# Lessons Learned from 15 years of Refrigerated Facility Simulation

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**ASHRAE Annual Conference**
**Louisville, Kentucky**
**June 23, 2009**

# Topics

- **Simulation tool background**
- **California new construction incentive program**
- **Lessons learned**
- **Incremental analysis case study**
- **Simulation limitations and challenges**

# Simulation tool background

- **1993 – need for refrigeration simulation tool:**
  - Supermarket emphasis (space/fixture interaction)
  - Address “component” based refrigeration systems
- **Funding by CA utilities and others**
- **Completed in 1998 as DOE2.2R**
- **Key aspects for refrigeration analysis:**
  - Mass flow based to allow component-level study
  - Built-in explicit control strategies
  - Detailed display case model
- **Plus: building envelope, HVAC, lighting**

# Key attributes for supermarkets

- **Balance between HVAC systems, fixtures, infiltration, ventilation air and controls**
- **Disaggregated display case loads:**
  - Transmission from space
  - Air exchange with space (sensible and latent)
  - Fan, lights, heaters with schedules and controls
  - Defrost heat, recovery over time
- **Detailed refrigeration system modeling**
- **Heat recovery from refrigeration**
  - Controls for holdback valves, various strategies

# Key attributes for warehouses

- **Mass-flow based system modeling:**
  - Two stage systems (and cascade HX)
  - Subcooling, desuperheating
- **Part-load controls and group staging controls**
- **Controls match common efficiency measures:**
  - Ambient reset, variable speed condenser control
  - Variable speed air unit controls
  - Floating suction controls
- **Infiltration and inter-zonal mass exchange:**
  - Density driven air exchange (ASHRAE formulas)
  - Wind driven air entry

# California new construction program

- **Savings By Design:**
  - Statewide incentive program for efficient new construction funded by public goods charge and administered by four major utilities
  - Separate program for supermarkets and refrigerated warehouses, due to special analysis and base case for refrigeration systems
  - Savings and incentive based on improvement over Title 24 (lighting and HVAC) and standard practice for refrigeration systems
  - Emphasis on design assistance to support owner investment decisions
  - Very limited recommendations on system sizing

# New construction project delivery

- **2001-2008 refrigeration projects:**
  - Yearly energy savings: 230 million kWh
  - Peak demand reduction: 34,000 kW
  - Approx. annual savings: $28 million
- **320 retail food stores**
- **150 refrigerated warehouses & food plants**
- **Mandatory whole-facility simulation for all refrigeration projects**
- **Savings vs. Title 24 or defined standard practice**

- **Plus analysis of many existing facilities for retrofit**

# Example projects

- **Large new refrigerated warehouse projects:**
  - Grocery distribution complex, 2 million SF
  - Ice cream manufacturing and distribution facility
- **Diverse process plants:**
  - Dairies, wineries
  - Packaged salads
  - High tech mushroom production facility
  - Seasonal fruit and produce pre-cooling & storage
- **Retail food chain new prototype development**
- **Nationwide retail study (skylights, reclaim)**
- **Regional best practices & economics analysis**

# Refrigeration base case definitions

- **Lack of code required a “standard practice” basis**
- **Base case definitions were developed for:**
  - Warehouse insulation
  - Condenser size (approach)
  - Specific efficiency method and standards for condenser power (condenser fan/pump Btuh/Watt)
  - Minimum condensing temperature setpoint
- **Considerable flexibility in compressor & system type, with efficiency vs. associated base case**
- **Use *either* air-cooled or evap-cooled as base case against which efficient options are evaluated**

# Typical supermarket measures

- **Lighting**
  - Lighting power density, skylights, controls
- **Refrigeration**
  - Condenser sizing, specific efficiency (low fan power)
  - Floating head pressure with variable speed drives, variable setpoint control
  - Mechanical subcooling
  - Floating suction pressure
  - Efficient evaporator coil motors
- **HVAC**
  - High EER package units
  - Variable speed drives for air handler motors
  - Heat recovery from refrigeration
- **Display fixtures**
  - Efficient case fan motors
  - Efficient lighting (LED lights)
  - Lighting control
  - Anti-sweat heater control

# Industrial refrigeration measures

- **Increased insulation, cool roof, high speed doors**
- **Refrigeration systems:**
  - Condensers, increased size and reduced fan power
  - Floating head with variable speed & setpoint
  - Variable speed control of air unit fan motors
  - Variable speed compressor control
  - Other system automation
- **Other specialized measures:**
  - Close approach HX (e.g. pasteurization regen)
  - Cool-recovery process water heat exchangers
  - Refrigeration heat recovery

# Evolving base case standards

- **As technology evolved and adoption increased, base case assumptions changed**
- **Supermarkets changes (03 to 09):**
  - Standard anti-sweat heater control
  - Standard EC motors in cases
  - Standard PSC then EC motors in walk-ins
  - Reduced minimum head pressure setpoint
  - Lower light level, mandatory skylights
- **Refrigerated warehouses changes (09):**
  - Condenser variable speed/floating head pressure
  - Air unit variable speed
  - Compressor variable speed (certain conditions)

# Lessons learned

- **Timing drives analysis focus**
- **A lot of discussion about “loads”**
- **Results from simulation work opens useful discussion concerning:**
  - Design vs. actual loads
  - Facility design basis
  - Component performance
  - Cost effectiveness
  - How systems really operate
  - Control strategies & capabilities
  - Equipment sizing
  - Vendor interactions
- **Simulation results drive interest in field studies**
- **Decision making process *(i.e. business decisions are financial decisions)***

# Timing impacts study focus

- **Early involvement:**
  - Fundamental concepts
  - Help define loads and expectations
  - Building shape and orientation (e.g. high rise)
  - Refrigerant choices and system types
- **Late involvement:**
  - Bolt-on improvements
  - Control strategies and setpoints
- **Chains with specification process:**
  - Continuous improvement – studies apply to future
  - Ongoing review of current design choices

# Lessons – Warehouses loads

- **Consistent large gap between system design capacity and peak simulation loads:**
  - Some obvious (40% floor load in large cooler)
  - Common rule-of-thumb and “last job” sizing
  - Simulation only as good as inputs
    - Some elements are guesstimates for design *and* simulation
  - Equipment catalog vs. “real world” variance
  - Need capacity for expansion, outages, aging
- **Loads difference resulted in study efforts:**
  - Field measurements and studies
  - Installation of real-time performance monitoring

# Lessons – Equipment performance

- **Air units often don’t perform as expected:**
  - New air units not reducing TD at lower loads
  - Old air units running 50-100% higher than design TD at design loads
- **Condensers often don’t perform as expected:**
  - Higher TD at part load/off-design than calculated on large evaporative condensers
  - Supermarket condensers frequently impacted by piping practice (excessive backflooding and cycling effects), may operate at double expected TD
- **Small system details can have very big impact (e.g. suction regulators and big capacity steps)**

# Produce facility example

- **Simulation studies for produce facilities showed fan power and associated cooling as an unexpectedly large fraction of energy use**
- **Field study undertaken at four locations to measure cooling load and fan power vs. total refrigeration power**
  - All locations pre-cool and store similar fruit
  - All have seasonal operations
  - Similarly designed ammonia refrigeration systems
  - Four month study – July through October

# Produce facility example

- **Comparison of seasonal fan power, including fan heat load on compressors for four locations through cooling season**

| Location | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Compressor HP | 825 | 675 | 1,035 | 510 |
| Capacity, Tons | 900 | 713 | 875 | 414 |
| Peak Load, Tons | 495 | 540 | 525 | 327 |
| Total fan kWh | 550,800 | 150,700 | 287,300 | 177,200 |
| Fans % of cooling load | 22.0% | 16.6% | 29.9% | 17.6% |
| Fans % of total kWh (1) | 46.6% | 35.7% | 52.8% | 41.9% |

(1) Including kWh for cooling load on compressors

- **Study preceded the wide adoption of variable speed fan controls in produce cooling facilities**

# Lessons – Supermarkets

- **HVAC system operation:**
  - Cooling hours are very low peak load annual frequently less than half or third of installed tonnage
    - Subsequently verified with history collection
  - Heat reclaim evaluated extensively, typically small electricity impact for large gas savings
- **HVAC interaction with refrigeration:**
  - Difficult to achieve refrigeration savings with lower humidity via HVAC system (reheat is not free)
- **Increased insulation seldom pays (in CA anyway):**
  - Supermarket is heating majority of the year
  - Use less insulation and invest capital elsewhere …

# Lessons – Supermarkets

- **Findings contrary to expectations:**
  - No savings from floating head pressure on systems with low efficiency condensers and fan cycling in moderate CA climates
  - Low fan power condensers have poor economics compared with average power condensers plus variable speed and variable setpoint control
  - No savings on condensers larger than 10/15 F TD
- **Air-cooled condenser motor efficiency:**
  - Direct drive condenser motor input power typically is not published and is often not related to referenced horsepower

# Lessons – Field verifications

- **Utility program field verifications provided observations to compare with analysis results:**
  - Skylight savings often far less than theoretical savings due to control variations
  - Control operation often very different than simulation – fast response from feedback control even though load changes slowly
  - Sensor error can have large impact on efficiency; easy for humidity sensor drift to cause simultaneous heating and cooling with no dehumidification

# Financial presentation

- **Simulation inherently resolves system interactions, allowing marginal analysis**
- **Most savings are not additive:**
  - 15% + 15% + 15% + 15% = 60% savings (??)
  - 0.85 x 0.85 x 0.85 x 0.85 = 0.52 = 48% (at best)
- **Two methods for presenting economics:**
  - Combinations of measures
  - Incremental comparison
- **Incremental savings – what to start with?**
  - Simplest technology?
  - Fastest payback?

# Financial presentation

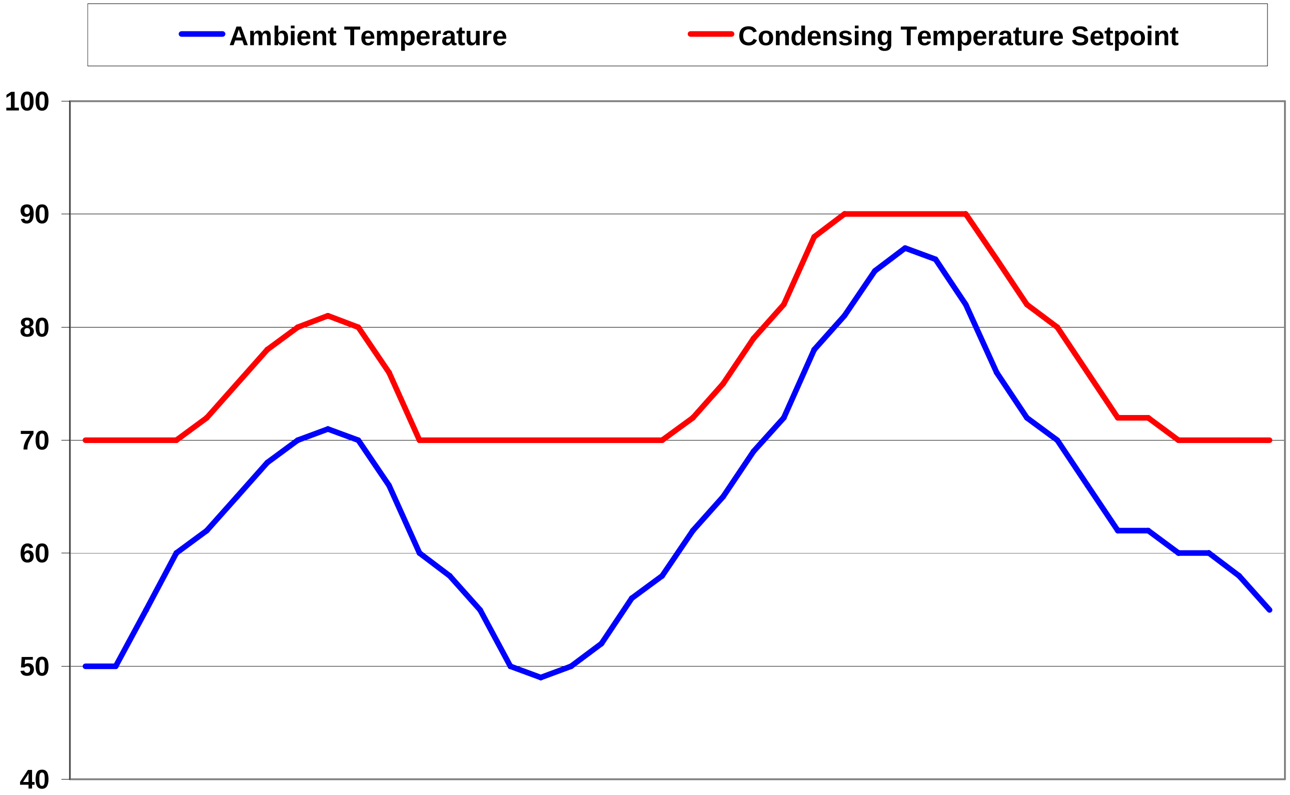
- **Examples of Combinations of Measures:**
  - Combination 1: Measures A, B, C and D
  - Combination 2: Measures A, B and D
  - This presents to choices, typically better when measures must be designed as one combination or another.
- **Example of Incremental Comparison:**
  - Measure A
  - Measure A and B
  - Incremental Savings of B – A
  - Measure A, B and C
  - Incremental Savings of C – (A and B)

# Incremental savings: FHP case study

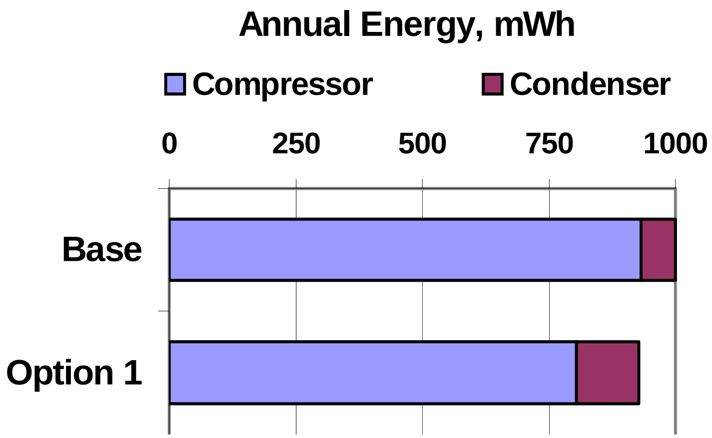
- **Cold storage warehouse in Stockton, CA**
- **Evaporative condenser (average efficiency)**
- **Hourly simulation analysis**
- **Base case = fixed setpoint at 85 F SCT**
- **Analysis options**
  - Float SCT using fixed setpoint
  - Add variable setpoint
  - Add variable speed with fixed setpoint
  - Add variable speed with variable setpoint

- **Results show importance of control strategy**

# Variable setpoint floating head

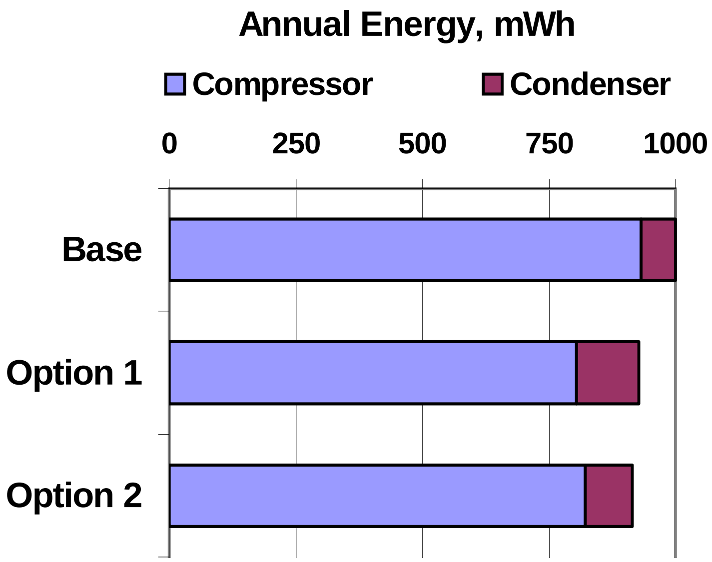


# Fixed setpoint



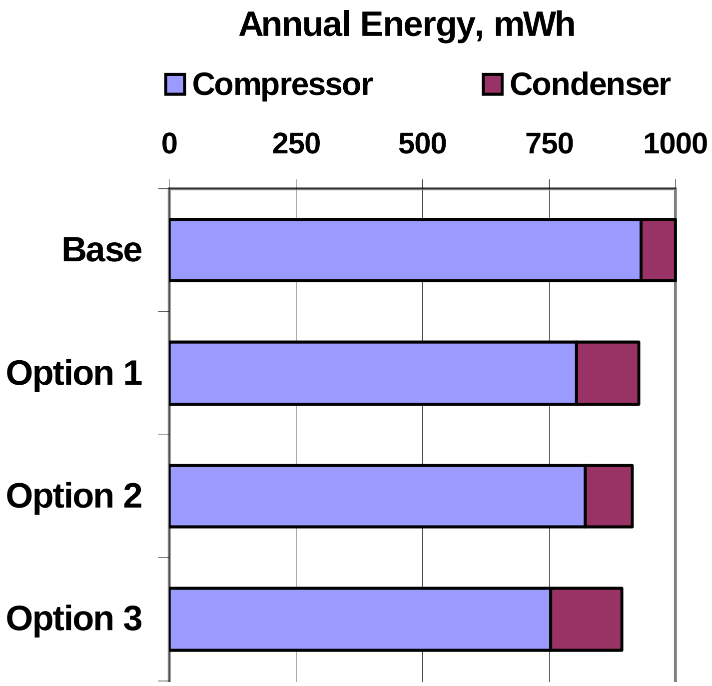
| Control Options | | | | | | |
|---|---|---|---|---|---|---|
| FHP | FSP | VSP | VFD | Savings | Payback | NPV |
| X | X | | | $ 6,400 | 0.3 | $ 63,500 |

# Variable setpoint



| | Control Options | | | | | | |
|---|---|---|---|---|---|---|---|
| | FHP | FSP | VSP | VFD | Savings | Payback | NPV |
| | X | X | | | $ 6,400 | 0.3 | $ 63,500 |
| | X | | X | | $ 8,400 | 0.6 | $ 80,300 |

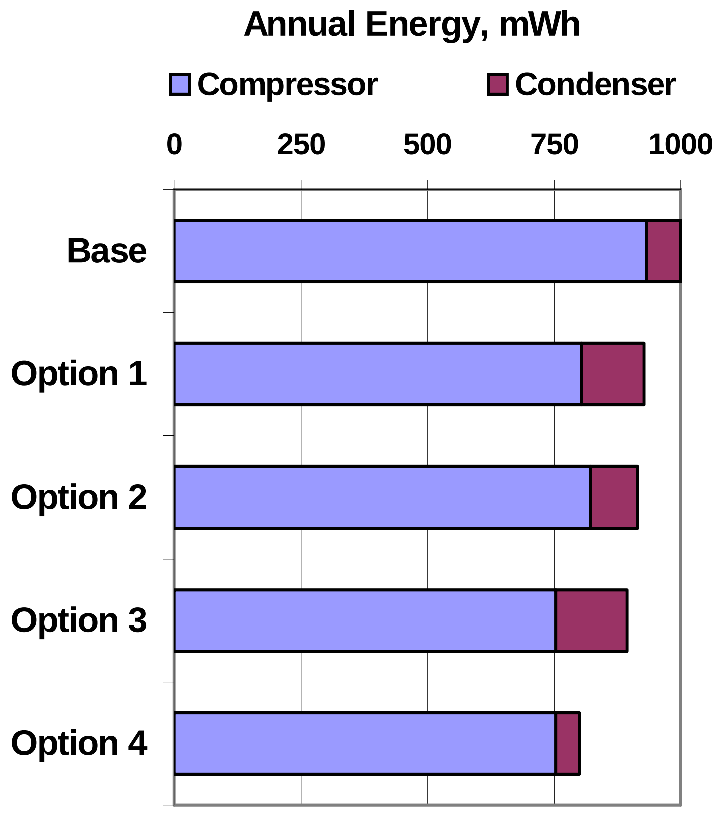
# Fixed setpoint and variable speed



**Control Options**

| | FHP | FSP | VSP | VFD | Savings | Payback | NPV |
|---|---|---|---|---|---|---|---|
| Option 1 | X | X | | | $ 6,400 | 0.3 | $ 63,500 |
| Option 2 | X | | X | | $ 8,400 | 0.6 | $ 80,300 |
| Option 3 | X | X | | X | $ 9,100 | 4.4 | $ 52,900 |

# Variable setpoint and variable speed



| Control Options | | | | | | |
|---|---|---|---|---|---|---|
| FHP | FSP | VSP | VFD | Savings | Payback | NPV |
| X | X | | | $ 6,400 | 0.3 | $ 63,500 |
| X | | X | | $ 8,400 | 0.6 | $ 80,300 |
| X | X | | X | $ 9,100 | 4.4 | $ 52,900 |
| X | | X | X | $ 21,600 | 2.1 | $175,300 |

# Simulation limitations & challenges

- **Inherent difference in simulation and real control:**
  - Simulation assumes “perfect” control operation that matches load requirements
  - Standard feedback controls react quickly even though underlying loads may change very slowly
- **Adjust simulation parameters for realistic results:**
  - Program speed overrides to address realistic temperature/speed control response, particularly related to “third-power” fan savings
  - Choose settings to address impact of transients, compressor cycling between stages, control valve effects

# Simulation limitations & challenges

- **Evaporative condenser ratings:**
  - Published capacity factor tables lack “average” conditions, simulation extrapolates
- **Air-cooled condenser ratings:**
  - Tables assume perfect Q=UATD at any TD and EAT. Questionable for simulation (and design)
- **Semi-hermetic compressor RGT rating:**
  - Return gas temperature based on 65 F, fully productive refrigeration
  - Correction factors are not published (electronic ratings allow other RGTs using simple density adjustment)

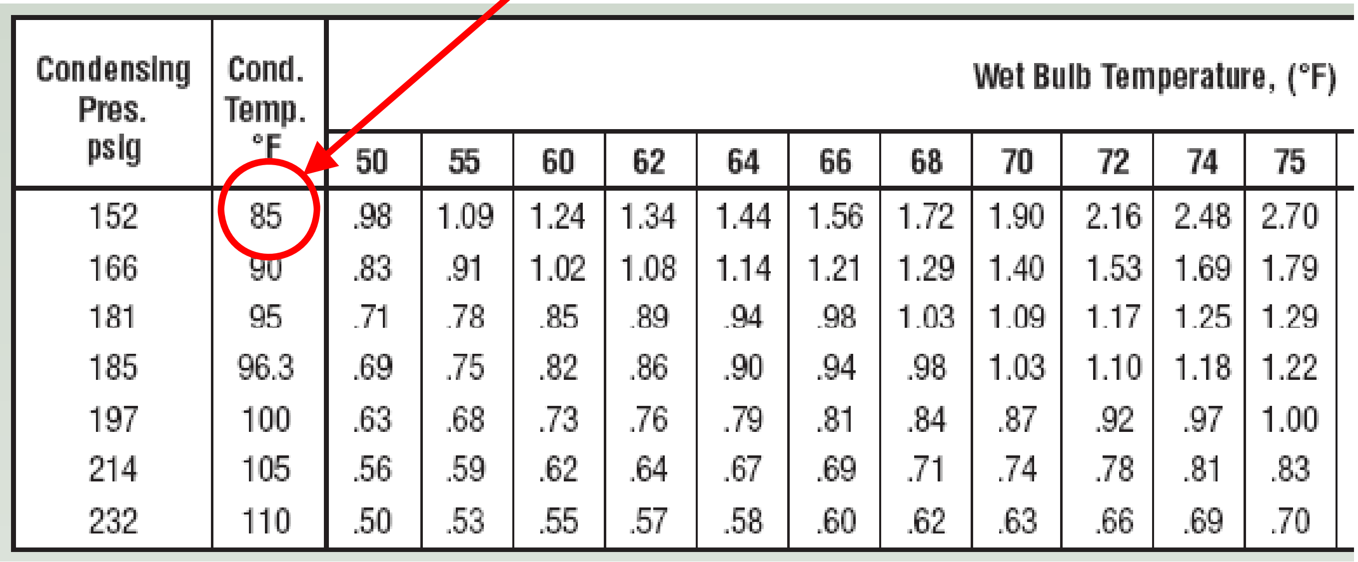
# Future improvements

- **Program features:**
  - Secondary cooling loops and heat exchangers
  - Refrigeration/HVAC water loop integration
  - Improved air unit model
- **Equipment information:**
  - Accurate motor watts for condensers and air units
  - Improved part-load/off-design performance data for air- and evap-cooled condensers
  - Adoption of rating standards and certification of equipment performance for refrigeration equipment
  - Refrigeration simulation inherently at component level, so need component performance data

# Improvements needed – equip info

## Example – evap condenser heat rejection factors

Lowest condensing temperature on chart is 85 F vs. typical operation at 70 F SCT or lower

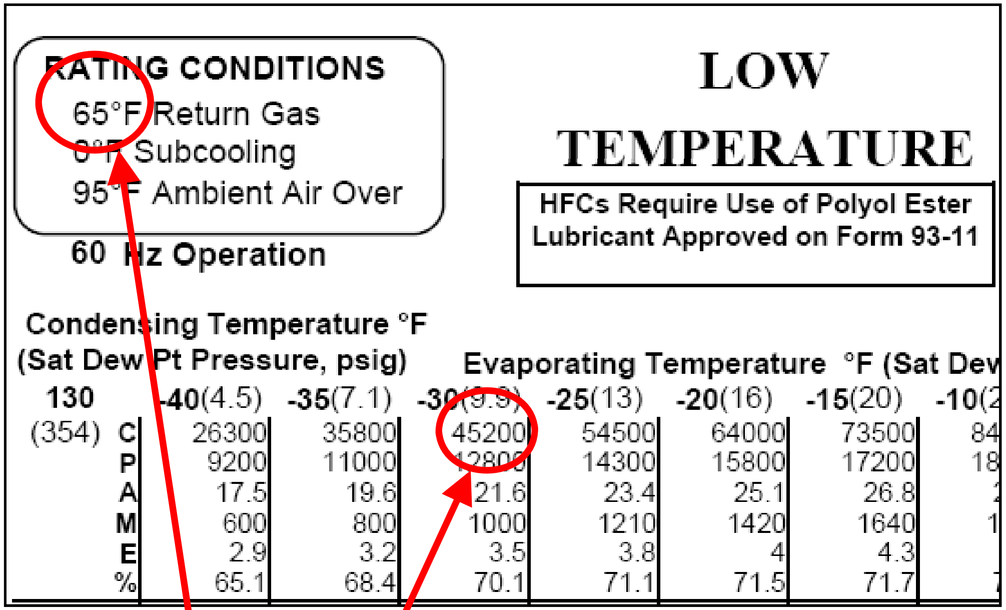


| Condensing Pres. psig | Cond. Temp. °F | Wet Bulb Temperature, (°F) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 50 | 55 | 60 | 62 | 64 | 66 | 68 | 70 | 72 | 74 | 75 |
| 152 | 85 | .98 | 1.09 | 1.24 | 1.34 | 1.44 | 1.56 | 1.72 | 1.90 | 2.16 | 2.48 | 2.70 |
| 166 | 90 | .83 | .91 | 1.02 | 1.08 | 1.14 | 1.21 | 1.29 | 1.40 | 1.53 | 1.69 | 1.79 |
| 181 | 95 | .71 | .78 | .85 | .89 | .94 | .98 | 1.03 | 1.09 | 1.17 | 1.25 | 1.29 |
| 185 | 96.3 | .69 | .75 | .82 | .86 | .90 | .94 | .98 | 1.03 | 1.10 | 1.18 | 1.22 |
| 197 | 100 | .63 | .68 | .73 | .76 | .79 | .81 | .84 | .87 | .92 | .97 | 1.00 |
| 214 | 105 | .56 | .59 | .62 | .64 | .67 | .69 | .71 | .74 | .78 | .81 | .83 |
| 232 | 110 | .50 | .53 | .55 | .57 | .58 | .60 | .62 | .63 | .66 | .69 | .70 |

**Adequate for peak design, but without extended ratings, energy analysis requires guesswork**

# Improvements needed – equip info

## Example: commercial refrigeration compressors



**RATING CONDITIONS**
65°F Return Gas
0°F Subcooling
95°F Ambient Air Over

**60 Hz Operation**

**LOW TEMPERATURE**

**HFCs Require Use of Polyol Ester Lubricant Approved on Form 93-11**

| **Condensing Temperature °F (Sat Dew Pt Pressure, psig)** | | Evaporating Temperature °F (Sat Dew | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **130** | | **-40**(4.5) | **-35**(7.1) | **-30**(9.9) | **-25**(13) | **-20**(16) | **-15**(20) | **-10**(2 |
| (354) | C | 26300 | 35800 | 45200 | 54500 | 64000 | 73500 | 84 |
| | P | 9200 | 11000 | 12800 | 14300 | 15800 | 17200 | 18 |
| | A | 17.5 | 19.6 | 21.6 | 23.4 | 25.1 | 26.8 | 2 |
| | M | 600 | 800 | 1000 | 1210 | 1420 | 1640 | 1 |
| | E | 2.9 | 3.2 | 3.5 | 3.8 | 4 | 4.3 | |
| | % | 65.1 | 68.4 | 70.1 | 71.1 | 71.5 | 71.7 | 7 |

Published Rating Conditions at 65° F RGT. Rated capacity includes all superheat from -30 ° F to 60° F.

- **Rated capacity at 130° F and -30° F including all superheat = 45.6 Btuh/Lb refrigerating effect (404A)**
- **At same mass flow, refrigerating effect with 10 F superheat is 28.8 Btuh/Lb, 37% less**
- **Mass flow would be higher with RGT lower than 65° F, but relevant data to allow analysis is not published**

# Conclusions

- Simulation is useful at early stages, but also effective to fine-tune control strategies and set performance expectations
- Essential to include experience and judgment in analysis assumptions, but also have to “follow” simulation results that may be counter-intuitive
- Essential to review intermediate results, system and hourly reports for sanity and consistency
- Moving perspective from peak design loads to hourly energy analysis is a challenge
- For many owners, accurate economics has become more important than incentives

# Questions?