-rated values were used for defining SIZE and EIR in the DOE-2 input file.

VisualDOE Chiller Curve Definition- DATA Method

Figure 23: Chiller Curve defined in VisualDOE using the data method, where X is the PLR, and Z is the EIRFPLR.



DOE-2.1e EIRFPLR Curve- DATA Method

Figure 24

```
$*******************************************************$
$   DOE-2.1e EIRFPLR Curve - DATA Method       $
$*******************************************************$
$ Insert curve under PLANT-ASSIGNMENT in the PLANT portion of
$ the DOE-2 input file
TYP-EIRFPLR = CURVE-FIT
TYPE = QUADRATIC
DATA
$ (PLRi,EIRFPLRi)
DATA  =
(1.000,1.0000)         $kw/ton = 0.667
(0.843,0.8595)         $kw/ton = 0.637
(0.749,0.7448)         $kw/ton = 0.621
(0.656,0.6549)         $kw/ton = 0.624
(0.562,0.5649)         $kw/ton = 0.628
(0.468,0.5195)         $kw/ton = 0.693
(0.375,0.4396)         $kw/ton = 0.733
(0.281,0.3598)         $kw/ton = 0.800
(0.187,0.3049)         $kw/ton = 1.017
(0.094,0.2549)         $kw/ton = 1.700
..
$********************************************************$
$          END DOE-2.1e EIRFPLR Curve - DATA Method        $
$********************************************************$
```

The CAPFT evaluated at the current temperature conditions would be calculated as:

$$CAPFT_i = \frac{1150}{1200} = 0.958$$

The EIRFT evaluated at the current temperature conditions would be calculated as:

$$EIRFT_i = \frac{698\,kW \times 1200\ tons}{1150\ tons \times 708\,kW} = 1.029$$

The EIRFPLR point would be calculated as:

$$PLR_i = \frac{797\ tons}{1{,}150\ tons \times 0.958 \times 1.029} = 0.703$$

$$EIRFPLR_i = \frac{355\,kW}{698\,kW \times 0.958 \times 1.029} = 0.516$$

Using the DATA method, a typical EIRFPLR curve in DOE-2.1e would be defined shown in Figure 24.

The same EIRFPLR curve, representing part-load chiller performance for a chiller without a Variable Speed Drive (VSD), should be entered in DOE-2.2 as shown in Figure 25.

DOE-2.1e EIRFPLR Curve without VSD- DATA Method

```
$*******************************************************$
$      DOE-2.2 EIRFPLR Curve without VSD - DATA Method   $
$*******************************************************$
$ Insert curve after the last entry for SPACE
"TYP-EIRFPLR" = CURVE-FIT
   TYPE             = QUADRATIC
   INPUT-TYPE       = DATA
   INDEPENDENT    = (1.000, 0.843, 0.749, 0.656, 0.562,
                   0.468, 0.375, 0.281, 0.187, 0.094)
    $ independent dataset includes all PLRi terms
   DEPENDENT            = (1.000, 0.8595, 0.7488, 0.6549, 0.5649
                        .5195, 0.4396, 0.3598, 0.3049, 0.2549)
    $ dependent dataset includes all EIRFPLRi terms
   ..
$************************************************************$
$    END DOE-2.2 EIRFPLR Curve without VSD - DATA Method  $
$************************************************************$
```

Figure 25:

A sample DOE2.2 EIRFPLR curve for a chiller with a VSD that is shown in figure 30.

In the COEFFICIENT method, inputs for PLR and EIRFPLR are folded into an input matrix which can be solved for the three curve coefficients using the least squares linear regression routine.[24] The format for the EIRFPLR curve is as follows:

Figure 26

$$EIRFPLR_i = a_1 + b_1 \times PLR + c_1 \times PLR^2 \tag{22}$$

Where a_1, b_1, and c_1 are the regression coefficients for the curve.

The matrix for the EIRFPLR curve appears as follows:

$$\begin{bmatrix} EIRFPLR_1 & PLR_1 & PLR_1^2 \\ EIRFPLR_2 & PLR_2 & PLR_2^2 \\ \ldots & \ldots & \ldots \\ EIRFPLR_n & PLR_n & PLR_n^2 \end{bmatrix} \tag{23}$$

The EIRFPLR curve should be defined in DOE-2.1e as shown in Figure 26.

DOE-2.1e EIRFPLR Curve- Coefficients Method

```
$*******************************************************$
$       DOE-2.1e EIRFPLR Curve - COEFFICIENTS Method    $
$*******************************************************$
$ Insert curve under PLANT-ASSIGNMENT in the PLANT portion of
$ the DOE-2 input file
TYP-EIRFPLR = CURVE-FIT
TYPE = QUADRATIC
$ COEF = (a1, b1, c1)
   COEF=(0.27715900,-0.02504500,0.73693600)
..
$********************************************************$
$   END DOE-2.1e EIRFPLR Curve - COEFFICIENTS Method    $
$********************************************************$
```

In DOE-2.2, the EIRFPLR curve for VSDs should be modified to include a third value for each point of data that indicates the differential between the condenser and chilled water supply temperatures.[24] The curve type should be selected as "BI-QUADRATIC-RATIO&dt," where the first independent dataset lists the values for PLR_i, the second independent dataset lists the values for the temperature differential between the condenser and entering chilled water, and the dependent dataset lists the values for EIRFPLR. The sample code shown in Figure 30 demonstrates the format for defining this curve in DOE-2.2.

Once the three chiller curves have been defined, they should each be attached to the corresponding chiller. In DOE-2.1e, this is accomplished by associating each chiller curve

[24] More details regarding the definition of this curve, defined as a "BI-QUADRATIC-RATIO&dT" curve can be found in the "New Features," Volume 6 manual by James Hirsch (see footnote 3 from chapter 1).

eQuest Chiller Curve Definition

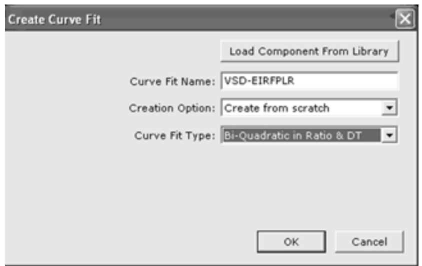


Figure 27: Define EIRFPLR curve for variable speed chiller as"Bi-Quadratic in Ratio & dT" in eQuest.

with the corresponding chiller type. For example, for an open centrifugal chiller, selected as OPEN-CENT-CHLR, the curves would be attached under EQUIPMENT-QUAD using the keywords OPEN-CENT-CAP-FT for the CAPFT curve, OPEN-CENT-EIR-FT for the EIRFT curve, and OPEN-CENT-EIR-FPLR for the EIRFPLR curve (see Figure 31).

Energy Pro Chiller Curve Definition- COEFFICIENTS Method

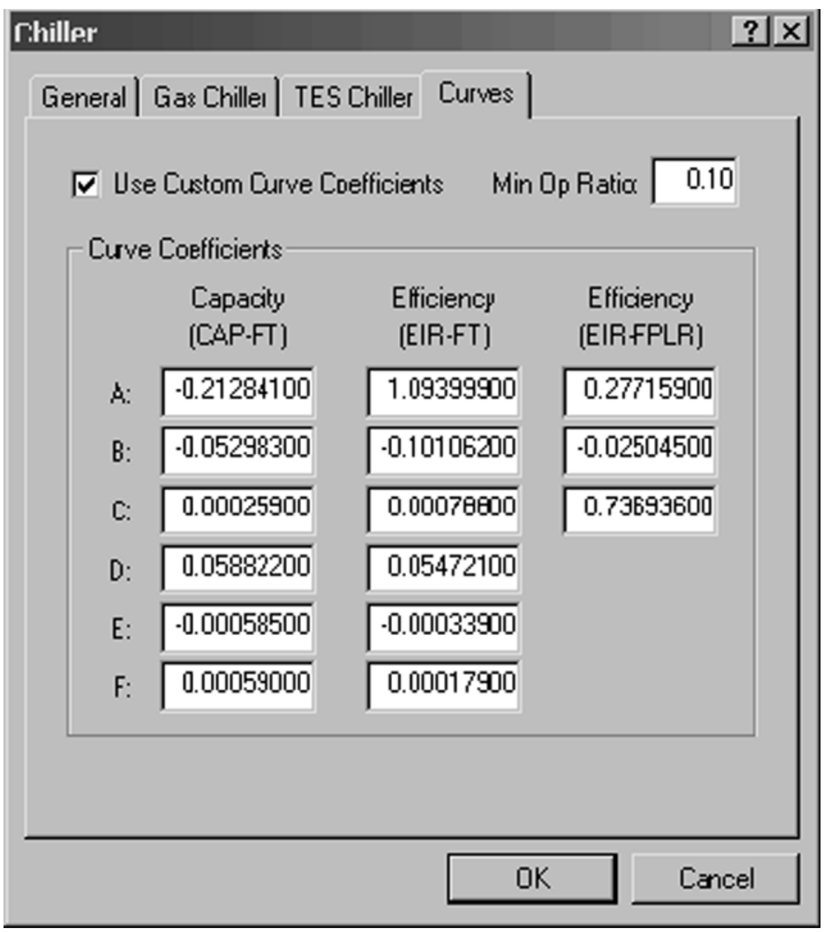
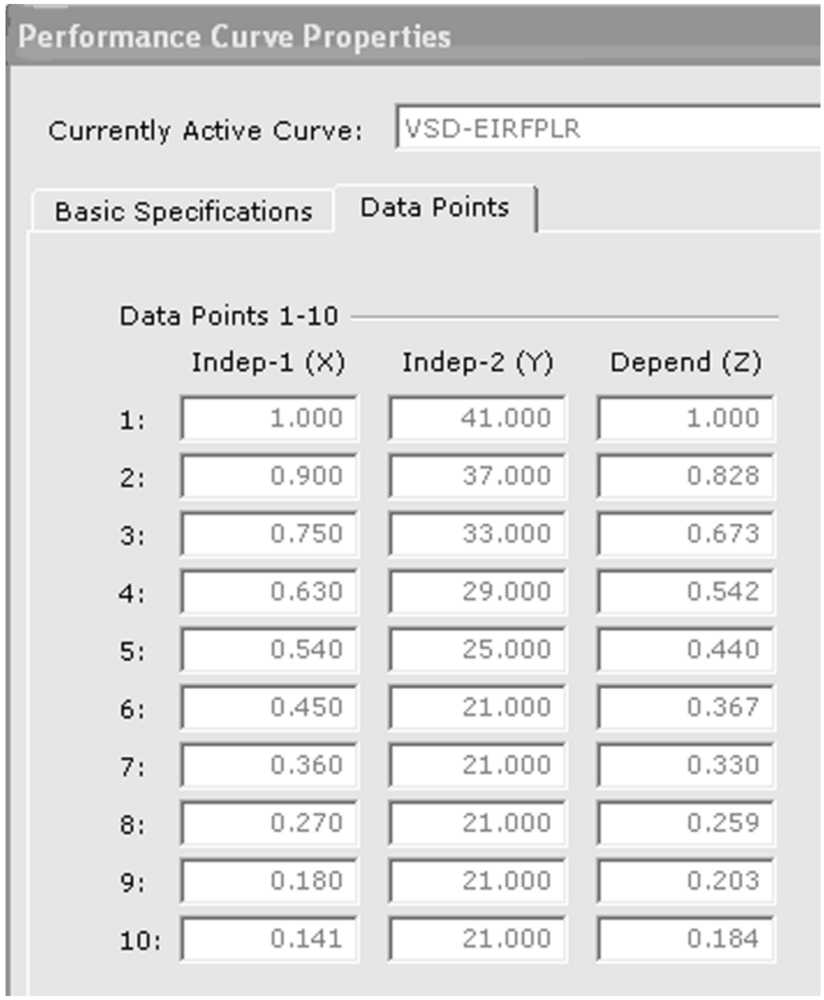


Figure 28: Chiller curve defined in Energy Pro using the coefficients method.

eQuest Chiller Curve Definition- DATA Method

Figure 29: Insert points for EIRF-PLR curve for Variable Speed Chiller in eQuest.



DOE-2.2 EIRFPLR Curve for Chillers with Variable Speed Drives- DATA Method

Figure 30

```
$************************************************************$
$       DOE-2.2 EIRFPLR Curve - DATA Method                  $
$ (TO BE USED FOR CHILLERS WITH VARIABLE SPEED DRIVES)       $
$************************************************************$
$ Insert curves after the last input for SPACE
     "VSD-EIRFPLR" = CURVE-FIT
     TYPE          = BI-QUADRATIC-RATIO&dt
     INPUT-TYPE    = DATA
     INDEPENDENT-1  =   (1.000,0.900,0.751,0.630,0.540
                         0.450,0.360,0.270,0.180,0.141)
                         $ independent dataset # 1 includes all PLRi terms
     INDEPENDENT-2  =   (41.000,37.000,33.000,29.000,25.000
                         21.000,21.000,21.000,21.000,21.000)
                         $ independent dataset # 2 includes all dti terms
     DEPENDENT   =      (1.000,0.828,0.673,0.542,0.440
                         0.367,0.330,0.259,0.203,0.184)
                         $ dependent dataset includes all EIRFPLRi terms
     ..
$***********************************************************$
$ END DOE-2.2 EIRFPLR Curve - DATA Method for VSD Chillers  $
$***********************************************************$
```

DOE-2.1e Sample Code showing how to Attach Chiller Curve to a Chiller

FIGURE 31

```
$**************************************************$
$       DOE-2.1e Attach Chiller Curves to Chiller        $
$**************************************************$
$ TYP-CAPFT curve, TYP-EIRFT curve, and TYP-EIRFPLR curve
$ are defined under PLANT-ASSIGNMENT as shown in
$ Figures 20, 22, 24, and 26
OPEN-CENT-CAP-FT       TYP-CAPFT
                          $Attaches TYP-CAPFT curve to open centrifugal chiller
OPEN-CENT-EIR-FT       TYP-EIRFT
                          $Attaches TYP-EIRFT curve to open centrifugal chiller
OPEN-CENT-EIR-FPLR     TYP-EIRFPLR
                          $Attaches TYP-EIRFT curve to open centrifugal chiller
      ..
$******************************************************$
$ END DOE-2.1e Attach Chiller Curves to Chiller $
$******************************************************$
```

In DOE-2.2, chiller curves are attached to the chiller at the position of the code where the chiller is defined. The format for attaching chiller curves in DOE-2.2 is shown in Figure 32.

DOE-2.2 Sample Code showing how to Attach a Chiller Curve to a Chiller

FIGURE 32

```
$**************************************************$
$  DOE-2.2 Attach Chiller Curves to Chiller   $
$**************************************************$
"Typical Chiller" = CHILLER
   TYPE              = ELEC-OPEN-CENT
   CAPACITY          = 3.66
   ELEC-INPUT-RATIO = 0.1726
   CAPACITY-FT       = "Typ-CAPFT"     $ TYP-CAPFT curve attached to chiller
   EIR-FT            = "TYP-EIRFT"          $ TYP-EIRFT curve attached to chiller
   EIR-FPLR  = "TYP-EIRFPLR"    $ TYP-EIRFPLR curve attached to chiller
   CHW-LOOP          = "Chilled Water Loop"
   CHW-PUMP          = "Primary CHW Loop Pump"
   CONDENSER-TYPE    =  WATER-COOLED
   CW-LOOP           = "Condenser Water Loop"
   ..
$******************************************************$
$ END DOE-2.2 Attach Chiller Curves to Chiller   $
$******************************************************$
```

Guidelines for Creating Accurate Custom Chillers

Due to the complexity involved in creating custom chiller curves, energy modelers have been known to improperly develop them and end up with results that are less accurate than those available using default curves. To ensure the greatest accuracy when modeling custom chiller curves, follow these important guidelines:

- Get accurate data from the chiller manufacturer. Make sure that the "full load" data is truly at an operating point with the chiller fully loaded.

- Derate the data based on the ARI tolerance curve. Do not derate the capacity, but use the full tolerance to derate the stated power at each point of operation.

- Make sure that the data points used for the curves extends over the full range of simulated operation. If you extrapolate performance beyond the data points, you will get useless results.

- Use sufficient amounts of data. Results will increase in accuracy as the number of data points is increased, provided that the data points cover the full range of conditions that will be simulated in the energy analysis program.

- Pay attention to the order of data input. Whether using the COEFFICIENT method or the DATA method to define chiller curves, the order of the data input must be entered as outlined in this simulation guidebook. For example, in the EIRFPLR curve, information for PLR should be listed first in the data pair, and EIRFPLR should be listed second. If the order of the data is reversed, then the energy efficiency of the chiller at various part-load conditions will be calculated incorrectly, and therefore, overall chiller energy use will be inaccurate.

Summary

Using the chiller modeling methodology described in this guidebook, energy modelers can assist the design team in developing chiller plants with tremendous potential savings. When energy modelers combine the advanced control sequences modeling strategies discussed in the third section of this simulation guidebook with these strategies for modeling chiller curves, the energy model can become a particularly effective tool for optimizing chilled water plant performance. For example, an article entitled "Commissioning Tools & Techniques Used in a Large Chilled Water Plant Optimization Project,"[17]

[25] Hydeman, M.; S. Tylor; C. Speck; and K. Gillespie. "Commissioning Tools & Techniques Used in a Large Chilled Water Plant Optimization Project." Proceedings of the 7th National Conference on Building Commissioning. PECI, Portland Oregon. May 1999.

reported a 6.5 GWH/year reduction in plant energy through chiller replacement and controls in a 17,000 ton chiller plant. Careful development of calibrated energy models for this plant enabled the team to analyze the various design options, and achieve the maximum possible energy and cost savings for the plant. These savings were verified by post-retrofit monitoring.

Steps for Creating Custom Chiller Curves in DOE-2-Based Programs

1. Procure 20-40 points of data from chiller manufacturers, where each point includes condenser temperature, chilled water supply temperature, chiller capacity, input power, and percent loading. Data should include both part-load and full-load data over the full range of condenser and chilled water temperatures for which the chiller will operate.
2. Select the reference point by which the chiller curves will be normalized. For DOE-2.1e, the reference point should be selected at ARI-rated conditions. For recent versions of DOE-2.2, the reference point should correspond to the most common full-load operating conditions.
3. Generate CAP-FT Curve
    a. For each set of full-load data, calculate CAPFTi, defined in equation 16 above.

    b. DATA Method: Enter each set of full load data points for the CAPFT curve into a DOE-2 based simulation program, where each point includes a term for chilled water temperature, condenser temperature, and CAPFTi. Confirm that the CAPFTi for the first point is normalized to 1.0 based on the reference point identified in Step # 2 above. Figure 20 defines the format for entering CAPFT curves in DOE-2.1e, and Figure 21 indicates the format for DOE2.2 CAPFT curves.

    c. COEFFICIENTS Method: Input each set of full load data points including chilled water temperature, condenser temperature, and CAPFTi into the matrix shown in equation 17, and solve for the six regression coefficients. Define the curve coefficients in DOE-2.1e using the format shown in Figure 22.

4. Generate EIR-FT Curve
    a. For each set of full-load data, calculate EIRFTi, defined in equation 18 above.

    b. DATA Method: Enter each set of full load data points for the EIRFT curve into a DOE-2 based simulation program, where each point includes a term for chilled water temperature, condenser temperature, and EIRFTi. Confirm that the EIRFTi for the first point is normalized to 1.0 based on the reference point identified in Step # 2 above. Figure 20 defines the format for entering EIRFT curves in DOE-2.1e, and Figure 21 indicates the format for DOE2.2 EIRFT curves (where in each case the term for EIRFTi replaces the term for CAPFTi).

    c. COEFFICIENTS Method: Input each set of full load data points including chilled water temperature, condenser temperature, and CAPFTi into the matrix shown in equation 19, and solve for the six regression coefficients. Define the curve coefficients in DOE-2.1e using the format shown in Figure 22.

5. Generate EIR-FPLR Curve

    a. For each set of part-load data, calculate the PLR_i and $EIRFPLR_i$ as defined in equations 20 and 21 respectively. Note that you will need to calculate the $CAPFT_i$ and $EIRFT_i$ at each point in order to calculate the PLR_i and $EIRFPLR_i$. If you are defining a curve for a variable speed chiller in DOE2.2, you should also calculate dT as defined in equation 15.

    b. DATA Method: Enter each set of full load data points for the EIRFPLR curve into a DOE-2 based simulation program, where each point includes a term for PLR_i and $EIRFPLR_i$. Confirm that the PLR_i and EIRFPLRi for the first point are normalized to 1.0 based on the reference point identified in Step # 2 above. For curves defined in DOE-2.1e, use the format shown in Figure 24. For chillers without variable speed drives, defined in DOE-2.1e, use the format shown in Figure 25. For chillers with variable speed drives defined in DOE2.2, include terms for PLRi, dT, and EIRFPLRi as demonstrated in Figure 30.

    c. COEFFICIENT method: Input the data for PLRi and EIRFPLRi into the matrix shown in equation 23, and solve for the three regression coefficients. Enter the curve coefficients in DOE-2.1e using the format shown in Figure 26.

6. Attach the custom chiller curves to the appropriate chiller using Figure 31 for DOE-2.1e, and Figure 32 for DOE2.2.

PART 3: Advanced Control Sequences

The recent widespread use of digital controls in building construction has greatly expanded the opportunities for optimizing building efficiency. Using digital controls provides more accurate sensing of data and enhances flexibility for modifying control logic. However, relatively few buildings that use digital control technologies attain their full potential for cost-effectively minimizing energy demand and consumption. Common problems that prevent the use of efficient digital control technologies include:

- Misinformation regarding the risks and benefits of the technology;
- An inadequate understanding of the energy and cost benefits associated with these strategies, and
- Complete ignorance regarding the availability of such strategies.

Energy models that accurately demonstrate the operating cost benefits of these technologies can present decision makers with compelling reasons for implementing the strategies into the project design. Accordingly, this simulation guidebook highlights the following digital control strategies and sequences that may improve efficient operation of water-side systems. The guidebook also provides a guide for modeling each technology in EnergyPro, native DOE-2.1e, and eQUEST:

- Variable primary flow chilled water distribution (page 46)
- Primary/secondary chilled water distribution (page 48)
- Variable flow condenser water system (page 54)
- Cooling tower cell control (page 55)
- Cooling tower capacity control (page 55)
- Condenser water temperature reset (page 57)
- Chilled water temperature reset (page 59)
- Hot water temperature reset (page 60)

COMMON SIMULATION SOFTWARE

THIS GUIDEBOOK USES RESEARCH GENERATED FROM THE FOLLOWING ENERGY SIMULATION SOFTWARE PACKAGES:

ENERGYPRO V. 3.142, EQUEST V. 3.44 WITH DOE2.2 RELEASE 42K6, AND DOE-2.1E RELEASE 134.

KEEP IN MIND THAT THIS SOFTWARE IS CONSTANTLY UPDATED. REVIEW THE DOCUMENTATION OF LATER RELEASES FOR ANY CHANGES TO SOFTWARE INPUTS OR KEYWORDS THAT MIGHT IMPACT THE MODELING METHODOLOGY DISCUSSED IN THIS SIMULATION GUIDEBOOK.

Variable Speed Drive Control Sequences

When controlled correctly, variable speed drives (VSDs) installed on fan, pump, and compressor motors can significantly limit equipment energy usage by optimizing the part-load performance of the equipment. In recent years, VSDs have become an increasingly common option for HVAC system equipment due to the improved reliability of VSD technology and more stringent energy code requirements. However, design teams often only specify equipment with VSDs when this technology is required to minimally comply with energy code standards. To promote further use of these efficient technologies, California Title-24 2005 standards prescriptively require variable speed controls for pumps over 5 hp that serve variable-flow systems.

Following Through on Control Strategies

Each control strategy simulated in the final building energy model MUST match the equipment data and control schemes defined in the plans and control sequences for the building. Unfortunately, control strategies are often recommended based on initial energy models and incorporated into the final estimated energy savings for the building, but are excluded from final plans or control sequences. A building commissioning process should be used to confirm that control sequences described in the design document are used in the final building design, and to confirm that the control sequences function properly when the building is completed.

Using DOE-2 simulation programs to model variable-speed control sequences for waterside systems is often difficult due to (a) the limited modeling capabilities of DOE-2.1e-based software (i.e. EnergyPro), and (b) the vast range of available inputs in DOE-2.2 programs such as eQUEST. This portion of the simulation guidebook discusses methods for modeling the following variable-speed control strategies in EnergyPro, native DOE-2.1e, and eQUEST:

- Variable Primary Flow Chilled Water Distribution
- Primary/Secondary Chilled Water Distribution
- Variable Flow Condenser Water System

Note that the variable-speed, variable-flow-pumping algorithms in the LBNL/USDOE version of DOE-2.1e (which is used as the simulation engine for EnergyPro), provide only a rough approximation of actual variable speed pumping control, whereas later versions of DOE-2.1e, and DOE-2.2 incorporate much more accurate simulation of variable-speed pumping control.

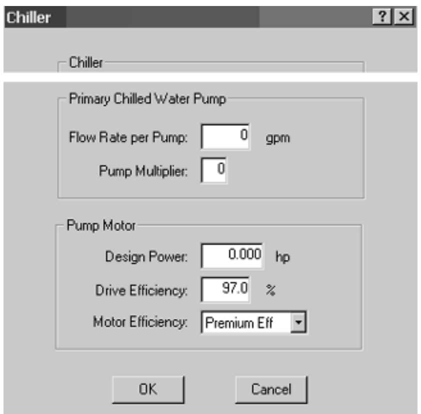
Variable Primary Flow Chilled Water Distribution

In a variable primary flow chilled water distribution system, VSDs on the primary chilled water pumps vary the flow through the chillers and out to the chilled water coils based on demand. These systems generally include a bypass loop to ensure minimum flow through the chiller. When properly implemented, variable primary pumping generally provides the most cost-effective and energy-efficient option for chilled water distribution. In EnergyPro, variable primary flow is modeled by defining the primary chilled water pump data under the secondary chilled water pump tab according to the following process:

• From the **Plant / Chilled Water** tab, click each chiller to view the primary pump inputs. Set **Flow Rate per Pump, Pump Multiplier,** and **Design Power** to a value of zero. Close the chiller window.

• Select the **Secondary Pumps** window by clicking the graphic titled either **No Secondary Pumps** or **Secondary Pumps**. Select the pump type as **Variable Speed,** and then enter the appropriate Minimum Flow Per Pump, as well as all the other relevant inputs pertaining to the primary chilled water pumps. In DOE-2.1e, energy modelers can simulate variable primary chilled water flow by setting CCIRC-PUMP-TYPE to VARIABLE-SPEED, and specifying the minimum electricity consumption as a fraction of full load consumption (CCIRC-MIN-PLR).

Variable Primary Flow Inputs for the Chiller Window in EnergyPro



Variable Primary Flow Inputs for the Secondary Chilled Water Pumps in EnergyPro

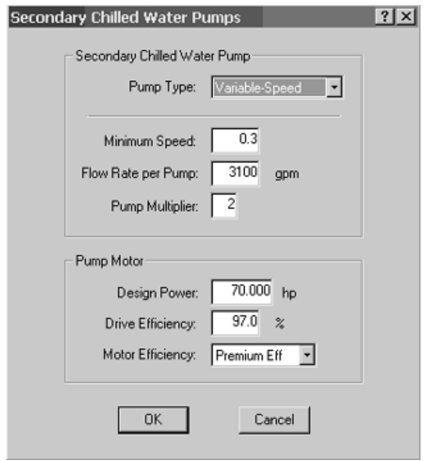


Figure 33 (Far left): To define variable primary flow in EnergyPro, set the values for flow, pump multiplier, and design power to 0 in the chiller window.

Figure 34 (top right): Define variable primary inputs in the secondary chilled water pump window in EnergyPro.

DOE-2.1e Variable Primary Chilled Water Flow

Figure 35

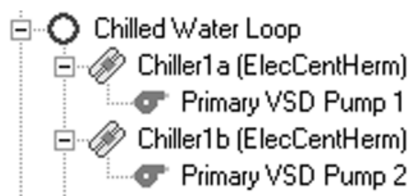
```
PLANT-PARAMETERS
$Chilled Water Variable Primary CHW Pumps
  CCIRC-PUMP-TYPE = VARIABLE-SPEED        $ defines primary flow as
                                          $ variablespeed; (FIXED-SPEED
                                          $  is the DOE-2default)
        CCIRC-MIN-PLR = 0.300             $ Minimum electricity
                                          $ consumption as fraction of
                                          $ full-load consumption
      CCIRC-HEAD = 100                    $ Defines the head pressure
                                          $ of the CHW loop
      CCIRC-IMPELLER-EFF = .7             $ CHW pump impeller
                                          $ efficiency
      CCIRC-MOTOR-EFF = .85               $ CHW pump motor efficiency
$ Other Plant Parameters not shown
..
```

In eQUEST, users can directly model variable primary chilled water flow in the wizard interface using the following steps:[25]

- From the **Cooling Primary Equipment** screen, select a pump configuration of **Single System Pump(s) Only.**[26]
- Select chilled water flow as **Variable.**
- Select **Pump Eff / Control as VSD**.
- If the chilled water loop design specifies a bypass to ensure minimum flow through the chiller, the loop minimum flow should be specified in the **Detailed Data Edit** interface under the chilled water loop inputs.
- eQUEST automatically defines all chilled water coils in a variable flow loop with 2-way valves. If the chilled water coils for any system attached to the chilled water loop have 3-way valves assigned to them, the **CHW Valve Type** for these systems should be changed to **Three-Way** in the **Detailed Data Edit** interface.

Variable Primary Chilled Water Flow Depicted in eQuest Detailed Edit Mode

FIGURE 36



Primary/Secondary Chilled Water Distribution

Primary/secondary chilled water distribution systems generally consist of a constant flow loop through the chillers and a variable flow loop to the chilled water coils. In EnergyPro, this configuration is modeled by (a) entering the constant speed pump data in the chiller window and (b) defining the variable speed secondary pump data in the secondary pumps window:

- From the **Plant / Chilled Water tab,** click each chiller to view the primary pump inputs. Set **Flow Rate Per Pump, Pump Multiplier**, and **Design Power** as specified in the project design. Close the chiller window.

[25] A sample variable primary flow system is shown in the DOE-2.2 Volume 3 Topics Manual released with the eQUEST program. See Example 7, pp. 310.

[26] The selection of "single system pumps only" indicates that the pumps are located at the loop level only, and no pumps are located at specific chillers. The loop pumps are sized to overcome all pressure drops associated with the entire system including chillers, piping, and coils. The pump configuration selection, "individual chiller pumps only," indicates that each of the chilled water pumps are associated with individual chillers, and no pumps are located on the chilled water loop. The pumps that serve each chiller are sized to overcome the pressure drop for the chiller they are assigned to plus the pressure drop across the entire loop.

- Select the **Secondary Pumps** window by clicking the graphic titled either **No Secondary Pumps** or **Secondary Pumps.** Select the **Pump Type** as **Variable Speed,** and input the appropriate minimum flow per pump, as well as all the other relevant inputs pertaining to the secondary chilled water pumps.

Variable Primary Chilled Water Floor Defined in eQuest Wizard

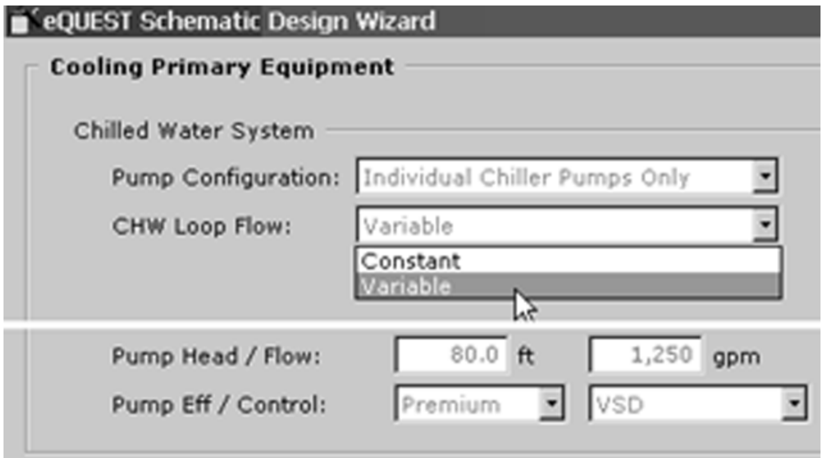


FIGURE 37

Although the primary/secondary pumping configuration cannot be directly modeled in DOE-2.1e, the energy usage of primary/secondary chilled water distribution systems can be approximated by (a) entering data for the variable flow secondary loop under the chilled water pump inputs and (b) inputting the primary constant flow loop data under the condenser pump inputs.[27] The effective head (TWR-PUMP-HEAD) for the combined condenser water pump(s) and primary chilled water pump(s) can be calculated by summing the products of the individual pump head and flow rate, and dividing by the net system flow rate through the condenser and evaporator (see Figure 38).[28]

Motor efficiency and impeller efficiency for the pumps should be calculated using the flow-weighted averages for the condenser water and primary chilled water pumps. This is shown in Figure 39.

In eQUEST, energy modelers can define primary/secondary flow by (a) entering the secondary chilled water loop inputs in the wizard interface and then (b) completing the primary chilled water loop inputs in the detailed interface:

- From the **Cooling Primary Equipment** wizard screen, select a pump configuration of Single System Pump(s) Only.
- Select **CHW Loop Flow** as **Variable** and **Pump Control** for the loop as **VSD**.
- When all wizard inputs have been entered, switch to **Detailed Edit Mode** by clicking **Mode /Detailed Data Edit.**

[27] This modeling approach assumes that condenser water pumps are constant speed.
[28] "Procedures for Modeling Buildings to MNECB and CBIP." Version 2.0, November, 2002.

Equations for Calculating Effective Head for Combined Condenser Water Pump(s) as an Input for DOE-2.1e.

FIGURE 38

$$\dot{V}_{net} = \left(\sum_i \dot{V}_{i,evaporator} \right) + \left(\sum_i \dot{V}_{i,condenser} \right) \tag{24}$$

$$p_{effective} = \frac{\sum_i \left(p_{i,\mathrm{CW\,pump}} \times \mathrm{V}_{i,\mathrm{CW\,pump}} \right) + \sum_i \left(p_{i,\mathrm{CHW\,pump}} \times \mathrm{V}_{i,\mathrm{CHW\,pump}} \right)}{\dot{V}_{net}} \tag{25}$$

$$\text{COMP - TO - TWR - WTR} = \frac{\dot{V}_{net}}{\sum_i Q_i} \tag{26}$$

Where:

$\dot{V}_{net}$ = Net System Flow Rate through the condenser and evaporator (in gpm).

$\dot{V}_{i,evaporator}$ = Flow Rate through the evaporator for each chiller (in gpm)

$\dot{V}_{i,\mathrm{CW\,pump}}$ = Flow Rate through each condenser water pump (in gpm)

$\dot{V}_{i,\mathrm{CHW\,pump}}$ = Flow Rate through each primary chilled water pump (in gpm)

$\dot{V}_{i,condenser}$ = Flow Rate through the condenser for each chiller (in gpm)

$p_{effective}$ (DOE-2 keyword: TWR-PUMP-HEAD) = Effective head for the system (in feet)

$p_{i,\mathrm{CW\,pump}}$ = Pump head for each condenser water pump

$p_{i,\mathrm{CHW\,pump}}$ = Pump head for each CHW pump

Q_i = Capacity of each chiller in tons

COMP-TO-TWR-WATER = DOE-2 Keyword to define flow (in gpm/ton)

Equations for Calculating Motor Efficiency and Impeller Efficiency for Combined Condenser Water Pump(s) and Primary Chilled Water Pump(s) as an Input for DOE-2.1e

Figure 39

$$\eta_{net\_motor} = \frac{\sum_i \left(\eta_{i,\,CW pump\,motor} \times \dot{V}_{i,\,CW pump}\right) + \sum_i \left(\eta_{i,\,CHW pump\,motor} \times \dot{V}_{i,}\right.}{\sum_i \left(\dot{V}_{i,\,CW pump}\right) + \sum_i \left(\dot{V}_{i,\,CHW pump}\right)} \quad (27)$$

$$\eta_{net\_imp} = \frac{\sum_i \left(\eta_{i,\,CW pump\,imp} \times \dot{V}_{i,\,CW pump}\right) + \sum_i \left(\eta_{i,\,CHW pump\,imp} \times \dot{V}_{i}\right.}{\sum_i \left(\dot{V}_{i,\,CW pump}\right) + \sum_i \left(\dot{V}_{i,\,CHW pump}\right)} \quad (28)$$

Where:

$\eta_{net,\,motor}$ = net motor efficiency (DOE-2 keyword TWR-MOTOR-EFF)

$\eta_{net,\,impeller}$ = net impeller efficiency (DOE-2 keyword TWR-IMPELLER-EFF)

$\eta_{i,\,CW\,pump\,imp}$ = condenser water pump motor efficiency for each pump

$\eta_{i,\,CW\,pump\,imp}$ = condenser water pump impeller efficiency for each pump

$\eta_{i,\,CHW\,pump\,motor}$ = primary chilled water pump motor efficiency for each pump

$\eta_{i,\,CHW\,pump\,imp}$ = primary chilled water pump impeller efficiency for each pump

DOE-2.1e Primary/Secondary Chilled Water System with Variable Flow to Chilled Water Coils

Figure 40

```
PLANT-PARAMETERS
$Chilled Water Primary/Secondary CHW Pumps
$ Primary CHW Pumps + CDW Pumps - Constant Speed (Condenser pump includes a weighted
$average including all the primary chilled water pumps and all condenser pumps)
    TWR-PUMP-HEAD = 10                 $ uses value for effective head described above
    TWR-IMPELLER-EFF = 0.77            $ net impeller efficiency
    TWR-MOTOR-EFF = 0.9                $ net motor efficiency
$Compression chiller('s) condenser and evaporator water flow in units of gpm/ton.
    COMP-TO-TWR-WTR = 5.4
$ Secondary CHW Pumps - Variable Speed
    CCIRC-PUMP-TYPE = VARIABLE-SPEED   $ defines secondary flow as variable speed;
    CCIRC-MIN-PLR = 0.300              $ For VSD Pumps, Minimum electricity
                                       $consumption as fraction of full-load consumption
    CCIRC-HEAD = 70                    $ Defines the head pressure of the secondary CHW loop
    CCIRC-IMPELLER-EFF = .75           $ Secondary CHW pump(s) impeller efficiency
    CCIRC-MOTOR-EFF = .90              $ Secondary CHW pump(s) motor efficiency
$ Other Plant Parameters not shown     ..
```

- Right-click the **Project** icon in the **Waterside HVAC** module, and then select **Create Pump.** Assign a name to the pump, and then select **Create from Scratch**. Enter the appropriate data for the primary pump(s) in the resulting pop-up window. Use caution to leave the pump capacity control as One-Speed Pump.
- Right-click the **Project** icon again, and then click **Create Circulation Loop**. Assign a name to the loop, and select **Create from Scratch**. Select **Circulation Loop Type** as **Chilled Water**. Enter the appropriate data for the primary chilled water loop in the resulting pop-up window. Select **Loop Pump** as the primary pump(s) just created.
- Double-click each chiller and change the **Loop Assignment** for CHW to the primary chiller loop created in the previous step.
- Double-click the **Secondary Loop** and set **Loop Subtype** to **Secondary**. Select the **Primary Chilled Water Loop** as the **Attached Primary Loop**, and then set **Head Setpoint Control** to **Fixed** or **Valve-Reset,** depending on the actual controls scheme that will be used in the building. In the resulting pop-up window, keep Valve-Type as Three Way, and enter any other pertinent information.

eQuest Detailed Interface for Primary/Secondary Chilled Water Loop

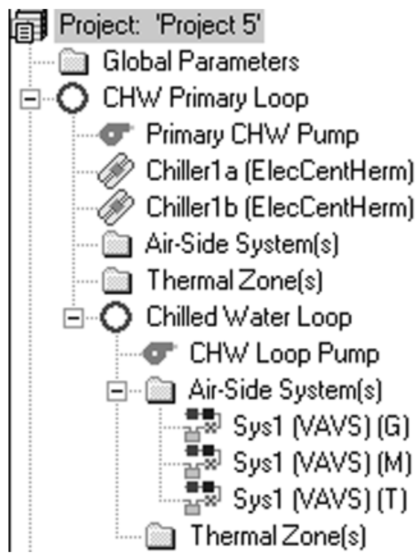


FIGURE 41: FINAL APPEARANCE OF PRIMARY/SECONDARY CHILLED WATER LOOP IN EQUEST DETAILED INTERFACE.

To create new pumps, or a new chilled water circulation loop in eQuest, right-click on the Project icon and select the appropriate icon.

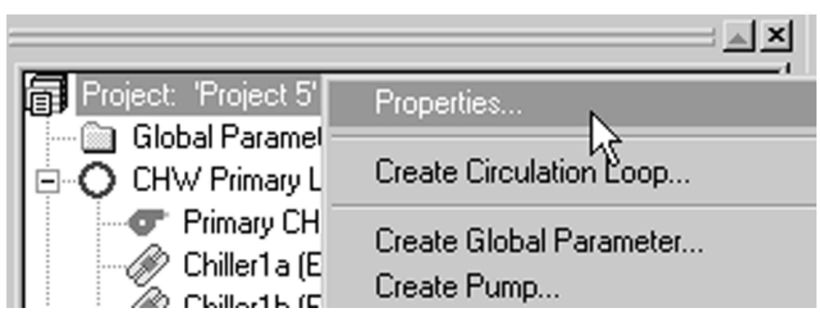


FIGURE 42

EQUEST provides an even simpler approach for modeling primary/secondary chilled water distribution in cases where the primary loop is served by only one chiller:

- From the **Cooling Primary Equipment** screen, select a pump configuration of **Both System** and **Chiller Pumps**.
- Set the **CHW Loop Flow** as Variable and **Pump Control** for the loop as **VSD**.
- Leave the pump control under the chiller as **Single Speed**.

Using this primary/secondary configuration, the pump that is attached to the chiller will cycle with the chiller during low loads. If this is not the way that the primary/secondary pumps will actually be controlled, the first option for modeling primary/secondary CHW pump configuration should be used.

Cautions for Modeling Variable-Speed Pumps and Variable-Chilled Water Flow in eQUEST

When energy modelers make their chilled water pumping selections within the eQUEST wizard, eQUEST provides reasonable assumptions regarding valve type and estimated chilled water flow. However, energy analysts who use **Detailed Edit Mode** to change flow configurations from constant to variable flow often make the following errors:

- CHW valve-types on air handling units are not modified to reflect variable flow. Energy savings for variable-flow CHW systems hinge on the inclusion of two-way chilled water valves in most, if not all of the air-handling units. If the valves are left as three-way valves, the chilled water flow remains constant, and VSDs on the pumps will have no impact on system performance.
- CHW flow for the comparison system is incorrectly sized using coincident peak flow. When performing a variable-flow analysis for Title-24 or Savings by Design, energy analysts should (a) model the base case with variable flow (i.e., two-way CHW valves on the air-handling units) and constant speed pumps; and (b) model the proposed case with variable-flow and variable-speed pumps. This ensures that the chilled water flow is sized based on the non-coincident peak flow rather than the sum of the peak flows through the air-handling units' chilled water coils.

Primary/Secondary pumping configuration with a single chiller defined in the eQuest wizard

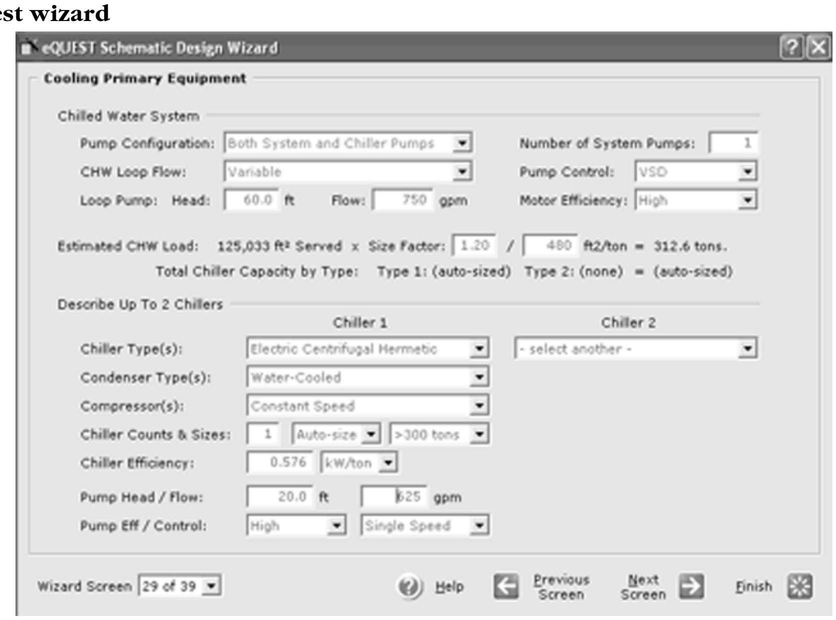


Figure 43

Variable Flow Condenser Water System

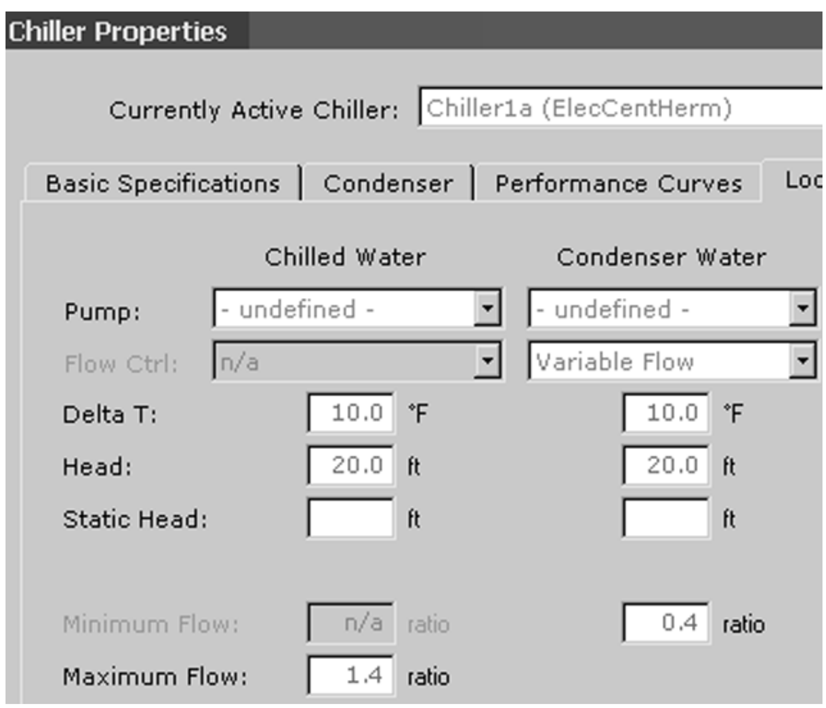
DOE-2.1e-based programs such as EnergyPro do not provide a means for effectively modeling variable-condenser water flow. Energy modelers can evaluate the impact of variable speed-condenser water flow control on building performance by using VSD manufacturer's software to calculate the annual energy consumption associated with variable speed versus constant speed-condenser water pumps, and integrating these values into the energy model outputs during post-processing of the results. However, the California Energy Commission has not approved this approach for demonstrating compliance with Title-24 standards.

In eQUEST, variable-condenser water flow is modeled in **Detailed Data Edit Mode** as follows:[29]

- When all wizard data has been finalized, select **Mode /Detailed Data Edit**.
- From the **Water-Side HVAC** module, select the condenser water loop pump(s) from the condenser water loop.
- Set **Capacity Control** as **Variable Speed Pump**, and then enter the appropriate data for the minimum speed of the pump.
- Select each chiller served by the condenser water loop. From the **Loop Attachments** tab, set **Condenser Water Flow Control** as **Variable Flow**. Select the **Minimum Condenser Water Flow**, defined as the "minimum allowable fraction of the design flow through the condenser," as specified in the control sequences. This minimum flow should be sufficiently high to maintain turbulent flow through the condenser.

Variable Condenser Flow defined in eQuest

FIGURE 44



[29] Variable condenser water flow can only be defined in recent versions of eQuest.

Although the variable condenser water flow strategies discussed above will generally improve the efficient operation of the chilled water plant, this strategy typically affords the greatest benefit when used with other condenser water system control strategies. The following section of the simulation guidebook discusses modeling techniques for three additional condenser water system control strategies:

- Cooling tower cell control
- Cooling tower capacity control
- Condenser water temperature reset

Cooling Tower Cell Control

Central plant designs specifying multiple cooling towers or multi-cell cooling towers can capitalize on the energy savings associated with variable speed tower fans by implementing control sequences to operate the maximum possible number of cells at any given time. In the Max Cells sequence, the control system enables the greatest number of cells that can operate above their specified minimum flow ratios at a given time, and spreads the load equally across these cells. Cooling tower applications designed to provide very low flow will see the greatest energy savings from Max Cells controls.

In EnergyPro, the software hard-codes the Max Cells option into the DOE-2 input file whenever multiple cell cooling towers are defined. In DOE-2.1e, cooling tower cell control can be defined under plant parameters by changing TWR-CELL-CTRL from MIN-CELLS to MAX-CELLS. The energy modeler should also check DOE-2 inputs for minimum part load ratios to confirm that they match the ratios defined in the system control sequences. In eQUEST, multi-cell cooling towers and cooling tower cell control sequences should be selected from the **Detailed Data Edit** mode as follows:

- Double-click the **Cooling Tower** icon in the **Water-Side HVAC** module. Enter the total number of cooling tower cells shown in the plans.
- Set **Cell Control** as **Maximum Cells**. Define the cell minimum flow as the smallest ratio of flow compared against the nominal flow for which each cell can operate.

Cooling Tower Capacity Control

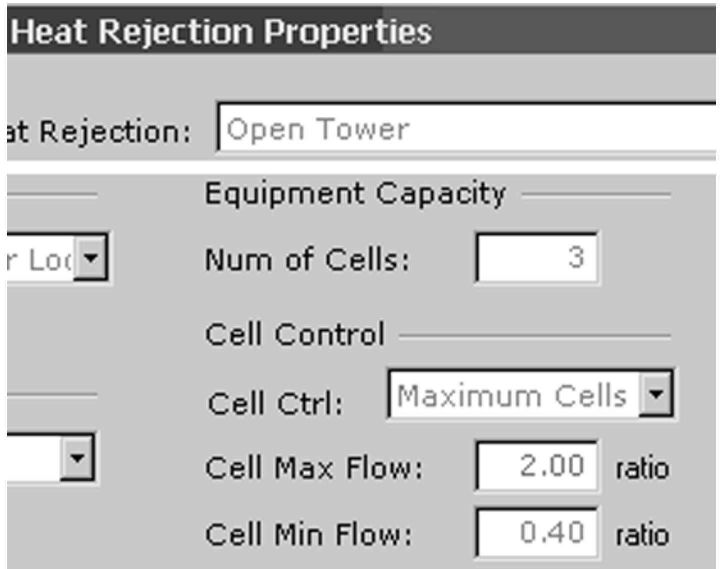
Cooling tower capacity control describes the method used for regulating the exit temperature for the water leaving the cooling tower. The four options most commonly seen in existing and new buildings include:[30]

- **Fluid Bypass**: a three-way valve bypasses water around the cooling tower, modulating as needed to maintain capacity. This is the least efficient control option, since cooling tower fans run continuously.

[30] A full description of each cooling tower fan capacity control keyword is included in EnergyPro, DOE-2.1e and eQuest documentation.

eQuest Detailed Edit mode input for maximum cell control

FIGURE 45

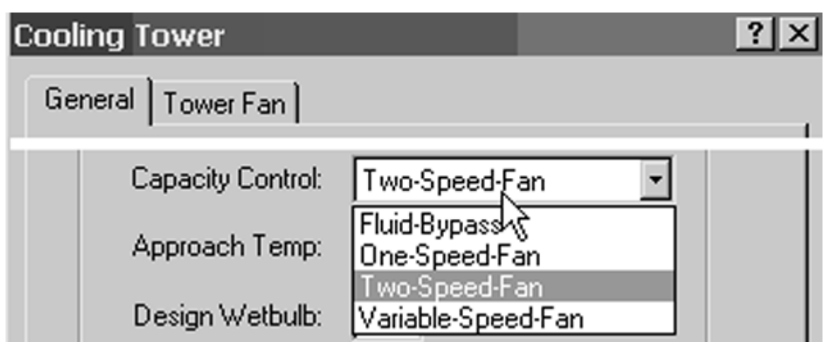


- **One-Speed Fan**: the fan cycles on and off to maintain the set-point temperature.
- **Two-Speed Fan:** the fan cycles between Off, Low-Speed, and High-Speed to regulate the exit water temperature.
- **Variable-Speed Fan:** a variable-speed drive controls fan speed, so that the heat rejection capacity exactly matches the load at the desired set-point. This is the most efficient option, and generally reduces wear and tear on the fan motor associated with one or two-speed fan operation.

In EnergyPro, the energy modeler can identify fan capacity control as follows:

Cooling Tower Capacity Control Selections in EnergyPro

FIGURE 46



- From the **Plant / Chilled Water** tab, double-click the cooling tower icon. A water-cooled chiller must be defined on the **Chilled Water** tab before the cooling tower icon will appear.
- Click **Cooling Tower** in the pop-up window, and then select an existing tower to edit, or create a new cooling tower. Select the capacity control to match the controls shown on the plans.

In DOE-2.1e, energy modelers can define cooling tower capacity in the PLANT-ASSIGNMENT section as follows:

- TWR-CAP-CTRL to FLUID-BYPASS, ONE-SPEED-FAN, TWO-SPEED-FAN, or VARIABLE-SPEED-FAN as defined in the plans.
- For two-speed fan control, enter the air flow ratio and fan power ratio for the low-speed setting as defined in equations 29 and 30:

$$TWR-FAN-LOW-CFM = \frac{\text{Fan CFM at low speed}}{\text{Fan CFM at high speed}} \quad (29)$$

$$TWR-FAN-LOW-ELEC = \frac{\text{Fan power at low speed}}{\text{Fan power at high speed}} \quad (30)$$

- For variable-speed fan control, use the DOE-2 keyword TWR-MIN-FAN-SPEED to enter the minimum fraction of nominal fan speed at which the fan can operate.

eQuest Detailed Edit Mode Inputs Associated with Variable Speed Fan Control

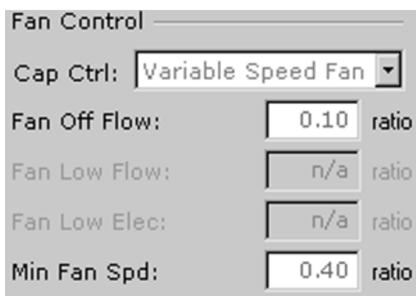


FIGURE 47

eQUEST includes fan capacity control selections from the Heat Rejection screen of the wizard. When wizard selections indicate two-speed or variable speed control, eQUEST generates default assumptions for minimum fan speed and power. The **Detailed Data Edit** mode allows the option for modifying these assumptions in the **Water-Side HVAC** module:

- For variable speed fan control, the **Min Fan Speed** represents the minimum fraction of fan speed where the fan can operate.
- Two-speed fan control, **Fan Low Flow** and **Fan Low Elec** are defined according to equations 29 and 30, respectively.

Condenser Water Temperature Reset

Chillers operate most efficiently when at low lift conditions where the differential between chilled water supply temperature and entering condenser water temperature reaches its minimum. Therefore, reducing condenser water supply temperatures at chiller part-load conditions results in demonstrable compressor energy savings. The condenser water reset strategies simulated in DOE-2.1e-based programs are limited to wetbulb temperature reset control, which reduces condenser water set point temperatures based on outside air wetbulb temperatures. This strategy rarely results in substantial energy savings. In contrast, a reset control that varies the cooling tower fan speed based on chiller load allows the leaving condenser water temperature to float with both wetbulb temperature and chiller load, producing sizable chiller energy savings. To demonstrate the energy benefit of condenser water load reset controls in EnergyPro or other DOE-2.1e-based programs, energy modelers can perform a separate analysis of these controls, and then integrate their findings into the DOE-2 results during post-processing of the models. However, the California Energy Commission has not approved this modeling approach for documenting Title-24 compliance.

Modeling Condenser Water Load Reset in eQUEST

eQUEST lets energy modelers select condenser water load reset and further refine the assumptions for load reset controls in the **Detailed Edit Mode**:

- From the **Primary Heat Rejection** screen, set **Temperature Control** as **Reset**, identify the **Minimum Condenser Water** temperature as defined in the control sequences, and then select the appropriate option for **Cooling Tower Fan Capacity** control. The system design must specify **Two-Speed** or **Variable-Speed** cooling tower fans for the load reset control strategy to function properly.
- When the project design employs condenser water load reset controls in conjunction with variable-condenser water flow, adjust inputs for minimum reset part-load ratio and maximum reset speed to reflect the actual control sequences defined in the system. From the **Detailed Data Edit** mode, double-click the cooling tower, and then specify the **Min Reset PLR** as the minimum part load of the fan at which the minimum condenser water flow occurs. Also define the **Max Reset Speed** as the maximum speed of the cooling tower fan during load reset operation.

eQuest Detailed Edit Mode Inputs Associated with Condenser Water Systems

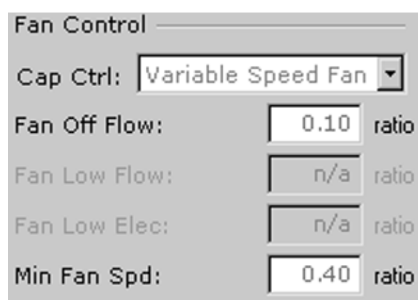


Figure 48: Enter the information shown in this graphic when both condenser water load reset and variable condenser water flow are implemented into the project design.

If implemented carefully, chilled water (CHW) temperature reset controls can reduce chiller energy usage as well as the losses associated with chilled water distribution by increasing the chilled water supply temperature set-point with decreasing load. The mechanical engineer should carefully examine chiller constraints when identifying the appropriate CHW reset schedule, since optimum efficiencies for different chillers can vary greatly for any given CHW temperature, CW temperature, and percentage load conditions. For example, constant speed centrifugal chillers reach maximum efficiencies when loaded to greater than 80%, while the same chiller model equipped with a VSD performs best at 30-50% load with a relatively high chilled water temperature. A chilled water temperature control strategy for the constant speed chiller would have a very low reset range, whereas the variable-speed chiller may have a reset temperature range of greater than 10ºF. For variable-flow chilled water loops, the design team must also be careful to optimize the chilled water flow and temperature reset controls to minimize combined chiller and CHW pump energy usage. EnergyPro does not provide a means for modeling chilled water temperature reset controls directly in the program interface. However, by modifying the input file generated from EnergyPro, and running the simulation directly in DOE-2.1e, the energy modeler can simulate the approximate impact of this strategy on building performance. The temperature range for chilled water reset control is defined in DOE-2.1e using the keyword CHILL-WTR-THROTTLE. To increase the chilled water temperature with decreasing load, a negative value must be entered for this keyword. For example, to specify a reset temperature range of 10ºF, the CHILL-WTR-THROTTLE should be -10ºF. While this modeling strategy loosely represents chilled water reset controls, the DOE-2 simulation results for this strategy are not exact.

Defining Chilled Water Temperature Reset in eQUEST

The eQUEST wizard interface provides a simple method for defining chilled water reset controls from the Chilled Water System Control and Schedule screen:

- Set **Setpoint** as **Reset.**
- Enter the appropriate values for **CHW Minimum** and **CHW Maximum** temperatures.
- When the chilled water circulation loop is a variable-flow loop, the loop flow reset should also be defined as follows:
  - From the **Detailed Data Edit** mode, double-click the chilled water circulation loop in the **water-side HVAC** module.
  - Select the **Controls** tab from the pop-up window, and then set the appropriate **Loop-Flow Reset.** The chilled water reset control sequence should use **Variable-Speed Pump** controls to limit the flow to the percentage defined for loop-flow-reset, and then hold the water flow constant while implementing the CHW reset control strategies.

eQuest Wizard Inputs for CHW Temperature Reset Controls

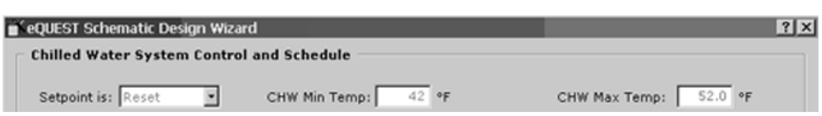


Figure 49

Hot Water Loop Temperature Reset

Hot Water (HHW) temperature reset controls generally reduce boiler energy usage and distribution losses by decreasing the hot water supply temperature set-point with decreasing load. Hot water reset control strategies cannot be modeled directly in DOE-2.1e or EnergyPro. However, in eQUEST, hot water reset is modeled similarly to chilled water reset; the energy modeler can select **Reset Control** from the **Hot Water System Control** and **Schedule** screen of the eQUEST wizard. For variable-flow loops, the energy modeler can enter data in Detailed Data Edit mode to define the loop flow reset ratio for the pumps, where hot water flow will be held constant as the hot water reset control strategy takes effect.

eQuest Wizard Inputs for HHW Temperature Reset Controls

Figure 50