



ASHRAE 09

Lessons Learned from 15 years of Refrigerated Facility Simulation

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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	How systems really operate
Facility design basis	Control strategies & capabilities
Component performance	Equipment sizing
Cost effectiveness	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 (??)
 - $0.85 \times 0.85 \times 0.85 \times 0.85 = 0.52 = 48\%$ (at best)
- **Two methods for presenting economics:**
 - Combinations of measures
 - Incremental comparison
- **Incremental savings – what to start with?**
 - Simplest technology?
 - Fastest payback?

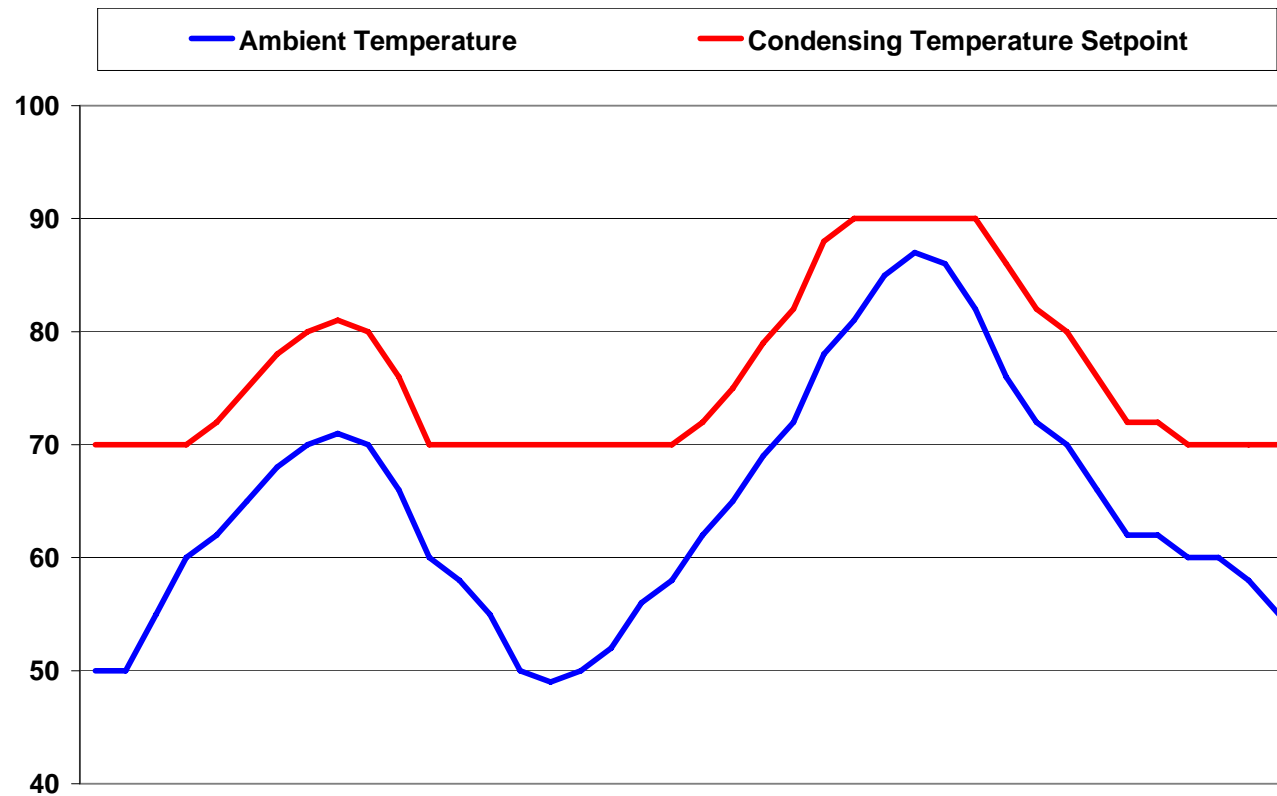
Financial presentation

- **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

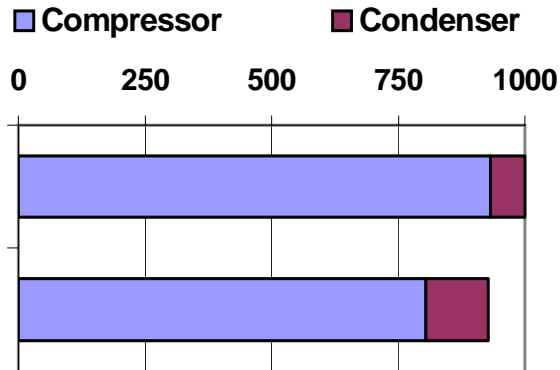
- **Cold storage warehouse in Stockton, CA**
- **Evaporative condenser (average efficiency)**
- **Hourly simulation analysis**
- **Base case = fixed setpoint at 85 F SCT**
- **Analysis options**
 - Float SCT using fixed setpoint
 - Add variable setpoint
 - Add variable speed with fixed setpoint
 - Add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

Variable setpoint floating head



Fixed setpoint

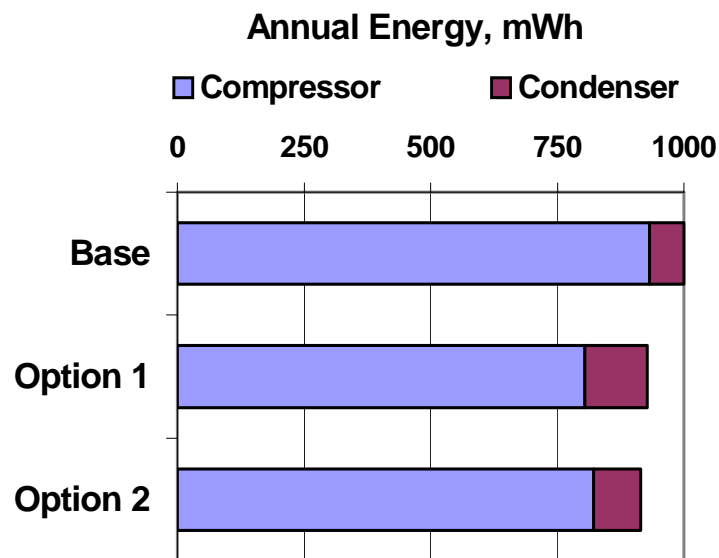
Annual Energy, mWh



Control Options

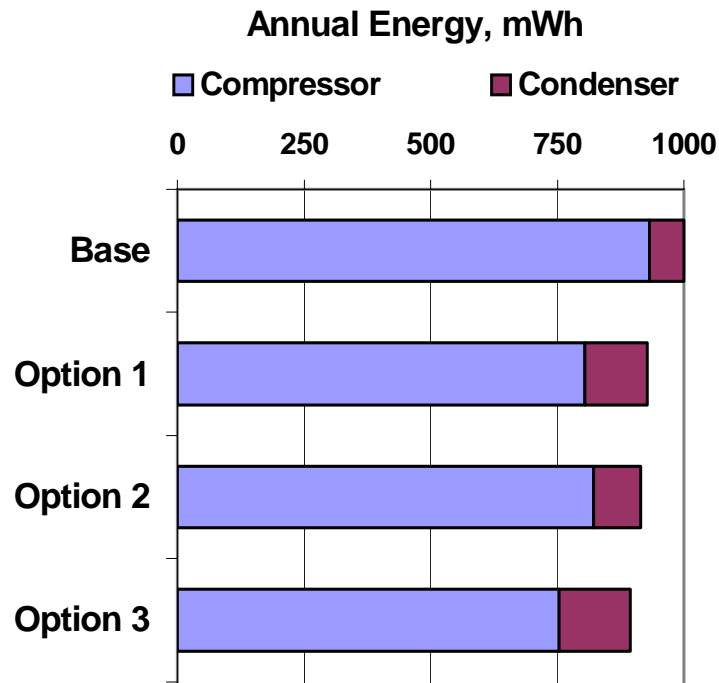
	FHP	FSP	VSP	VFD	Savings	Payback	NPV
Base							
Option 1	X	X			\$ 6,400	0.3	\$ 63,500

Variable setpoint



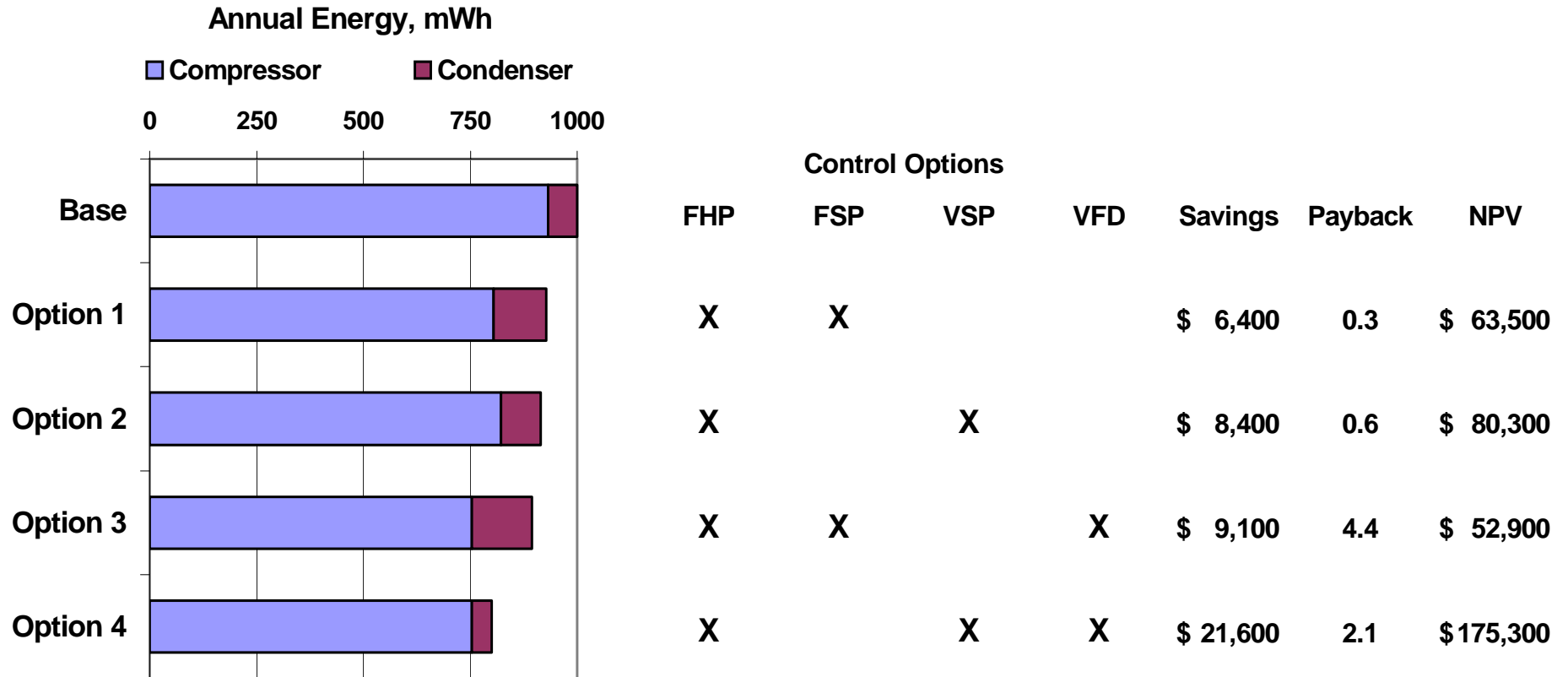
Control Options	Control Options				Savings	Payback	NPV
	FHP	FSP	VSP	VFD			
Base							
Option 1	X	X			\$ 6,400	0.3	\$ 63,500
Option 2	X		X		\$ 8,400	0.6	\$ 80,300

Fixed setpoint and variable speed



	Control Options				Savings	Payback	NPV
	FHP	FSP	VSP	VFD			
Base							
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



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		LOW TEMPERATURE						
65°F Return Gas		HFCs Require Use of Polyol Ester Lubricant Approved on Form 93-11						
8°F Subcooling								
95°F Ambient Air Over								
60 Hz Operation								
Condensing Temperature °F (Sat Dew Pt Pressure, psig)		Evaporating Temperature °F (Sat Dew Pt Pressure, psig)						
130 (354)	-40(4.5)	-35(7.1)	-30(9.9)	-25(13)	-20(16)	-15(20)	-10(24)	
C	26300	35800	45200	54500	64000	73500	84000	
P	9200	11000	12800	14300	15800	17200	18700	
A	17.5	19.6	21.6	23.4	25.1	26.8	28.4	
M	600	800	1000	1210	1420	1640	1870	
E	2.9	3.2	3.5	3.8	4	4.3	4.5	
%	65.1	68.4	70.1	71.1	71.5	71.7	71.8	

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?