Refrigeration Control for Operating Cost Reduction

ASHRAE 2007 Annual Meeting
Long Beach, California

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VaCom Technologies

Topics

- Fundamentals
- Control Strategies
- Economics & Case Studies
- Maintaining Performance

Concept flow

Fundamental Considerations	Control Concepts	Economics	Performance Monitoring
Off-peak weather Off-design load Non-linear relationships Dynamic vs. steady state Optimization (balance)	Reduced lift: Float head Float suction Variable speed Feedback vs. predictive control logic	Analysis methods, hourly sensitivity Incremental/ marginal impacts Payback vs. value Beyond low hanging fruit	High level metrics Key indicators Trends Efficiency “faults” Variance (vs. expectations)

Basic considerations

- Comparing design vs. hourly operation:
  - Actual hourly load vs. peak design load
  - Actual hourly weather vs. peak ambient
  - dynamic operation vs. steady state
  - Non-linear energy relationships
- Concepts relating refrigeration systems to energy use:
  - Vapor compression cycle
  - Temperature “lift”
  - Variable speed and “affinity” laws

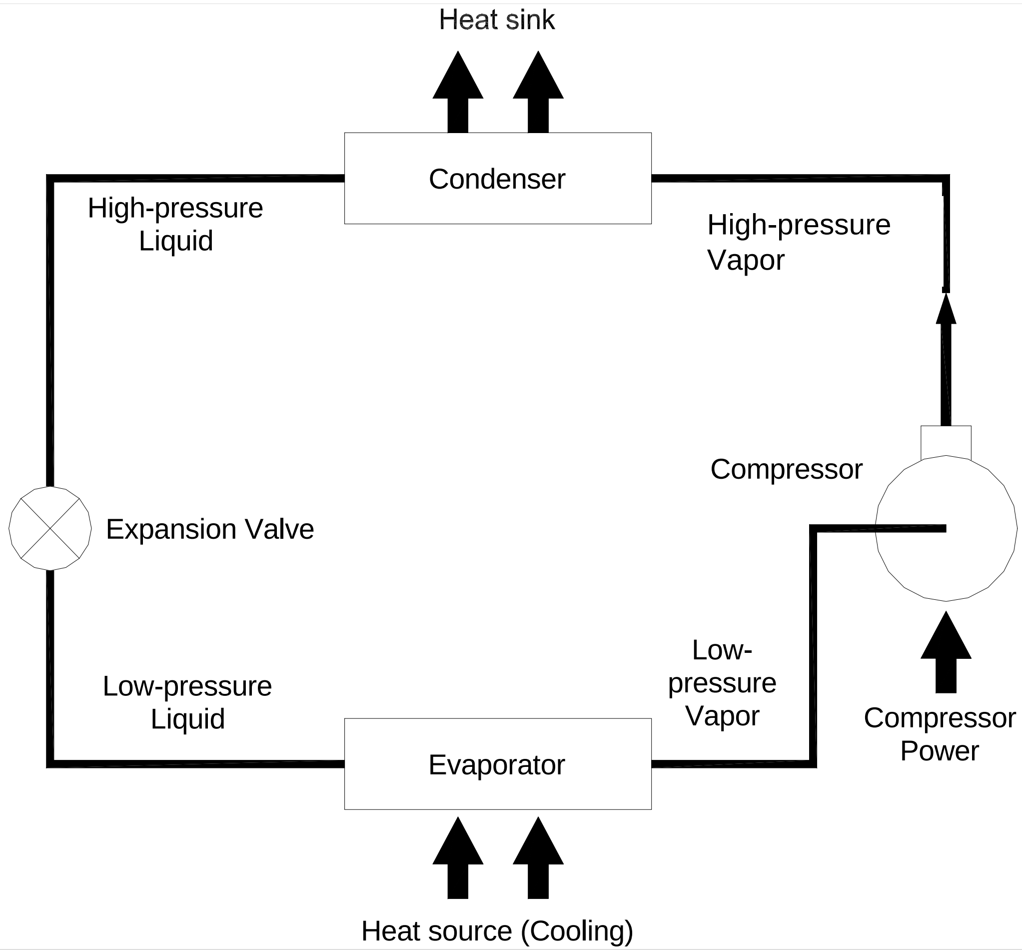
General opportunities

- Minimize lift
  - Float head pressure
  - Float suction
- Maximize <u>refrigerant</u> performance
  - Separate mass flow and enthalpy
- Condenser / evaporator performance
  - Utilize all surface all the time
  - Use inherent advantage of variable speed
- Ongoing maintenance opportunities
- Monitor performance

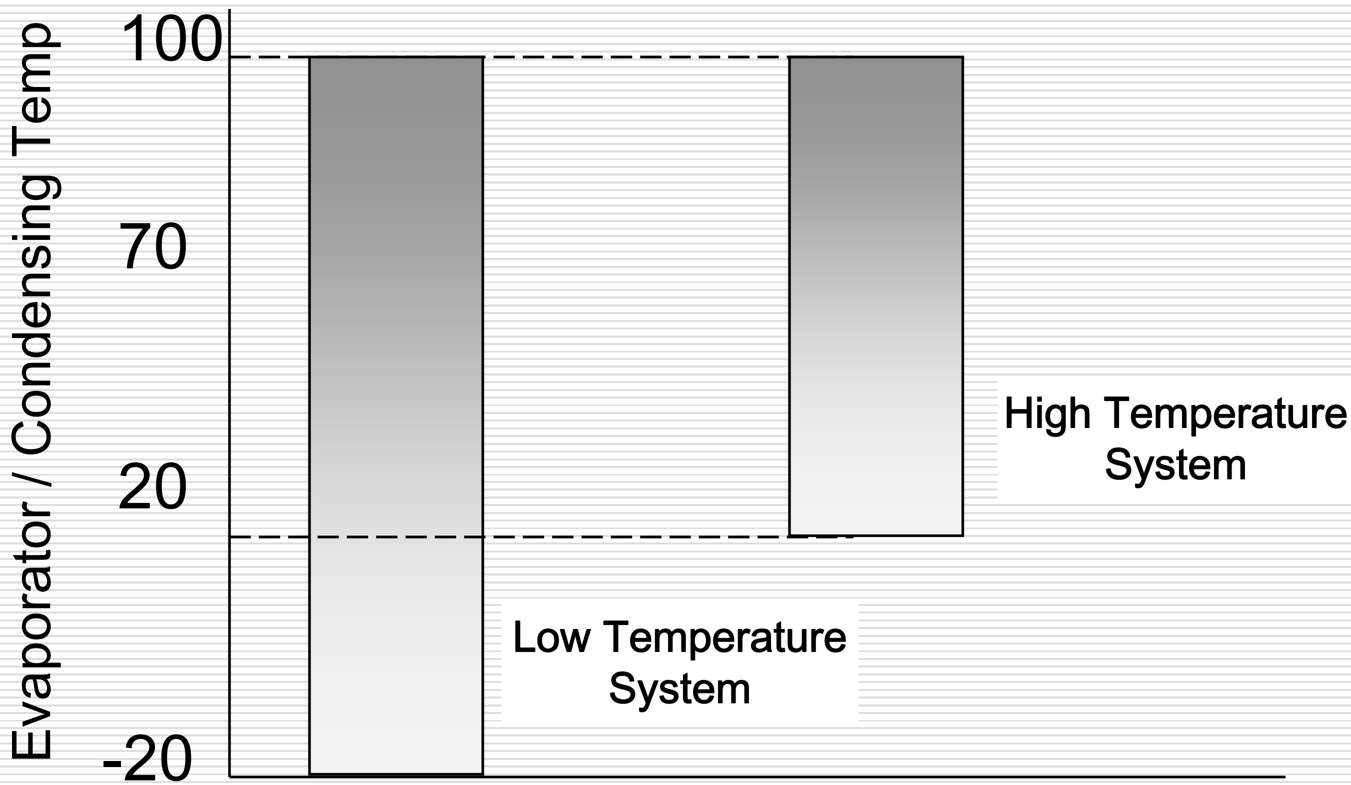
Vapor compression cycle

BASIC CONCEPTS

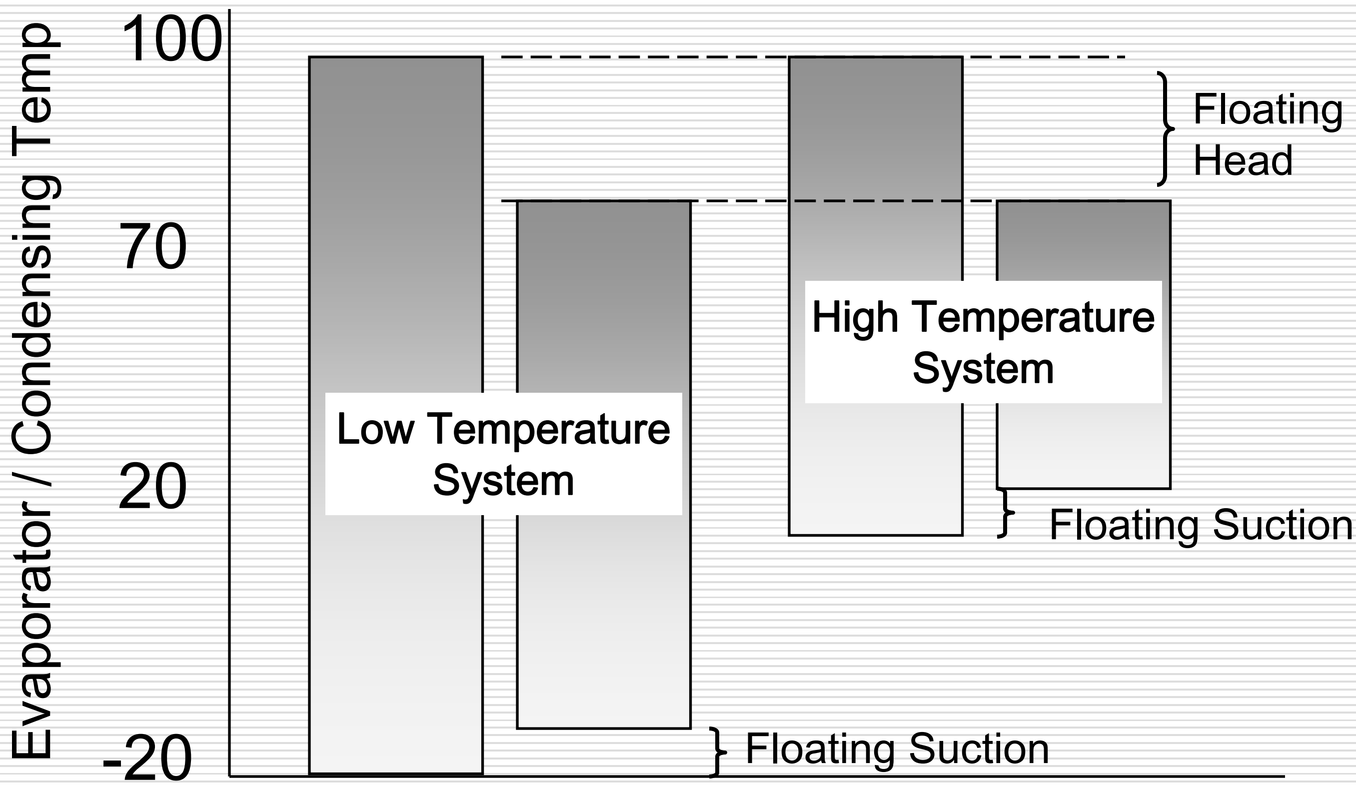
- **Refrigeration moves heat rather than creating cold**
- **Energy is conserved – energy in equals energy out**
- **Compressor pumps vapor; the refrigerant creates the cooling effect**



Cooling system "lift"



Reduced lift at non-peak, part load

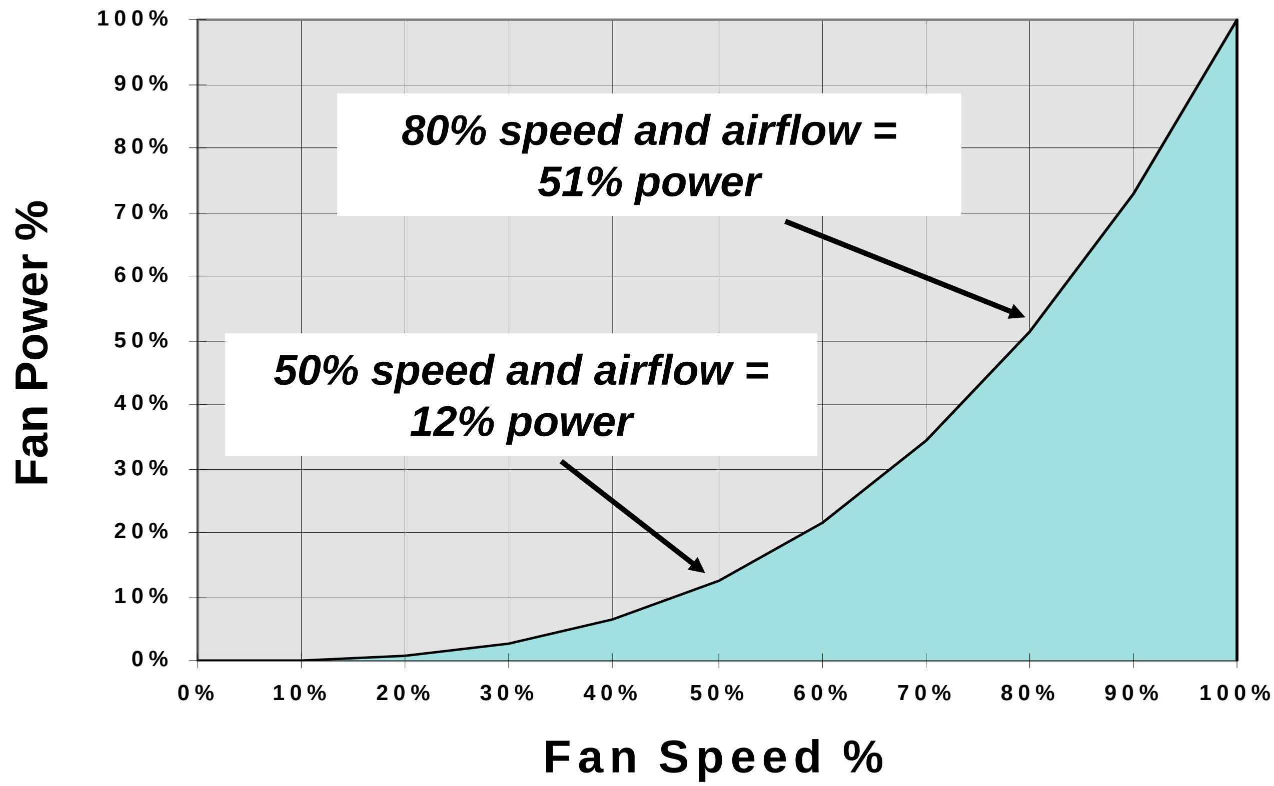


Variable speed fan control
Third power relationship ("affinity" laws)

Airflow varies directly with change in speed

Air pressure drop varies with the square of change in speed

Fan power varies with cube of change in speed



Heat Rejection

Heat rejection improvement

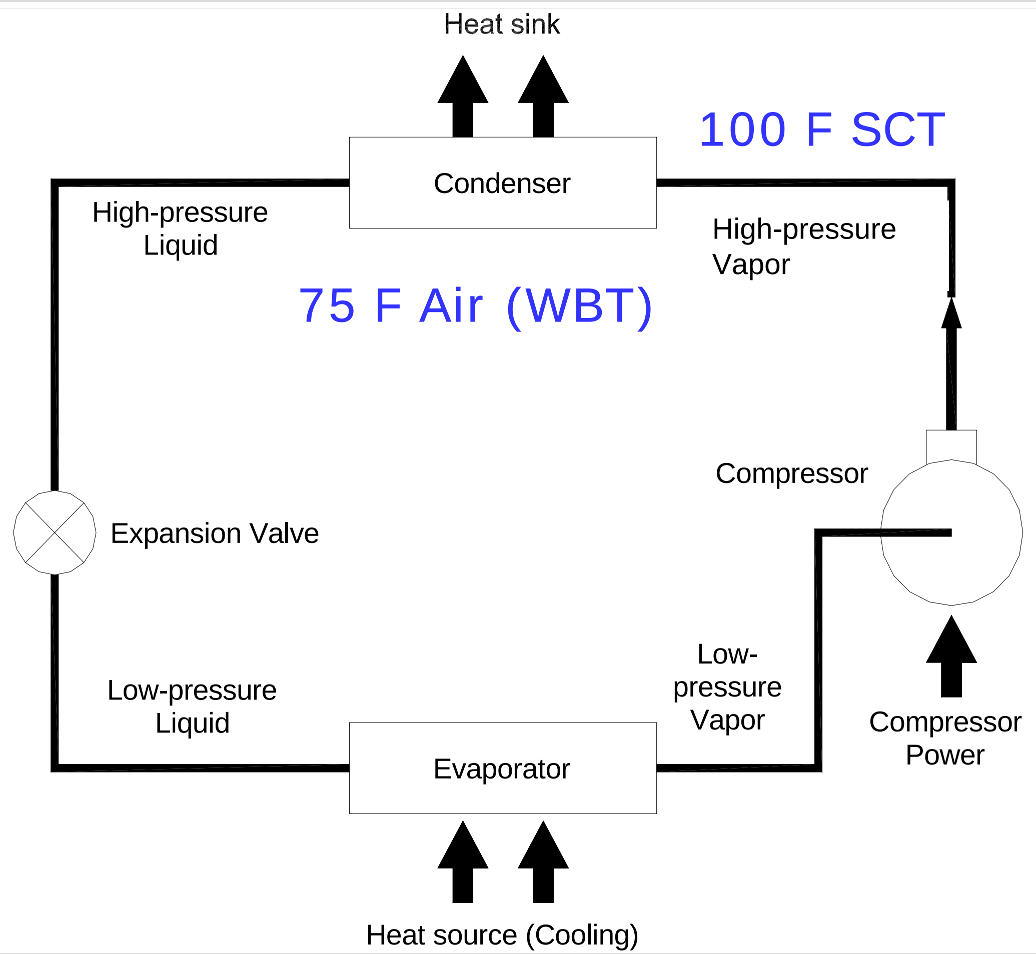
- Why start here?
  - All heat/energy leaves through condenser
  - Largest single savings opportunity on most systems
- Condenser sizing
  - Bigger is better, but bigger means more fan power
  - Goal: balance between size and power (and cost)
- Size shown by TD (temperature difference)
  - TD = condensing temperature – ambient temperature
  - Smaller TD = larger condenser
- Floating head pressure control strategies:
  - How low, how fan is controlled, how setpoint is set

Evap condenser TD example

Historical design:
75 F entering WBT +
25 F TD =
100 F condensing

Larger condenser:
75 F entering WBT +
14 F TD =
89 F condensing

= Lower Lift (by 11 F)

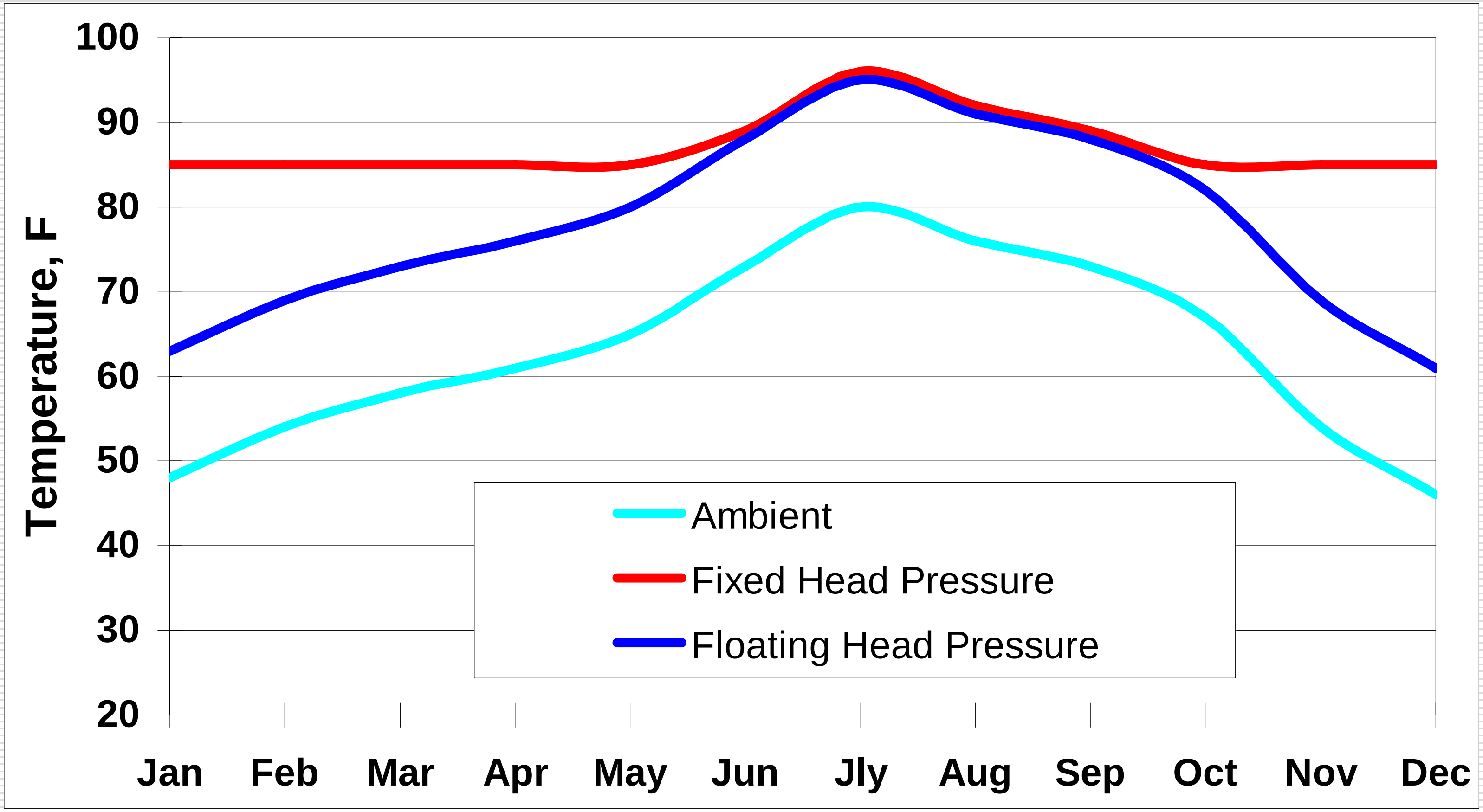


Specific efficiency example

Size	Motors	Capacity (10 F)	kW	BTUH/ Watt	% Difference
50	2 -- 5 HP	400	8.9	44.9	
52	3 -- 1.5 HP	450	4.0	112.3	150%

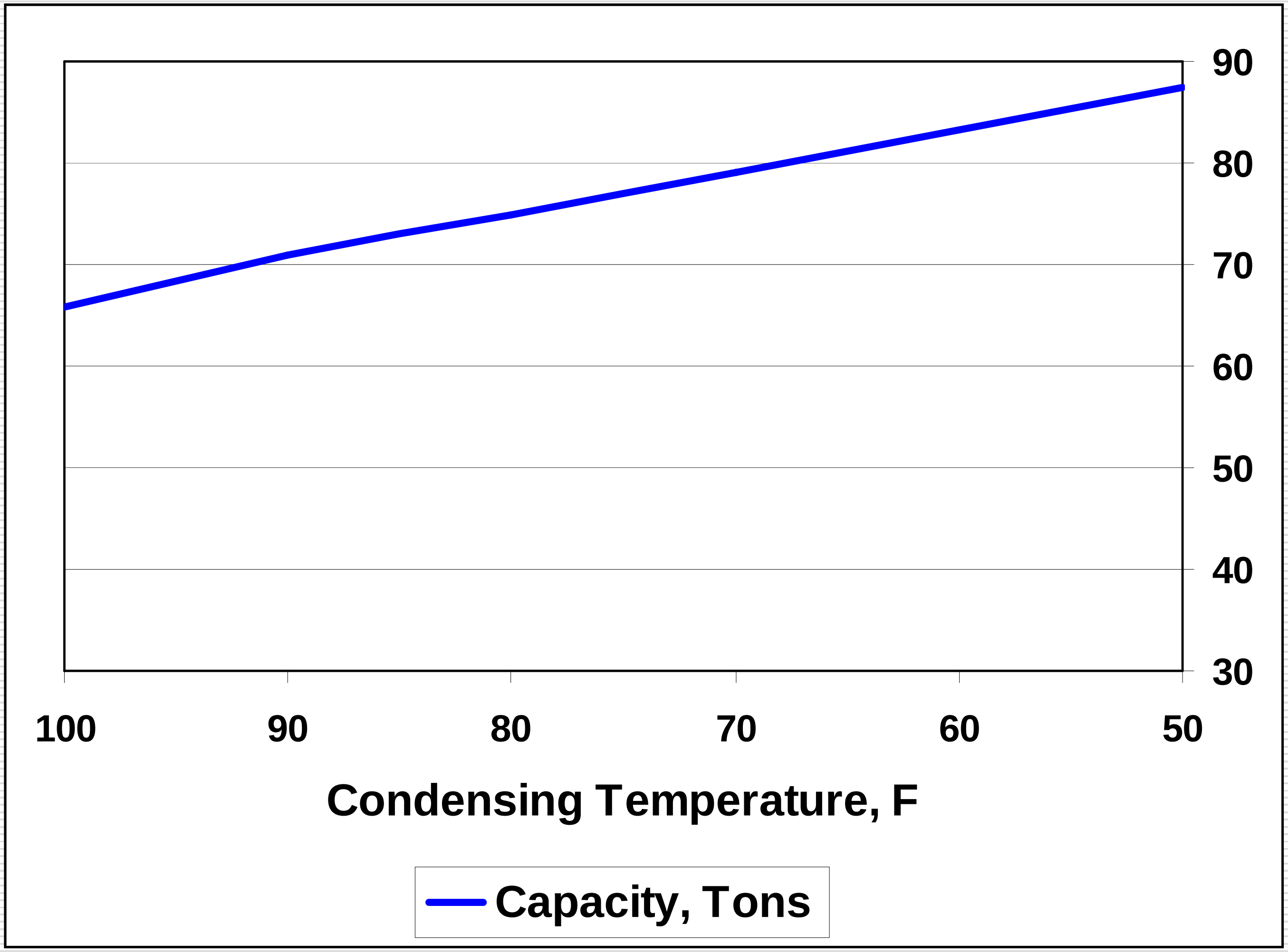
- Example of two consecutive air cooled condenser models from one manufacturer.
- Air velocity and fan motor size is used to achieve a large range of catalog sizes, first cost and footprint, some models are energy "hogs".

Fixed vs. floating head pressure
(floating condensing temperature)



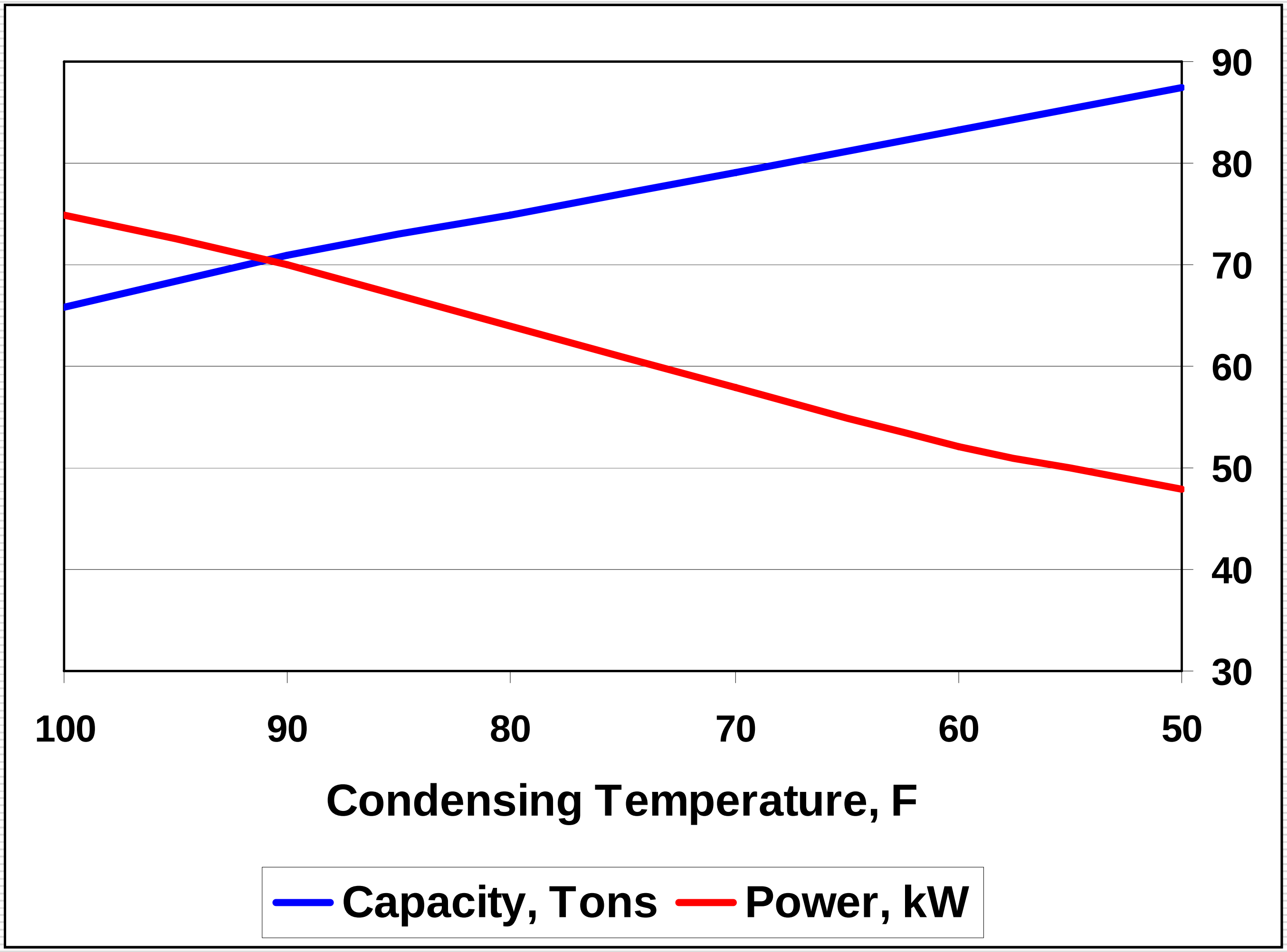
Floating head pressure

Impact on cooling capacity

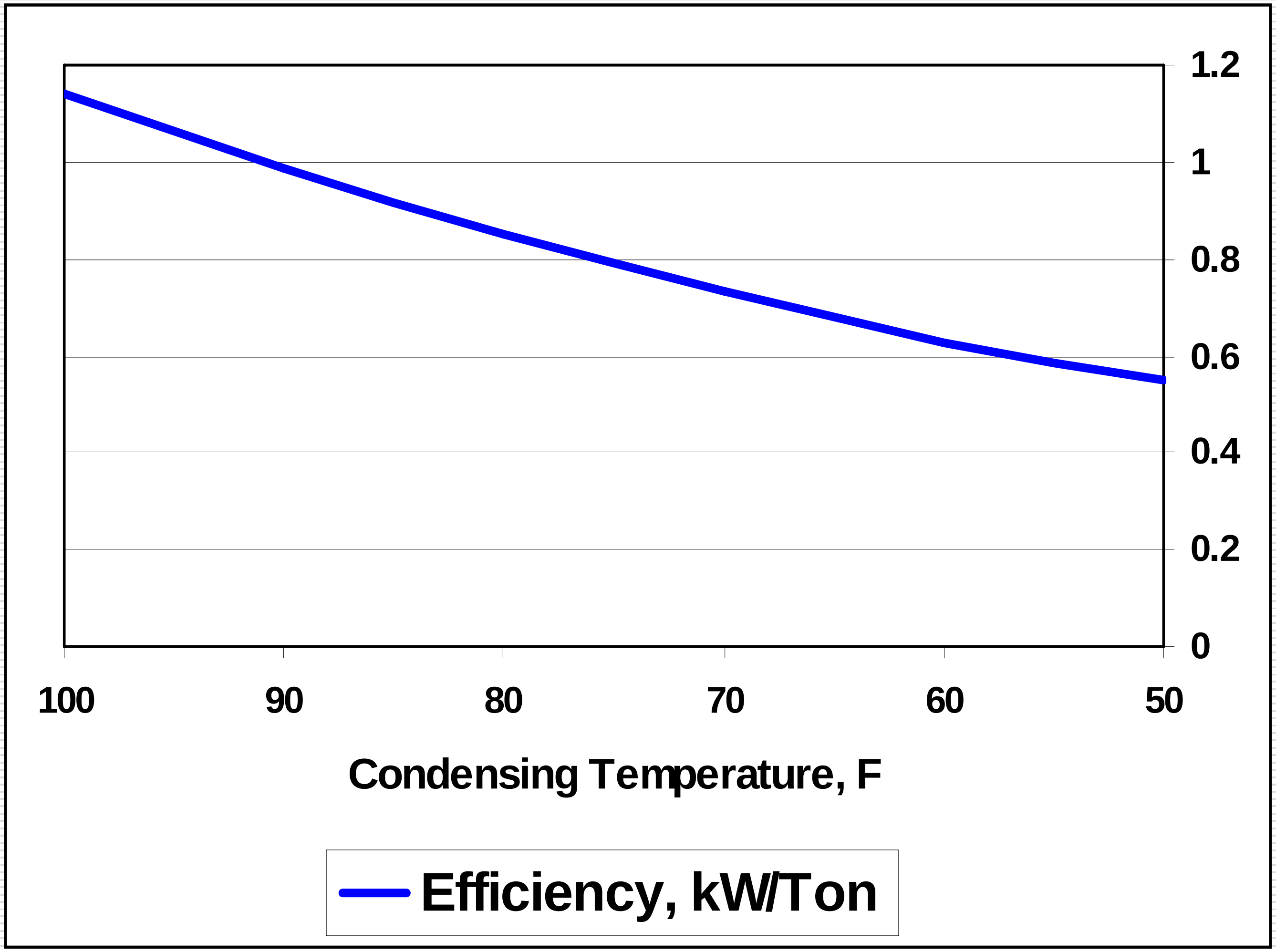


Floating head pressure

Impact on capacity and power



Floating head pressure
Net effect on efficiency



Floating head pressure

Compressor efficiency examples

Medium Temperature (+20 F)				
SCT (F)	Capacity	Power	EER (Btu/Watt)	Increase vs 100 SCT
100	79	7.5	10.5	0%
90	85	7	12.1	15%
80	90	6.4	14.1	34%
70	95	5.8	16.4	55%
60	100	5.2	19.2	83%
50	105	4.8	21.9	108%

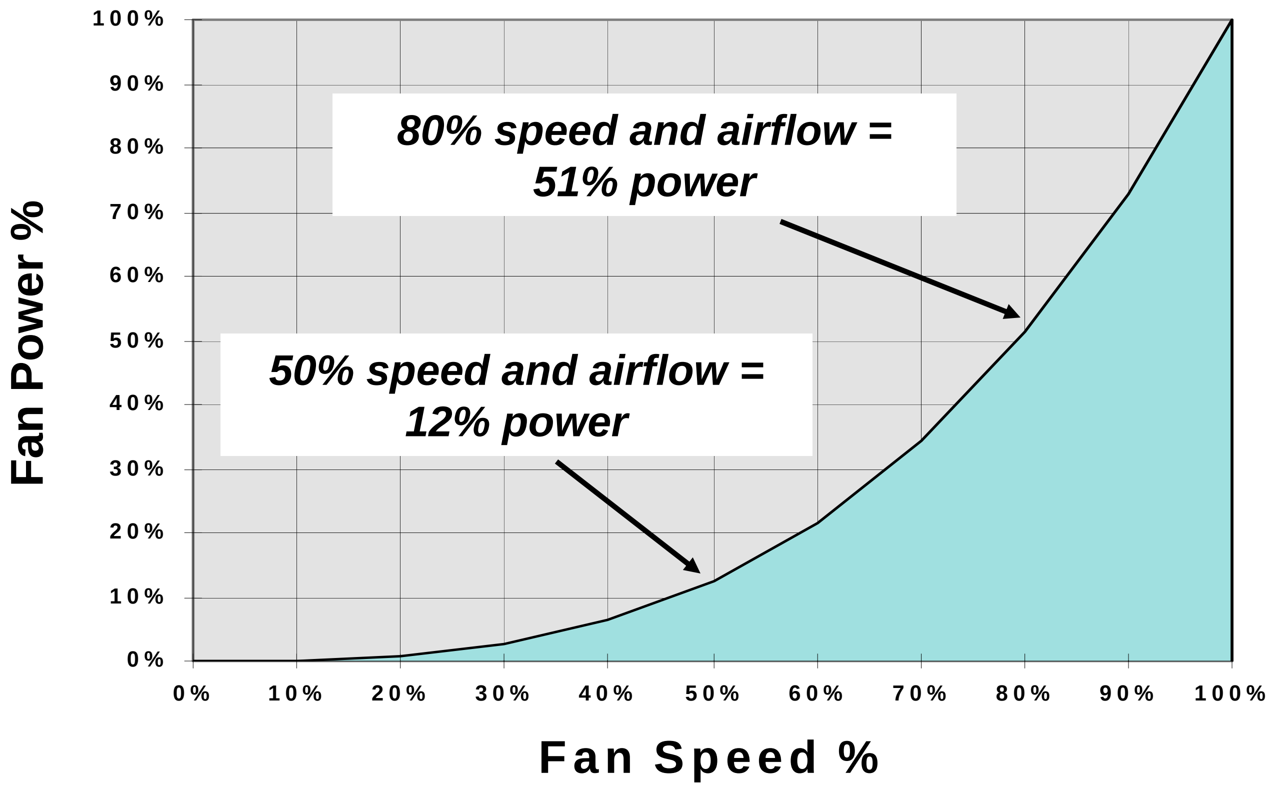
Low Temperature (-25 F)				
SCT (F)	Capacity	Power	EER (Btu/Watt)	Increase vs 100 SCT
100	48	8.4	5.7	0%
90	52	8.1	6.4	12%
80	55	7.7	7.1	25%
70	58	7.2	8.1	41%
60	61	6.8	9.0	57%
50	64	6.5	9.8	72%

Variable speed fan control (again)
Third power relationship ("affinity" laws)

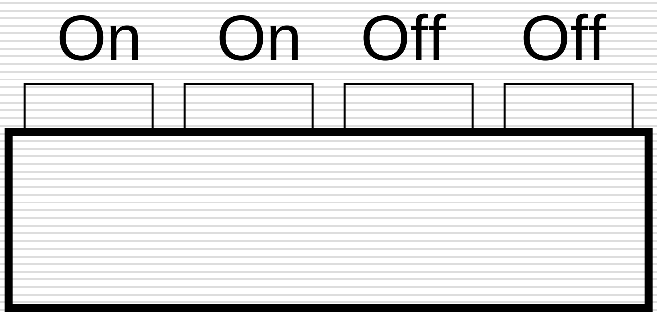
Airflow varies directly with change in speed

Air pressure drop varies with the square of change in speed

Fan power varies with cube of change in speed

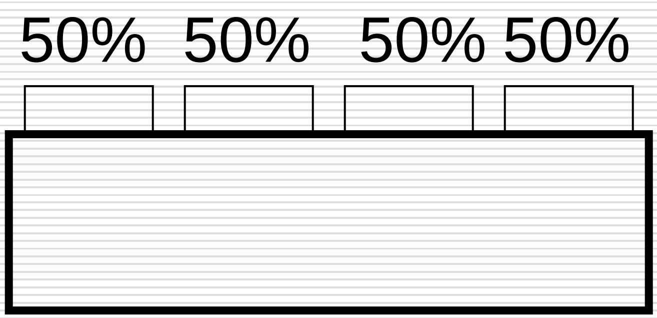


Part load performance
Variable speed vs. fan cycling



50% capacity
50% power

80 BTUH/Watt

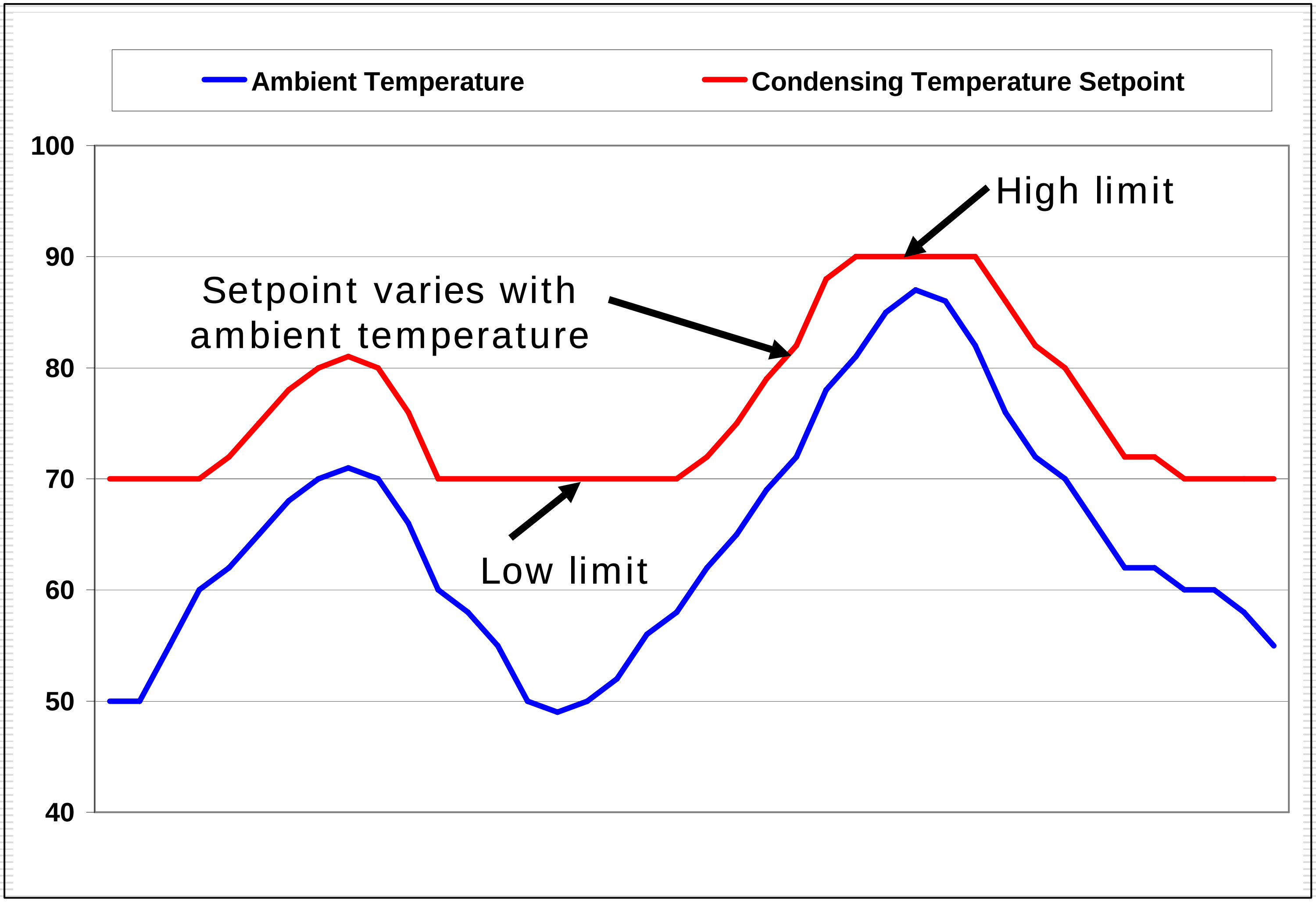


50% capacity
12% power

330 BTUH/Watt

Part load efficiency increased by 300% with variable speed

Floating head pressure
Variable setpoint control



Floating head pressure
Energy savings potential

Energy savings result from:

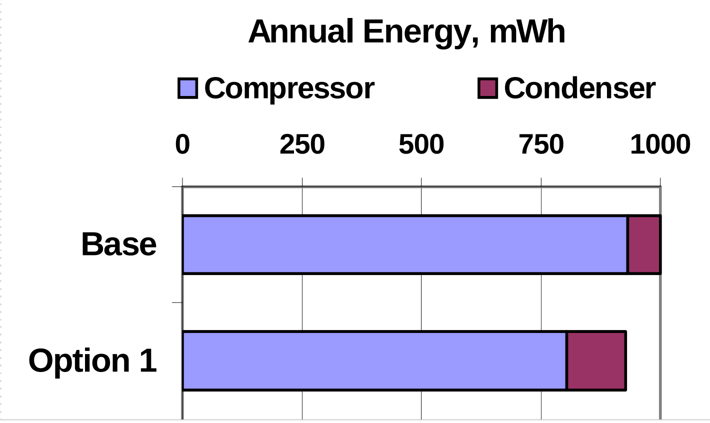
- Lower head pressure at compressor (and lower condensing temperature at condenser)
- Lower fan power
  - Variable speed
  - Variable setpoint
- Overall optimum system balance
  - Minimum total fan power + compressor power
- Savings with optimum FHP
  - 12-20% of annual compressor and condenser energy
  - *But, can be zero without proper control strategy*

FHP case study

- Cold storage warehouse in Stockton, California
- 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

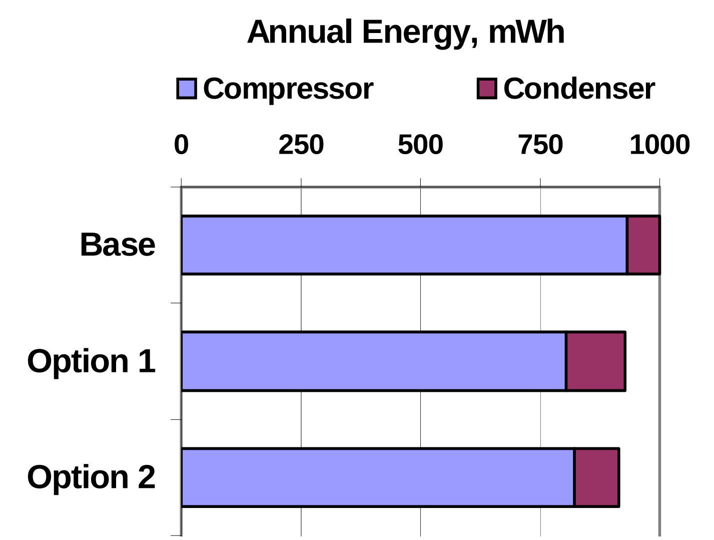
- Results show importance of control strategy

Results – fixed setpoint



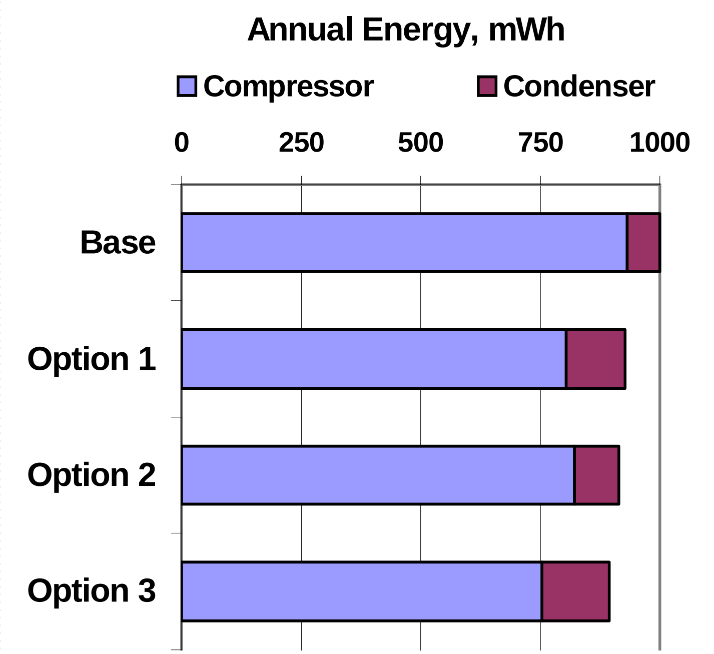
Control Options						
FHP	FSP	VSP	VFD	Savings	Payback	NPV
X	X			$ 6,400	0.3	$ 63,500

Results – variable setpoint



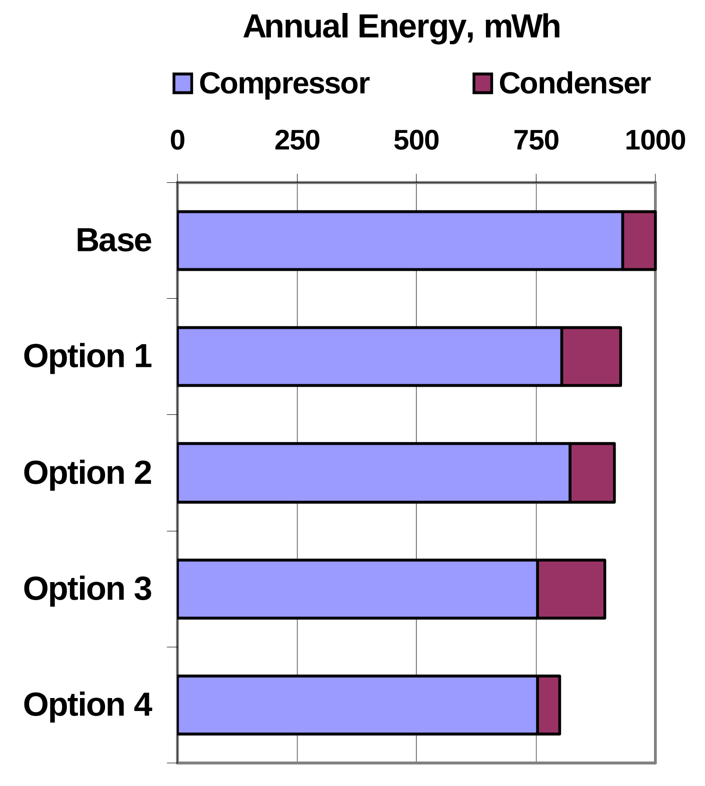
Control Options						
FHP	FSP	VSP	VFD	Savings	Payback	NPV
X	X			$ 6,400	0.3	$ 63,500
X		X		$ 8,400	0.6	$ 80,300

Results – fixed SP, 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

Results – variable SP & speed

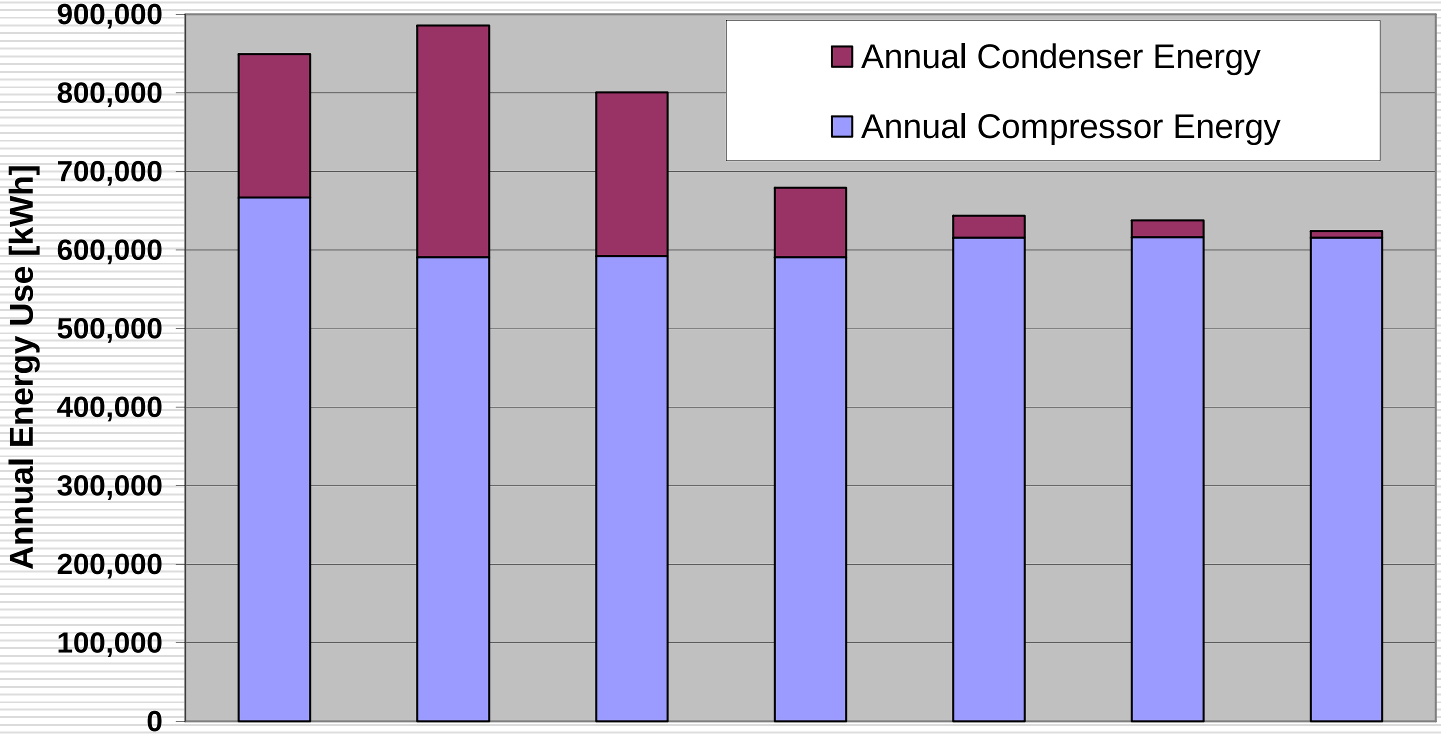


	Control Options						
	FHP	FSP	VSP	VFD	Savings	Payback	NPV
Option 1	X	X			$ 6,400	0.3	$ 63,500
Option 2	X		X		$ 8,400	0.6	$ 80,300
Option 3	X	X		X	$ 9,100	4.4	$ 52,900
Option 4	X		X	X	$ 21,600	2.1	$175,300

Supermarket condenser study

- Fort Worth TX weather, full size supermarket
- Hourly simulation (DOE2.2R)
- Comparison of condenser fan power
  - Standard (typical 1.5 HP 1140 RPM)
  - Mid-range (lower power and speed)
  - Very low power (1/2 HP motors 800 RPM or lower)
- Comparison of fan control
  - Fan cycling
  - Variable speed (assuming use of inverters for cost)
- Comparison of setpoint methods
  - Fixed setpoint
  - Variable setpoint (DBT plus TD)

Supermarket condenser study



Condenser Fan Power	Standard	Standard	Mid-Range	Very Low	Standard	Mid-Range	Very Low
Floating Head	No	Yes	Yes	Yes	Yes	Yes	Yes
Fan Control	Cycling	Cycling	Cycling	Cycling	Variable	Variable	Variable
Setpoint Control	Fixed	Fixed	Fixed	Fixed	Variable	Variable	Variable
Payback, Years		N/A	0.9	2.3	0.9	1.1	2.4
Incremental Payback				2.9		8.1	24.0

Note about variable setpoint

- *Variable setpoint or ambient following setpoint control is not the only means of optimizing the balance between condenser and compressor power. Other methods may be superior and ultimately displace ambient following control.*

Variable Volume Air Unit Control

Variable volume air unit control

- Vary fan speed in freezers and coolers as primary means of temperature control
- Strategy: reduce speed to 60-70%, then float suction up or cycle off cooling valve
- Third power rule applies to fan power
- Saving from:
  - Reduced fan energy
  - Reduced refrigeration cooling load

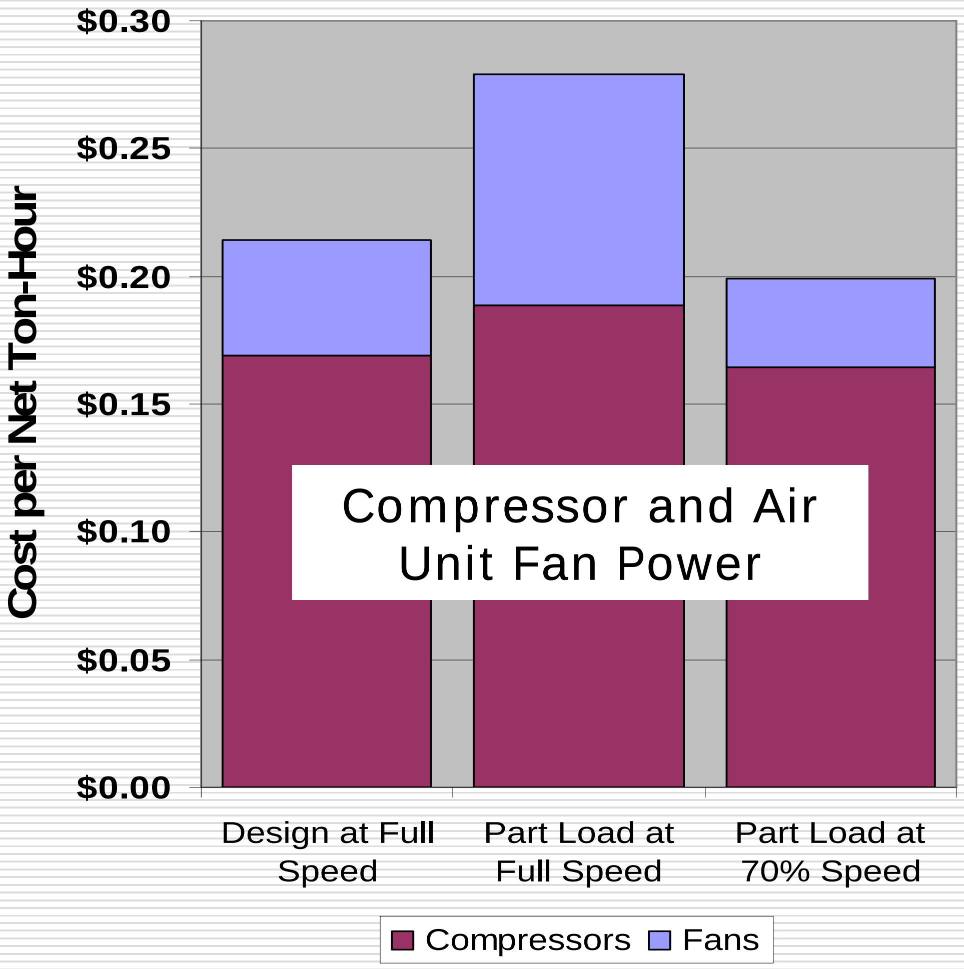
Fan power impact at average load

- Comparison of energy cost per ton-hour of net delivered cooling (before fan heat)
- Comparison:
  - Design values at 100% load and full speed fans
  - Average 50% cooling load with full speed fans
  - Average 50% cooling load with 70% fan speed
- 50,000 SF freezer, 200 tons design capacity

Fan power impact at average load

		Design	Part Load (50%)	
		Full Speed	Full Speed	70% Speed
Air Flow Rate (CFM/Ton)		1,852	3,017	2,385
Fan Power (Watts/Ton)		359	652	281
Cost ($/Ton-Hour)	Fan	$ 0.040	$ 0.080	$ 0.031
	Compressor	$ 0.167	$ 0.184	$ 0.163
	Total	$ 0.207	$ 0.264	$ 0.194
% Change from Design			28%	-7%
% Change from Part Load, Full Speed to Variable Speed				-27%
Annual Energy (KWh)	Fan		700,800	267,522
	Compressor		1,612,979	1,428,131
	Total		2,313,779	1,695,653
Annual Energy Cost (at $.10/kWh)		-	$ 231,378	$ 169,565
Annual Savings				$ 61,813
Savings per Cu. Ft.				$ 0.04

Fan power impact at average load



Case study – small distribution

- Cold storage warehouse in Ontario, California with 20,000 SF of cooler and freezer
- Hourly simulation
- Base case = fixed fan speed
- Savings based on variable speed with 70% minimum speed

Energy Savings, kWh	**280,000**
Annual Cost Savings	**$27,600**
Measure Cost	**$65,000**
Incentive	**$22,500**
Net Cost	**$42,500**
Payback, Years	**1.5**
IRR	**68%**
NPV	**$205,000**

Concerns and challenges

- Will air fall on the floor (not enough throw)?
  - Airflow reduction reduces terminal velocity not throw
- Will motors burn out?
  - Use proper motors, wiring practice, filters if needed
  - Don't (need to) run too slow
- Coils won't feed, won't defrost, etc.
  - Don't run too slow (diminishing returns)
  - Design and control anticipating variable volume
- Structure, racking and product obstructions
  - Issue of quantity of air vs. quality of distribution
  - Improve airflow quality: cost/benefit question

Energy Efficiency vs. Demand Management

Efficiency and demand hierarchy

Energy Efficiency ▶	Daily Load Shift ▶	Demand Response
Energy efficiency is reduction in kWh usage throughout the year.	Strategies to reduce or move load during all summer on-peak hours (kWh & kW)	Capability to reduce load (kW) when requested during unusual events
8,760 hours	6-900 hours	Occasional, Utility Dependant

Potential conflict between EE and DLS. Decreasing difference between on-peak and non-peak rates. Balance between two objectives requires coordination.

Control beyond DLS.
Payment for capability.
Payment for delivery.

Carbon footprint: This is a new perspective. Trade-offs no longer just based on billing cost. DLS savings at expense of increased kWh and greenhouses gases may not be justified. Metrics and trade-off formula are needed. (stay tuned)

Refrigeration & demand control

- Thermal mass
  - Refrigerated warehouses – inherent thermal storage in refrigerated product mass, cool during off-peak
- Variable speed changes the picture
  - Amount of cooling delivery can be modulated; essential to avoid 100% fan power
  - (May not be optimum to simply shut-off during on-peak and then overcool during non-peak)
- Scheduled cooling vs. setpoint control
  - Develop predictive load control (ton-hour delivery)
  - Optimize cost and resource use by delivery daily cooling in most effective manner

Maintenance and Energy Efficiency

Maintenance considerations

- How can refrigeration efficiency be optimized on a day-to-day basis?
- Compare operations with expectations:
  - Ambient + TD = expected SCT
  - Box temp – TD = expected SST
  - Use saturation temperatures not pressures
- Know the “sweet spots” (e.g. 60-80% speed)
- Proactive effort vs. tendency to wait until deficiency become a pressing need or “its number comes up”

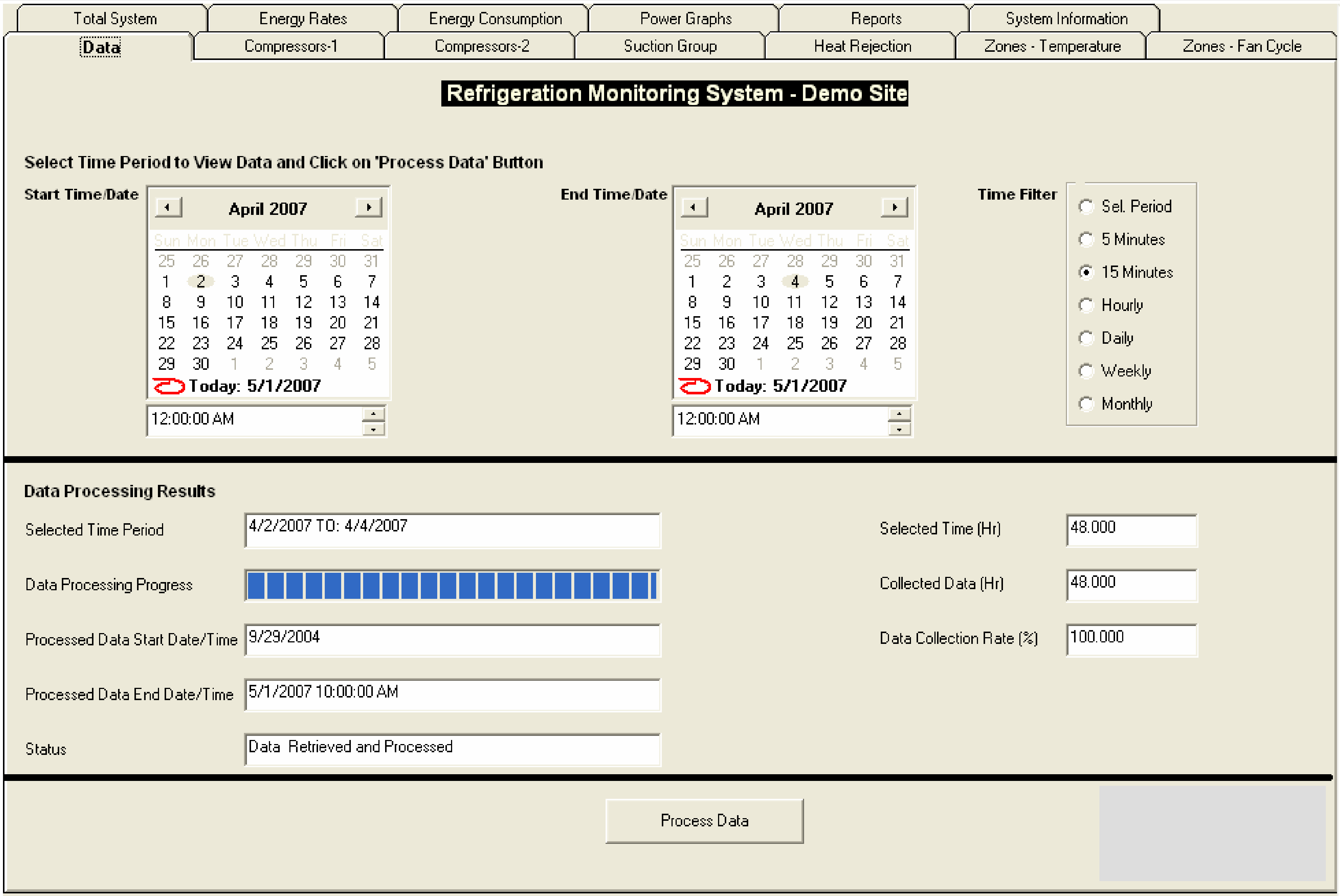
Efficiency faults

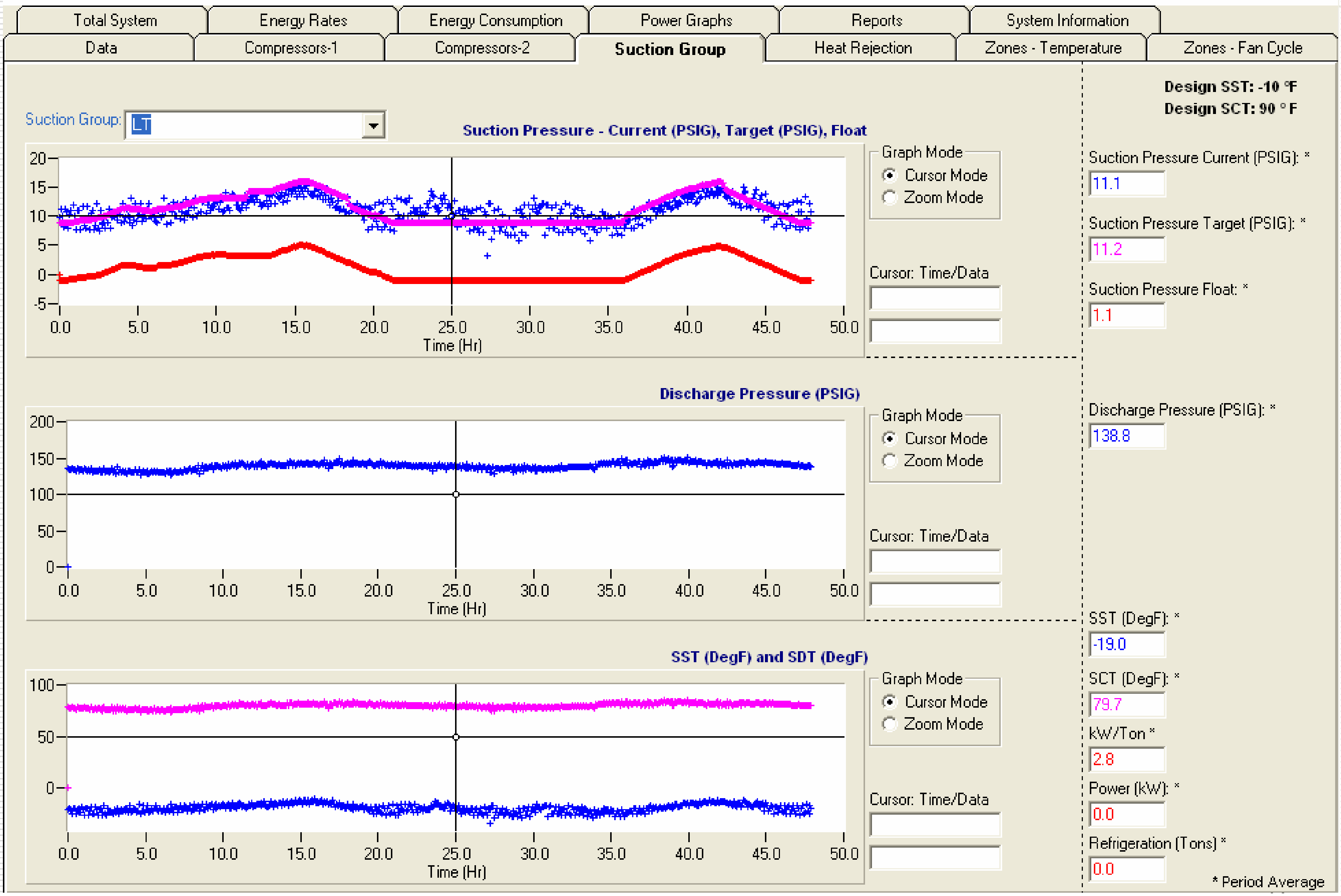
- Understand efficiency “faults” where system keeps working but energy use goes up
- Low refrigerant charge – how big is this?
  - Low charge equivalent to hot-gas bypass
  - Applies to DX systems AND industrial systems
- Refrigerant integrity
  - Moisture, non-condensables, oil (in wrong place)
  - Results in heat exchanger TD above expectations

Performance Monitoring

Performance monitoring

- Remote efficiency monitoring
  - Real time, continuous performance analysis
  - Web based results presentation (wider audience)
- Rationale
  - Management by exception, must measure to manage
  - Refrigeration systems don't come with efficiency "meters"; designed to always meet load
- Performance measures
  - Energy efficiency metrics: kW/Ton, $/Ton-Hr
  - Maintenance and performance indicators
  - Key trends (e.g. refrig. level, inventory)


Total System
Energy Rates
Energy Consumption
Power Graphs
Reports
System Information
Data
Compressors-1
Compressors-2
Suction Group
Heat Rejection
Zones - Temperature
Zones - Fan Cycle
Refrigeration Monitoring System - Demo Site
Select Time Period to View Data and Click on 'Process Data' Button
Start Time/Date
April 2007
Sun Mon Tue Wed Thu Fri Sat
25 26 27 28 29 30 31
1 2 3 4 5 6 7
8 9 10 11 12 13 14
15 16 17 18 19 20 21
22 23 24 25 26 27 28
29 30 1 2 3 4 5
Today: 5/1/2007
12:00:00 AM
End Time/Date
April 2007
Sun Mon Tue Wed Thu Fri Sat
25 26 27 28 29 30 31
1 2 3 4 5 6 7
8 9 10 11 12 13 14
15 16 17 18 19 20 21
22 23 24 25 26 27 28
29 30 1 2 3 4 5
Today: 5/1/2007
12:00:00 AM
Time Filter
Sel. Period
5 Minutes
15 Minutes
Hourly
Daily
Weekly
Monthly
Data Processing Results
Selected Time Period
4/2/2007 TO: 4/4/2007
Data Processing Progress
Processed Data Start Date/Time
9/29/2004
Processed Data End Date/Time
5/1/2007 10:00:00 AM
Status
Data Retrieved and Processed
Selected Time (Hr)
48.000
Collected Data (Hr)
48.000
Data Collection Rate (%)
100.000
Process Data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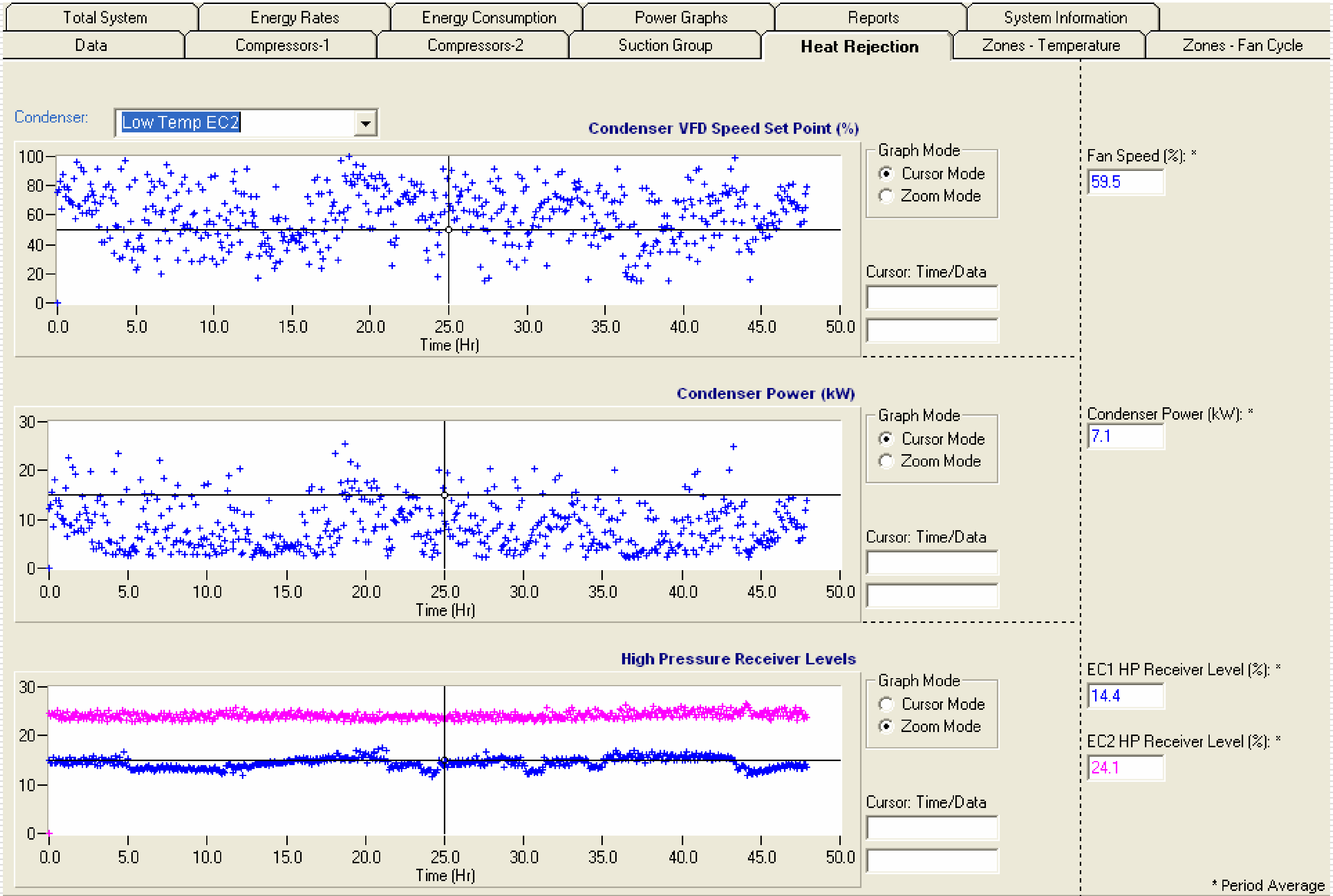
Compressors-1
Compressors-2
Suction Group
Heat Rejection
Zones - Temperature
Zones - Fan Cycle
Suction Group:
LT
Suction Pressure - Current (PSIG), Target (PSIG), Float
Design SST: -10 °F
Design SCT: 90 ° F
Graph Mode
Cursor Mode
Zoom Mode
Cursor: Time/Data
Time (Hr)
Suction Pressure Current (PSIG): *
11.1
Suction Pressure Target (PSIG): *
11.2
Suction Pressure Float: *
1.1
Discharge Pressure (PSIG)
Discharge Pressure (PSIG): *
138.8
SST (DegF) and SDT (DegF)
SST (DegF): *
-19.0
SCT (DegF): *
79.7
kW/Ton *
2.8
Power (kW): *
0.0
Refrigeration (Tons) *
0.0
* Period Average



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Compressors-1
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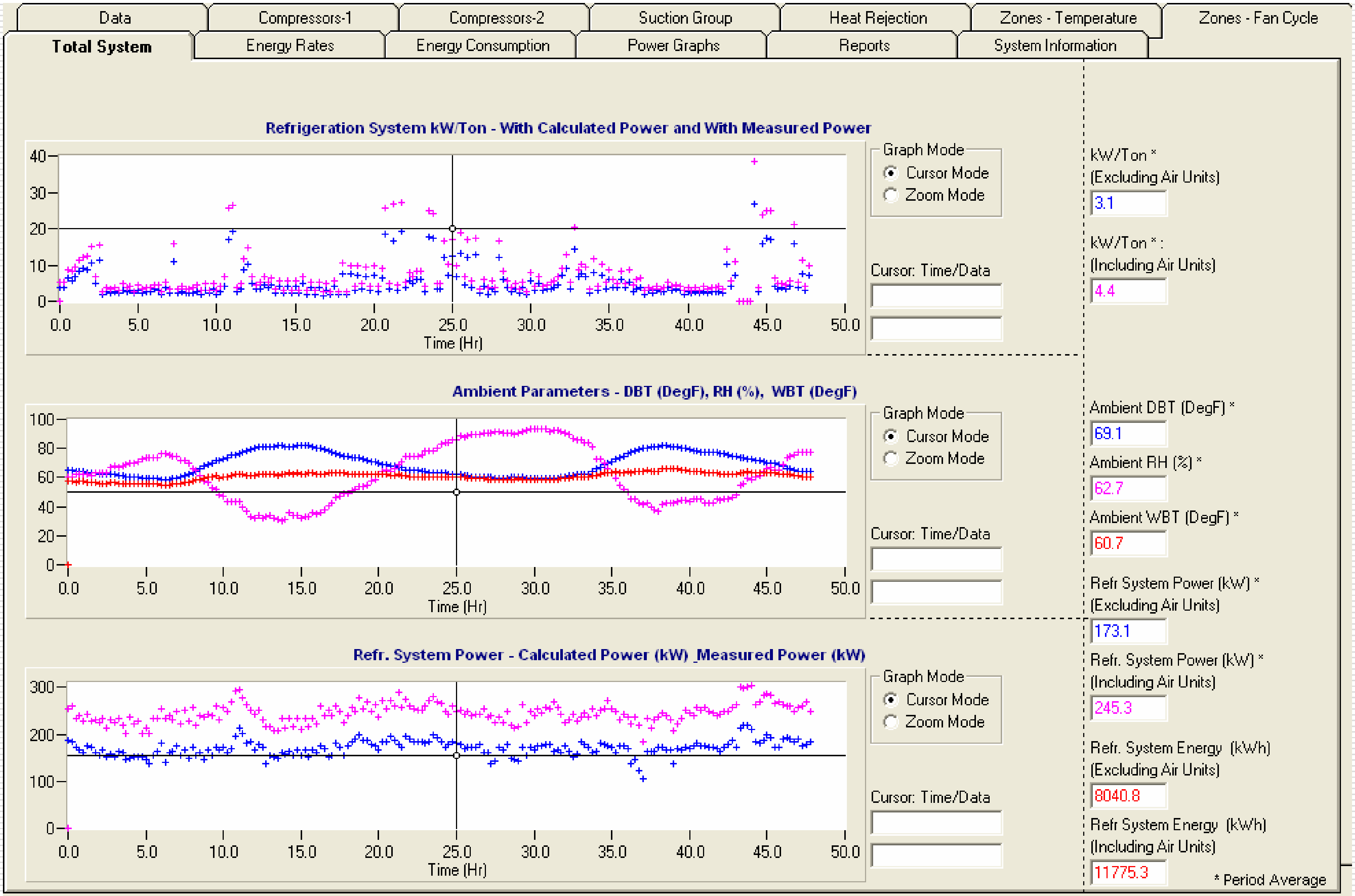
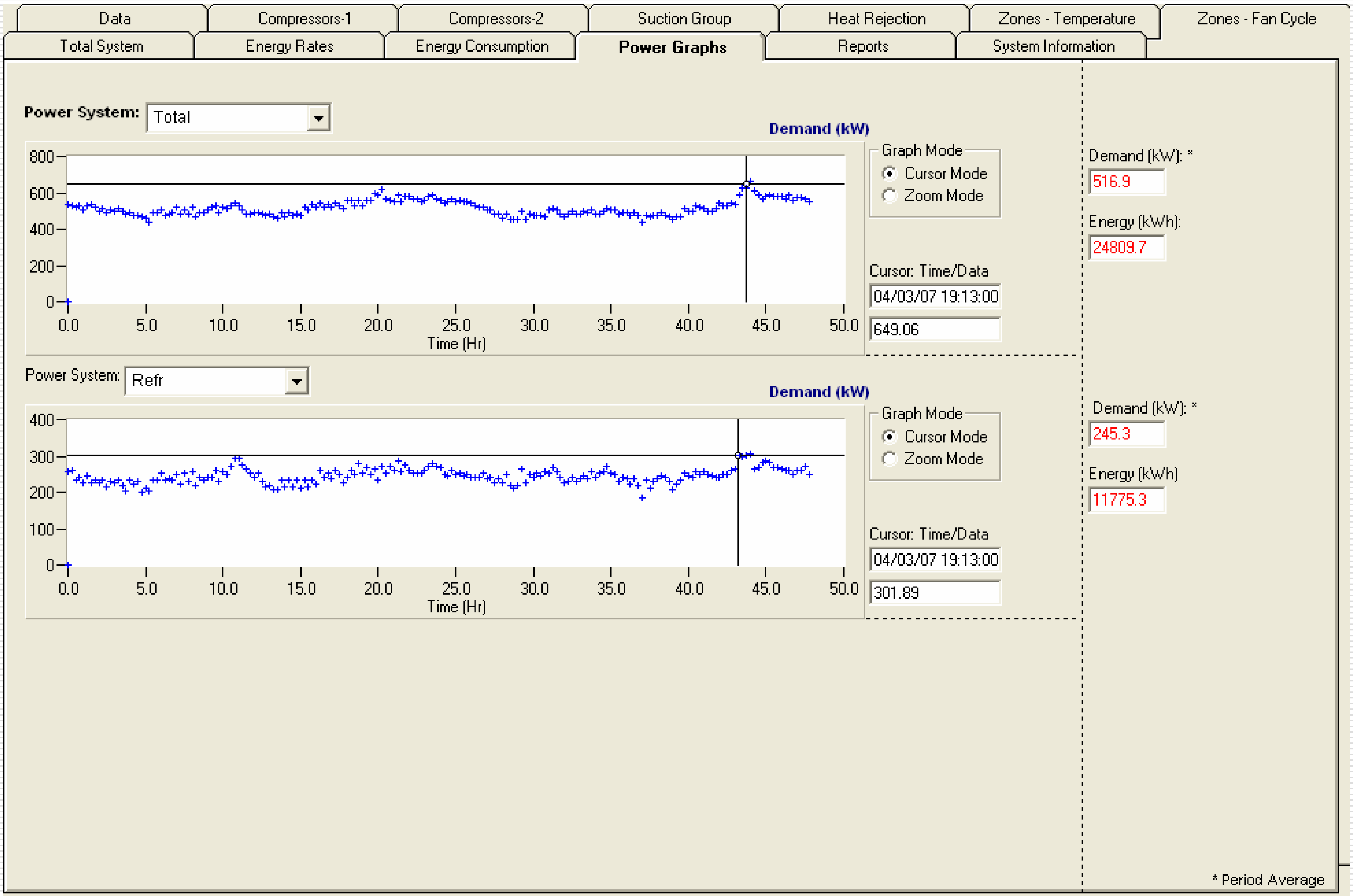
Suction Group
Heat Rejection
Zones - Temperature
Zones - Fan Cycle
Condenser:
Low Temp EC2
Condenser VFD Speed Set Point (%)
Graph Mode
Cursor Mode
Zoom Mode
Cursor: Time/Data
Time (Hr)
Fan Speed (%): *
59.5
Condenser Power (kW)
Condenser Power (kW): *
7.1
High Pressure Receiver Levels
EC1 HP Receiver Level (%): *
14.4
EC2 HP Receiver Level (%): *
24.1
* Period Average



Data
Compressors-1
Compressors-2
Suction Group
Heat Rejection
Zones - Temperature
Zones - Fan Cycle
Total System
Energy Rates
Energy Consumption
Power Graphs
Reports
System Information
Refrigeration System kW/Ton - With Calculated Power and With Measured Power
Time (Hr)
Graph Mode
Cursor Mode
Zoom Mode
Cursor: Time/Data
kW/Ton *
(Excluding Air Units)
3.1
kW/Ton * :
(Including Air Units)
4.4
Ambient Parameters - DBT (DegF), RH (%), WBT (DegF)
Ambient DBT (DegF) *
69.1
Ambient RH (%) *
62.7
Ambient WBT (DegF) *
60.7
Refr System Power (kW) *
(Excluding Air Units)
173.1
Refr. System Power - Calculated Power (kW) _Measured Power (kW)
Refr. System Power (kW) *
(Including Air Units)
245.3
Refr. System Energy (kWh)
(Excluding Air Units)
8040.8
Refr System Energy (kWh)
(Including Air Units)
11775.3
* Period Average



Data
Compressors-1
Compressors-2
Suction Group
Heat Rejection
Zones - Temperature
Zones - Fan Cycle
Total System
Energy Rates
Energy Consumption
Power Graphs
Reports
System Information
Power System: Total
Demand (kW)
800
600
400
200
0
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0
Time (Hr)
Graph Mode
Cursor Mode
Zoom Mode
Cursor: Time/Data
04/03/07 19:13:00
649.06
Demand (kW): *
516.9
Energy (kWh):
24809.7
Power System: Refr
Demand (kW)
400
300
200
100
0
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0
Time (Hr)
Graph Mode
Cursor Mode
Zoom Mode
Cursor: Time/Data
04/03/07 19:13:00
301.89
Demand (kW): *
245.3
Energy (kWh)
11775.3
* Period Average

Performance monitoring

Going forward

- Essential to achieve continued gains in energy efficiency and meet global environmental needs
- Global interest and attention (e.g. ASHRAE)
- Means to bring experts closer to needs
- Build into control systems (push down)
- Help connect end-to-end expectations
  - Do systems run per design?
  - Is equipment sized right?
  - Feedback to vendors, engineers and maintenance
- Bottom line: maximize life-cycle value

Questions?