Benchmark Performance Analysis Of An ECM-Modulated Air-To-Air Heat Pump With A Reciprocating Compressor

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PURPOSE OF ECM BENCHMARK ANALYSIS

- ✦ Determine Limits Of Existing Modulating Technology
  - High efficiency drives and heat exchangers
  - Reciprocating compressors
- ✦ Demonstrate Use of Modulating Design Tool
  - Extension of Mark III heat pump design model
    - 4 types of modulating drives for comp. and fans
    - extended flow-range air-side H.T. correlations
    - charge inventory prediction and balancing
    - extensive 1- and 2-D parametrics

HARDWARE ASSUMPTIONS

Modulating Drives and Heat Exchangers

- ✦ Same Hardware Constraints As Highest SEER Modulating Unit
  - ECM-driven compressor and fans
  - Same compressor turndown ratios
    - 1 to 0.28 in heating and cooling
    - no heating-mode overspeed operation
  - Reciprocating compressor
  - Same [total Hx area] / [ton of cooling capacity]

COMPONENT EFFICIENCY REPRESENTATIONS

Modulating Drives, Compressors, and Fans

- ✦ Modulating Drive Efficiencies -- Compressors and Fans
  - Functions of speed and torque ratios
- ✦ Modulating Compressor Efficiency
  - Functions of speed and operating conditions
    - map-based from discrete frequency data
    - induction-to-ECM drive conversion built-in
- ✦ Modulating Fans
  - Efficiencies assumed constant as speed changes
    - ODF efficiency varies with coil ΔP characteristic
    - IDF efficiency fixed at 45% under all ΔP conditions

REFRIGERATION COMPONENT PERFORMANCE

Heat Transfer and Refrigerant Flow Control

- ✦ Heat Exchangers
  - Hx geometry of first-generation modulating unit
    - validated fin-and-tube Hx configurations
    - air-side area/ton scaled to SOA
  - Added internal and external surface augmentation
    - louvered fins on air-side
    - 150% multipliers to ref-side H.T. and ΔP
- ✦ Idealized Variable-Opening Flow Control
  - Fixed low values of evaporator superheat
    - 10 F° in cooling, 1 F° in heating
  - Condenser subcooling used as design variable

STEADY-STATE DESIGN APPROACH

Maximize COP At Four Conditions

- ✦ Cooling Mode
  - 95°F — Max speed, nominal design capacity, acceptable S/T ratio
  - 82°F — Min speed, min capacity, acceptable S/T ratio
- ✦ Heating Mode
  - 47°F — Min speed, min capacity, acceptable min supply temp
  - 17°F — Min speed, max capacity

Four-Point Strategy

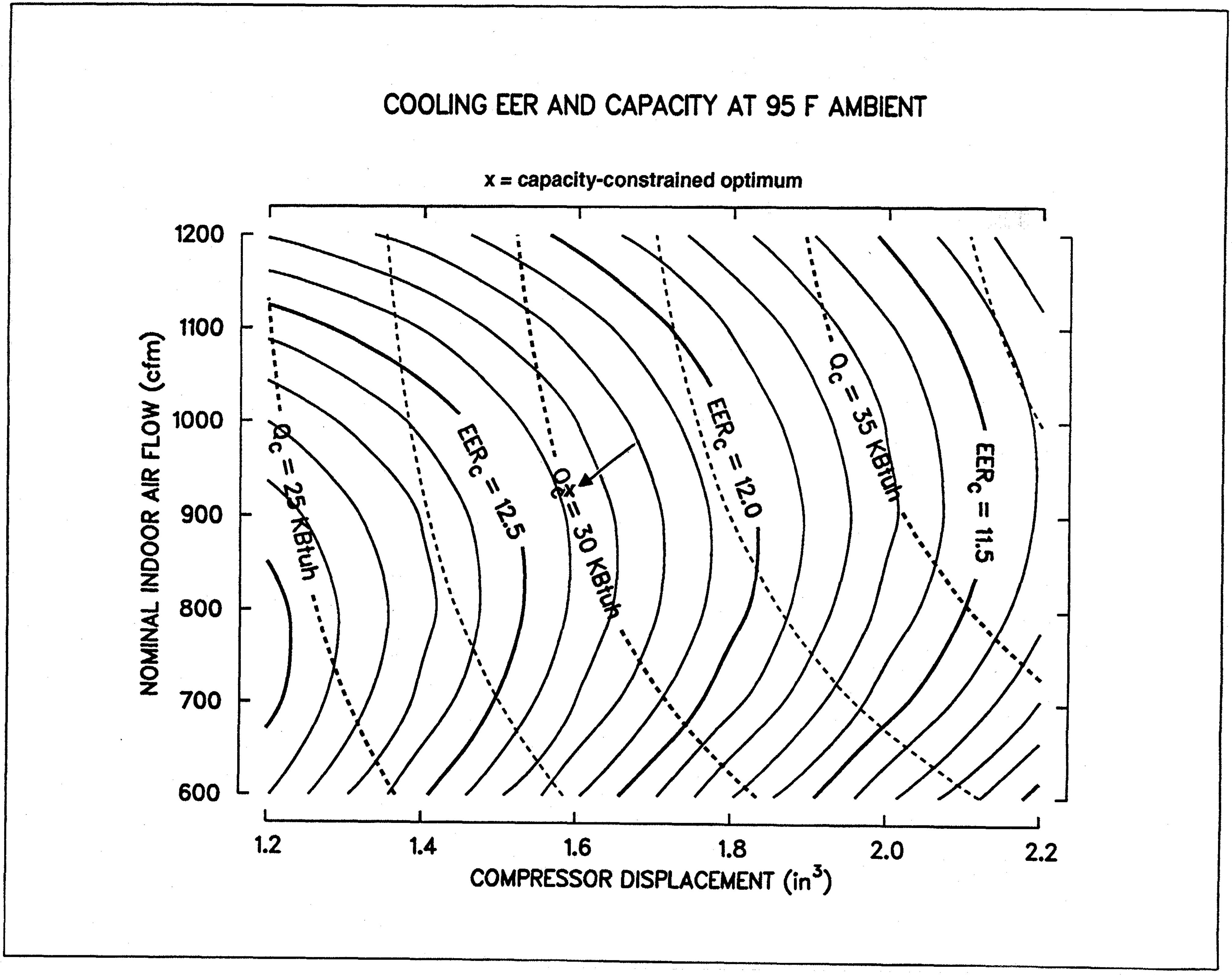
- ✦ Nominal Design (at 95°F) Determines
  - Compressor size and maximum airflows
  - Required motor sizes
  - Hx area ratio and configuration
- ✦ Off–Design Analyses (at 82°F, 47°F, 17°F)
  - Determine air and refrigerant flow-control variables
    - – fan speeds
    - – condenser subcooling
  - At min or max compressor speeds

Nominal Design Analysis

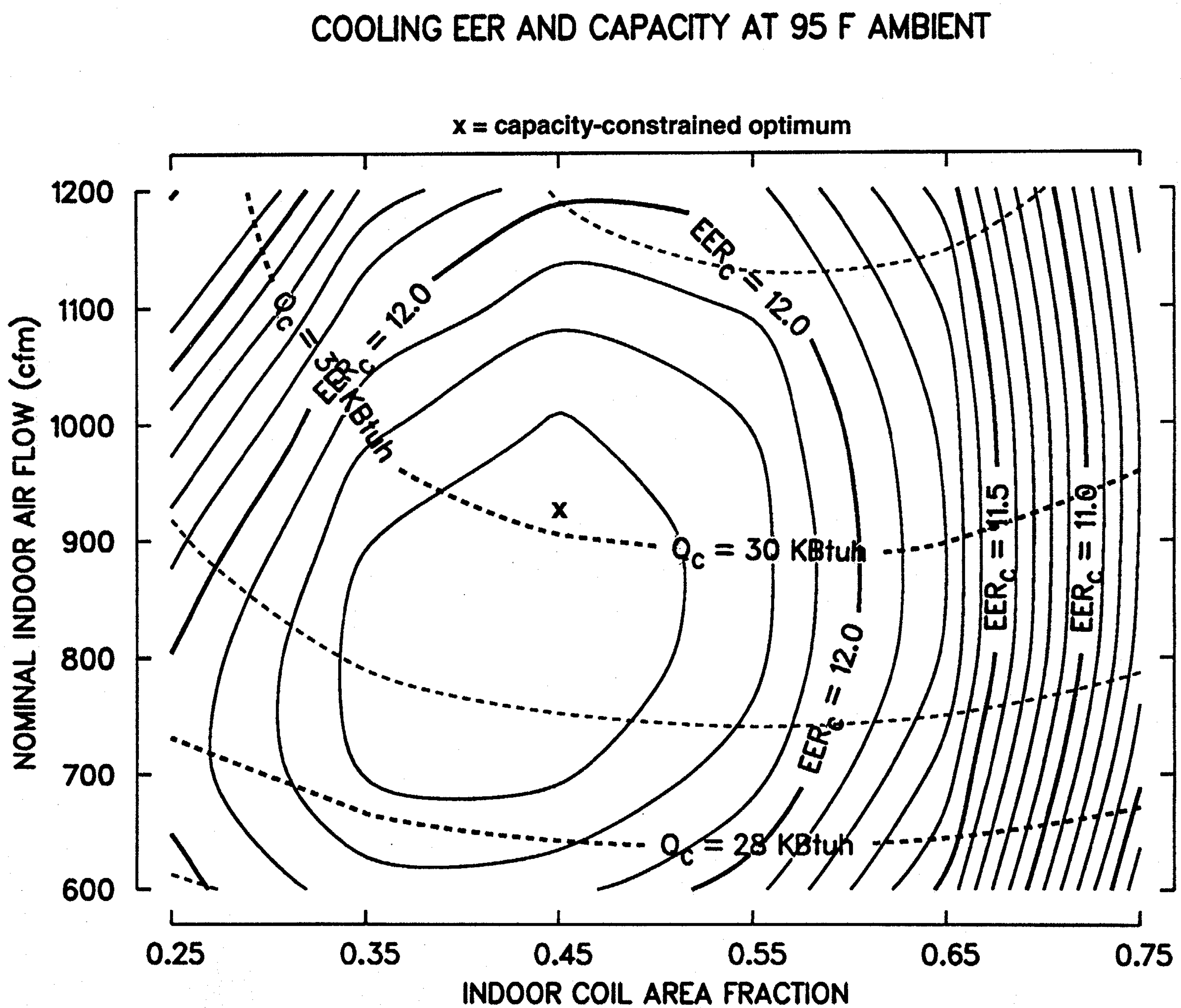
- Optimization Variables
  - Interdependent
    - Compressor displacement
    - Nominal airflow rates -- indoor and outdoor
    - Indoor fraction of total area
    - Condenser subcooling
  - Weakly-interacting
    - # of coil rows and circuits -- indoor and outdoor

Nominal Design Analysis (continued)

- Assumptions
  - Design capacity of 2 1/2 tons cooling
  - Auto-sizing of motors to nominal conditions
    - compressor motor sized to 130% of rated Hp
    - fan motors sized to 75% of rated Hp
  - External ΔP of 0.15 inches water
  - 10 F° evaporator superheat



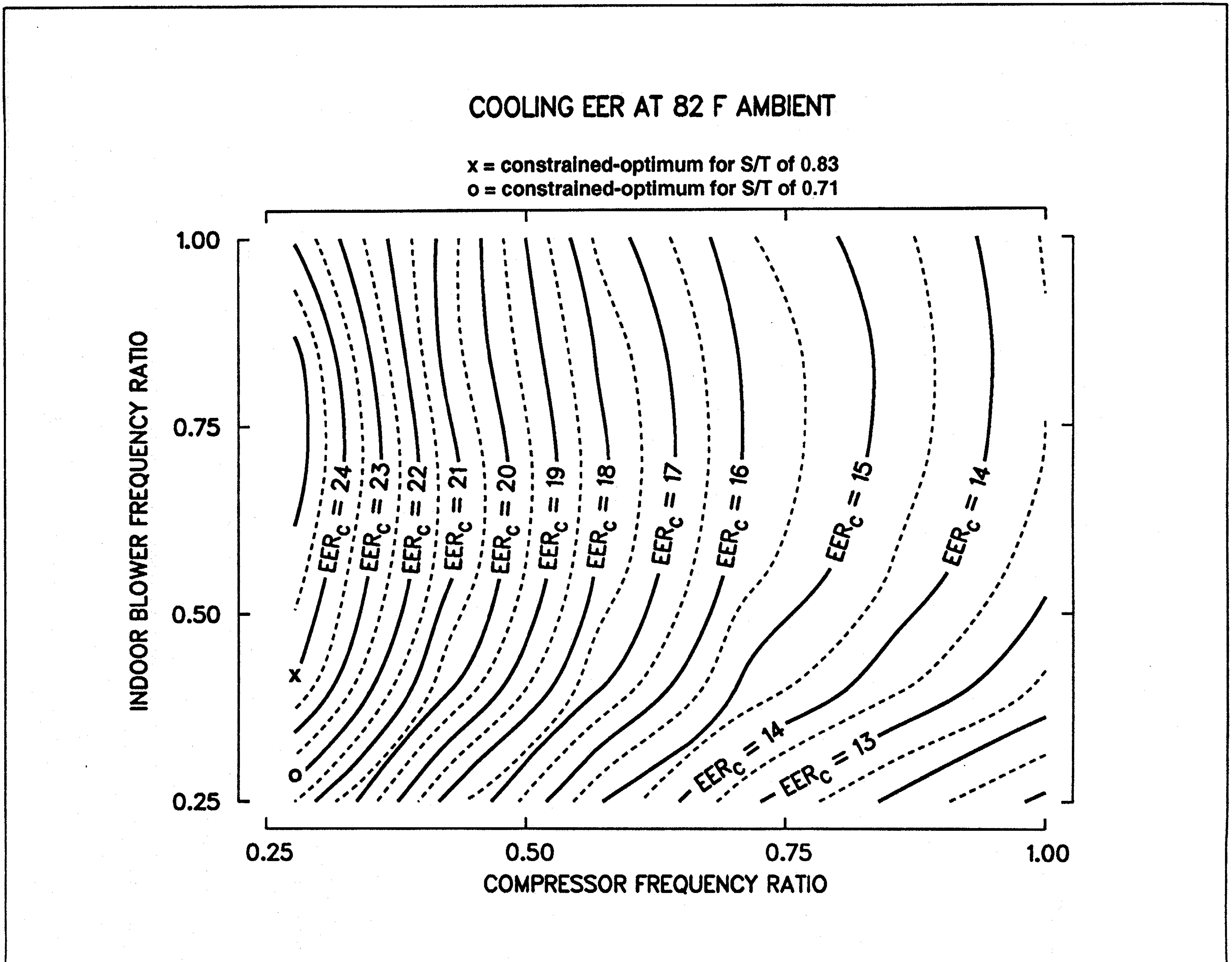
COOLING EER AND CAPACITY AT 95 F AMBIENT
x = capacity-constrained optimum
NOMINAL INDOOR AIR FLOW (cfm)
1200
1100
1000
900
800
700
600
1.2
1.4
1.6
1.8
2.0
2.2
COMPRESSOR DISPLACEMENT (in³)
Qc = 25 KBtuh
EERc = 12.5
Qc = 30 KBtuh
EERc = 12.0
Qc = 35 KBtuh
EERc = 11.5


COOLING EER AND CAPACITY AT 95 F AMBIENT
x = capacity-constrained optimum
NOMINAL INDOOR AIR FLOW (cfm)
INDOOR COIL AREA FRACTION
1200
1100
1000
900
800
700
600
0.25
0.35
0.45
0.55
0.65
0.75
EER_c = 12.0
Q_c = 30 KBtuh
Q_c = 28 KBtuh
EER_c = 11.5
EER_c = 11.0
x

STEADY-STATE DESIGN APPROACH (continued)

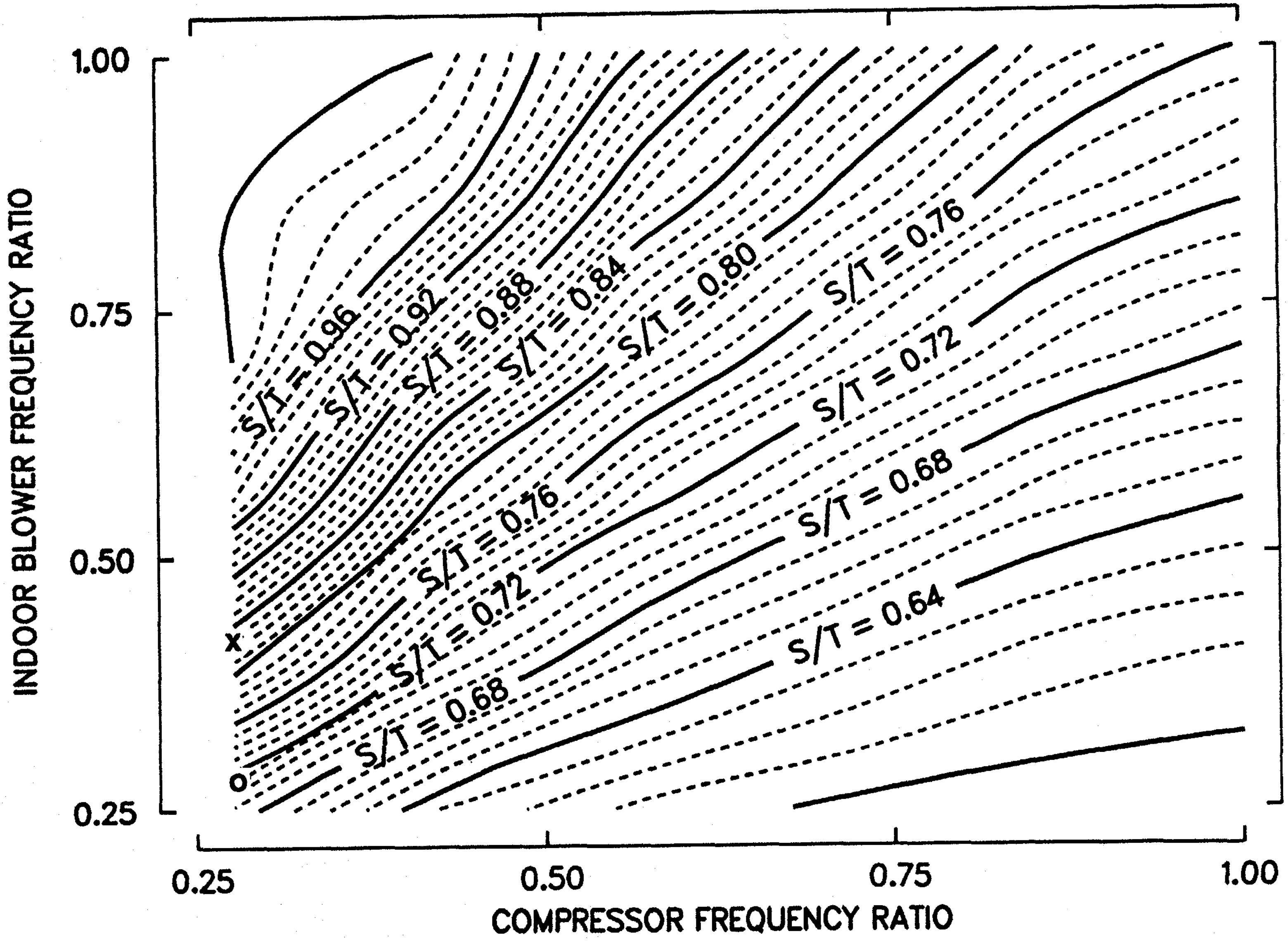
Off-Design Analysis

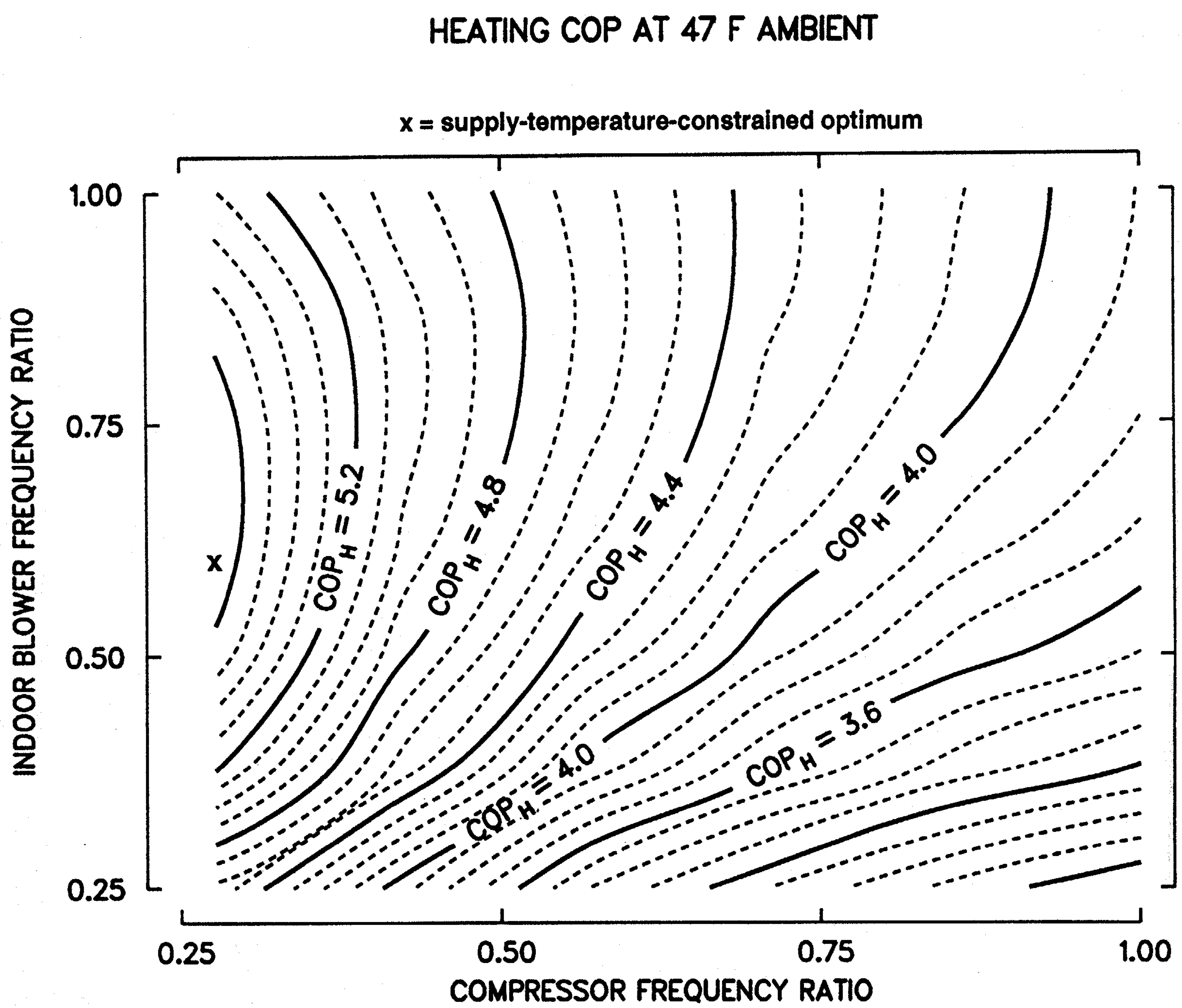
- Variables Optimized
  - Indoor and outdoor fan operating speed ratios
  - Condenser subcooling
- Design Constraints
  - Capacity -- Minimum or Maximum
  - Comfort Conditions -- S/T Ratios and Supply Temps
    - comparable to SOA reference unit
    - relaxed S/T ratio

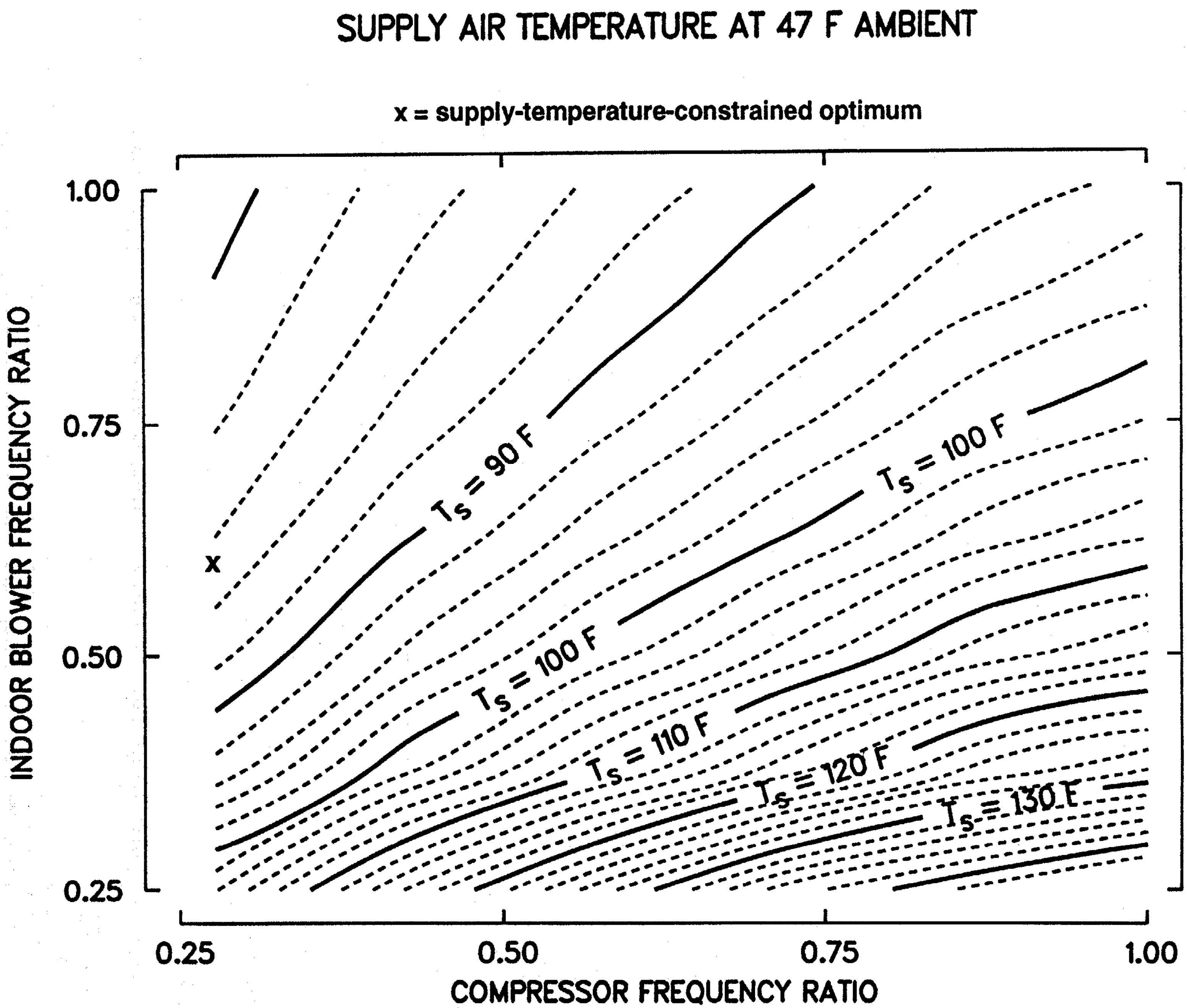

COOLING EER AT 82 F AMBIENT
x = constrained-optimum for S/T of 0.83
o = constrained-optimum for S/T of 0.71
INDOOR BLOWER FREQUENCY RATIO
COMPRESSOR FREQUENCY RATIO
1.00
0.75
0.50
0.25
0.25
0.50
0.75
1.00
EERc = 24
EERc = 23
EERc = 22
EERc = 21
EERc = 20
EERc = 19
EERc = 18
EERc = 17
EERc = 16
EERc = 15
EERc = 14
EERc = 14
EERc = 13
x
o

SENSIBLE–TO–TOTAL CAPACITY RATIO AT 82 F AMBIENT

x = constrained-optimum for S/T of 0.83
o = constrained-optimum for S/T of 0.71




HEATING COP AT 47 F AMBIENT
x = supply-temperature-constrained optimum
x
COP H = 5.2
COP H = 4.8
COP H = 4.4
COP H = 4.0
COP H = 4.0
COP H = 3.6
1.00
0.75
0.50
0.25
0.25
0.50
0.75
1.00
INDOOR BLOWER FREQUENCY RATIO
COMPRESSOR FREQUENCY RATIO



SUPPLY AIR TEMPERATURE AT 47 F AMBIENT
x = supply-temperature-constrained optimum
1.00
0.75
0.50
0.25
INDOOR BLOWER FREQUENCY RATIO
0.25
0.50
0.75
1.00
COMPRESSOR FREQUENCY RATIO
x
Ts = 90 F
Ts = 100 F
Ts = 100 F
Ts = 110 F
Ts = 120 F
Ts = 130 F

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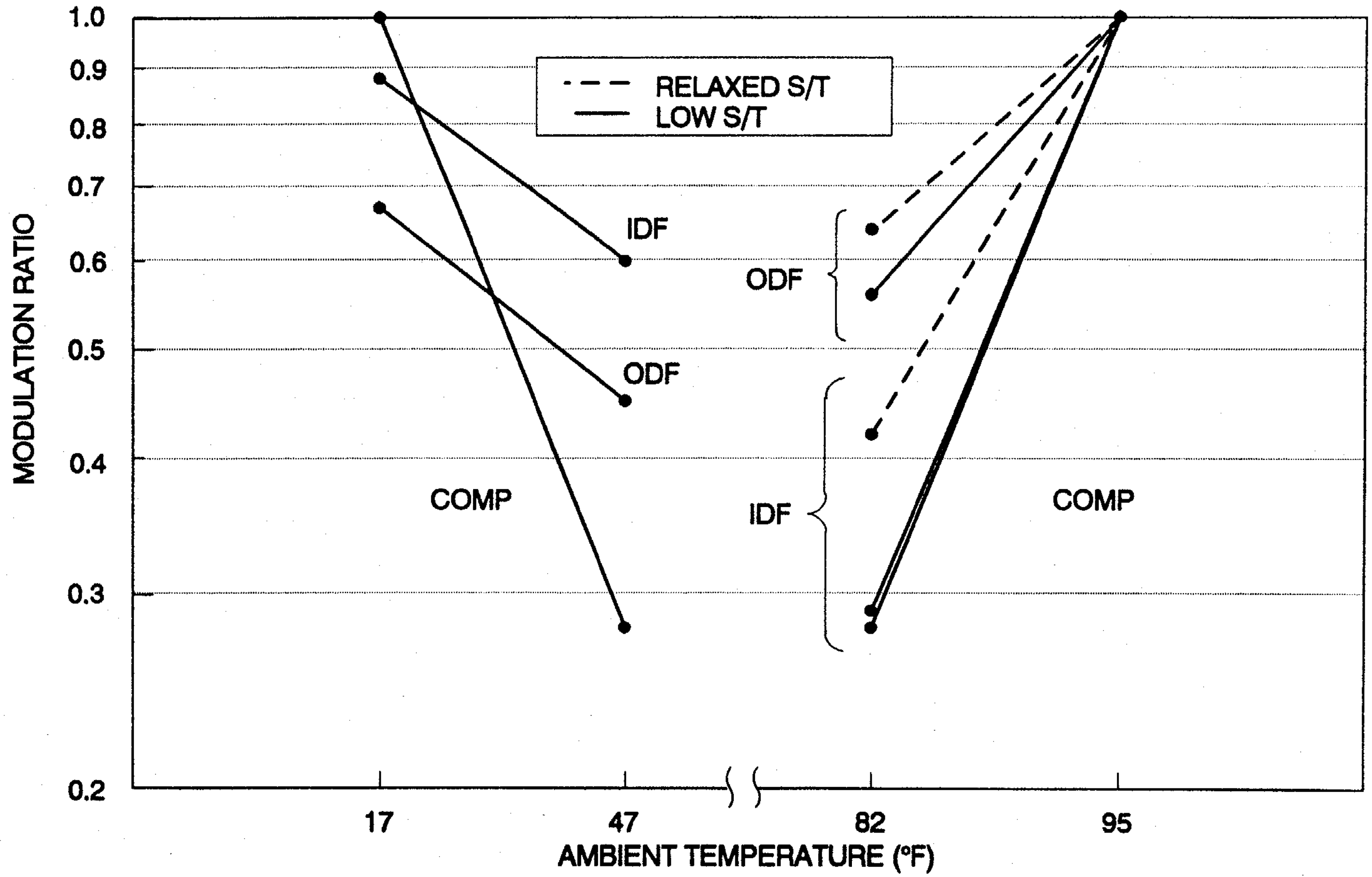
Fan Modulation Ranges Are Narrower Than The Compressor

OPTIMAL CONTROL STRATEGIES



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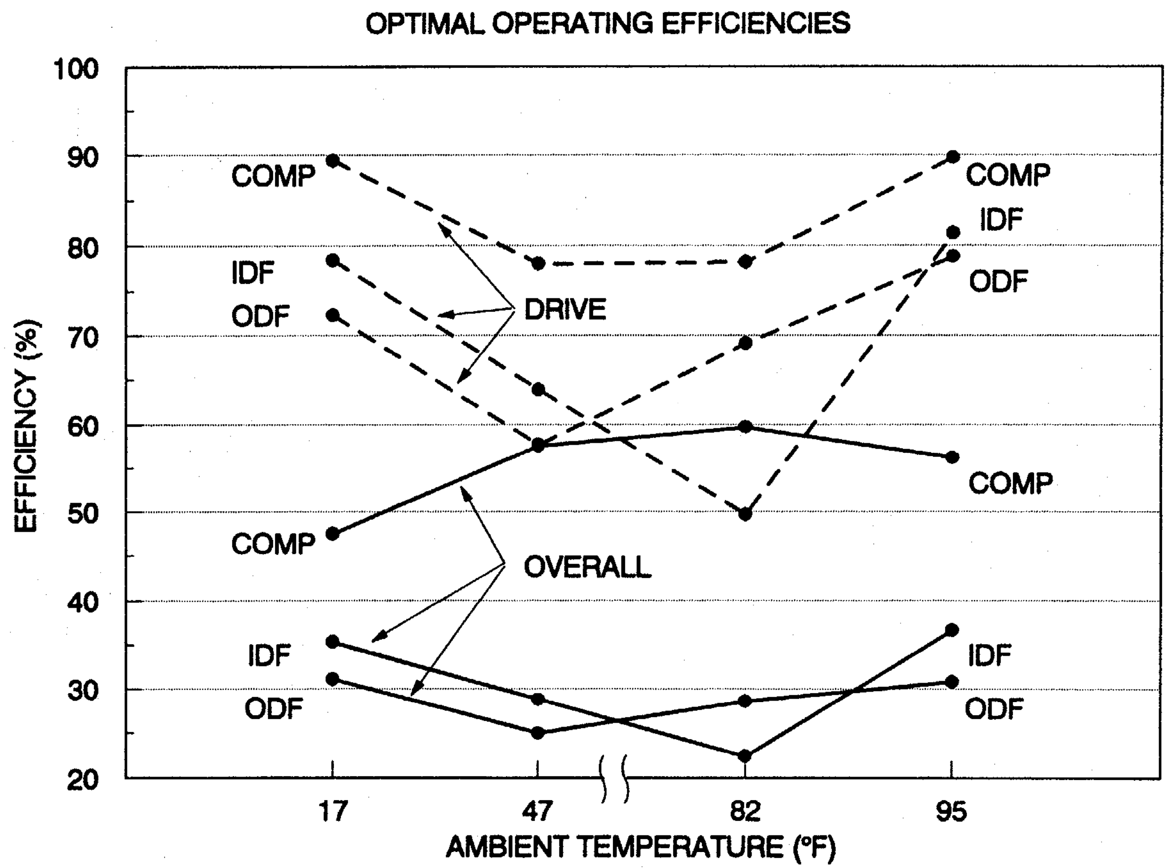
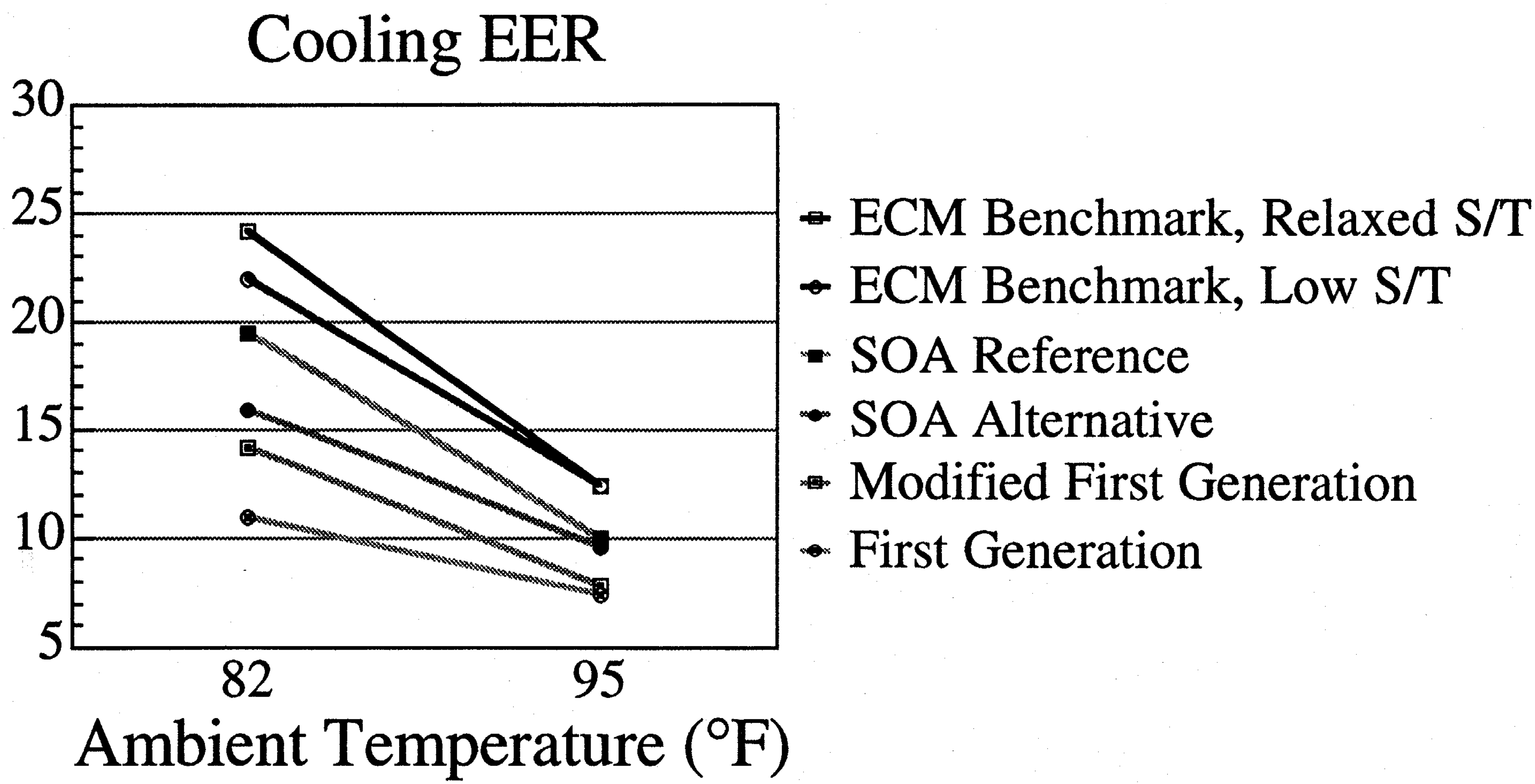
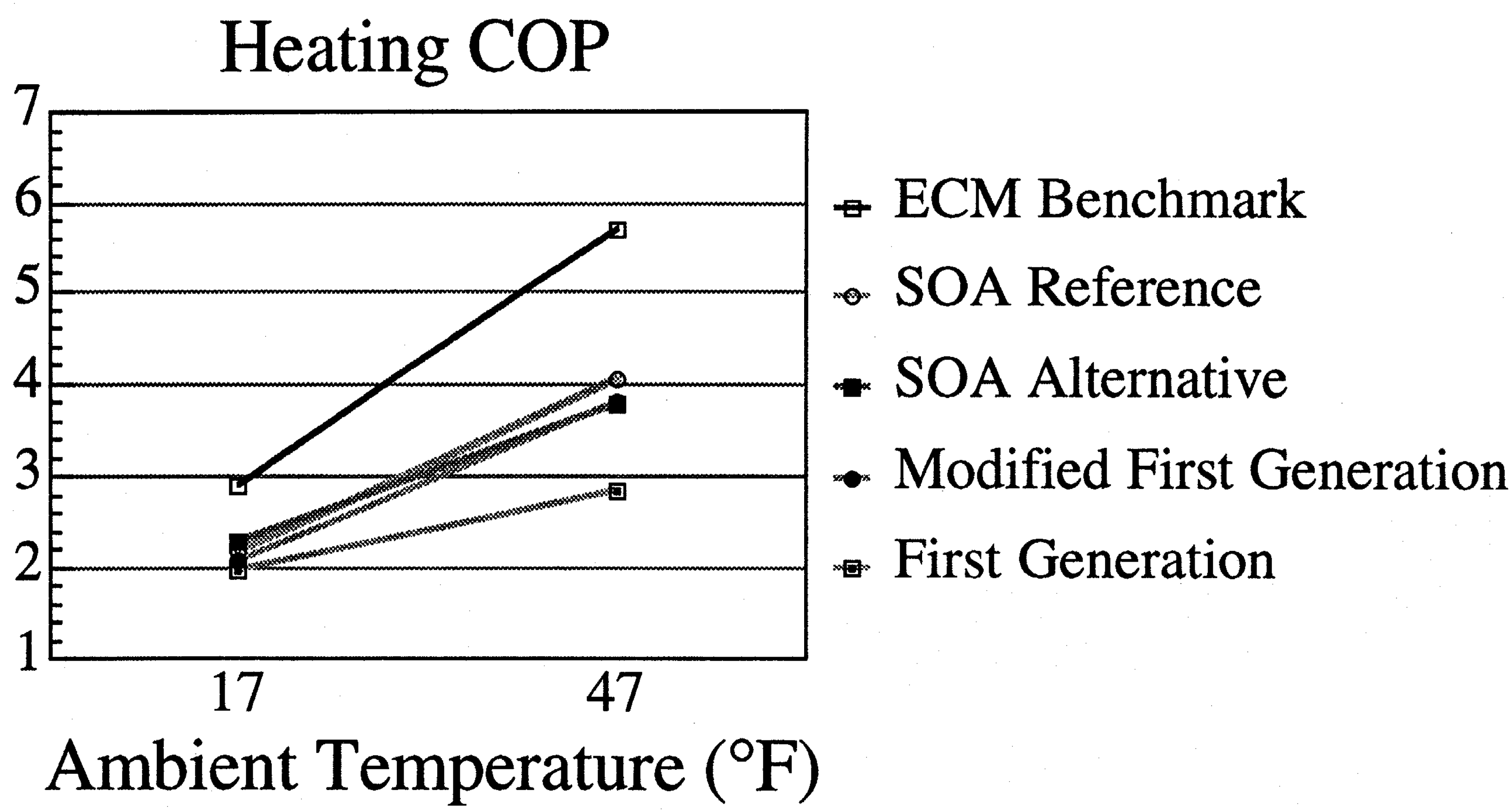
Drive and Overall Component Efficiencies Vary Considerably Over Operating Ranges

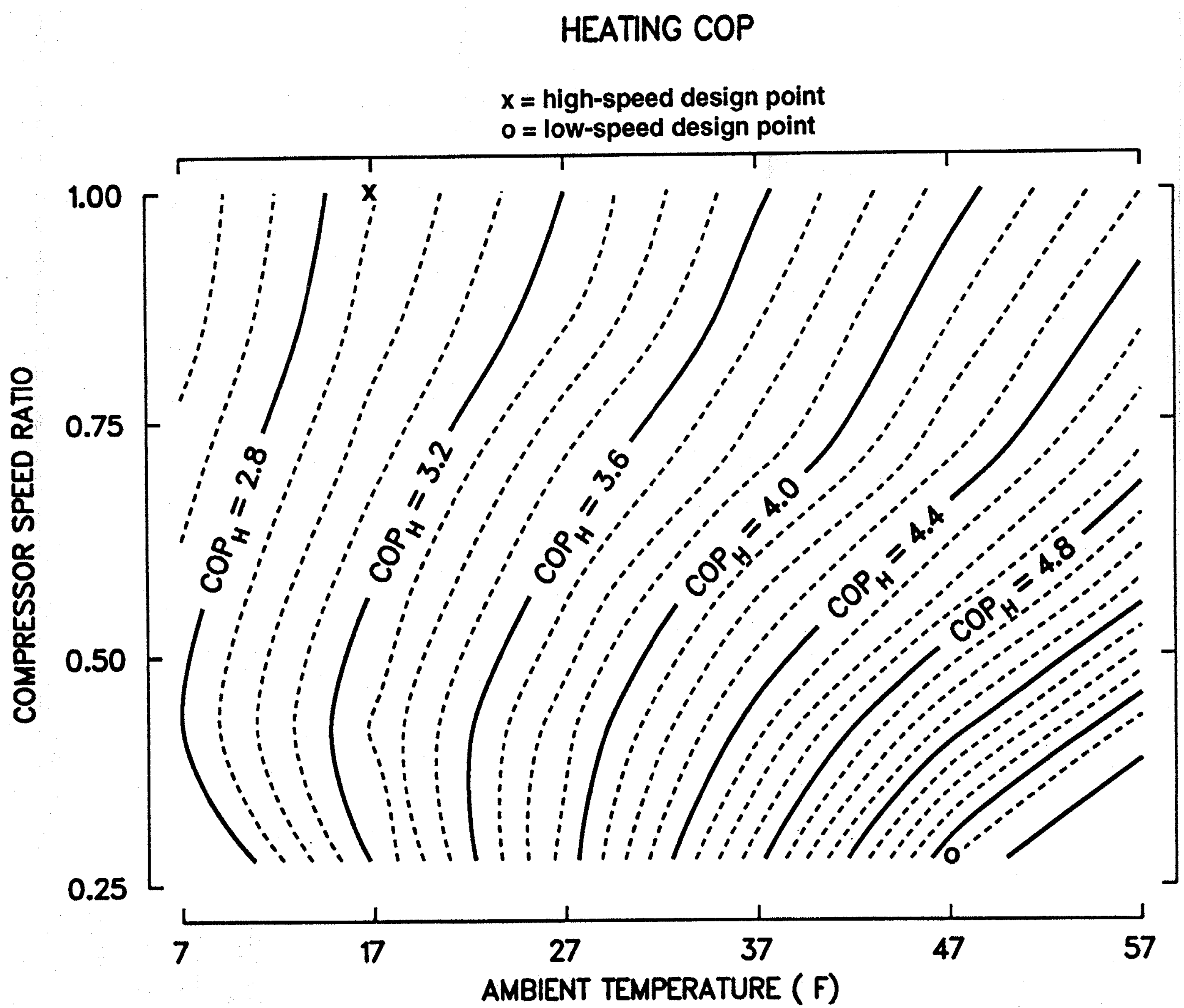


COMPARISON OF STEADY-STATE RESULTS

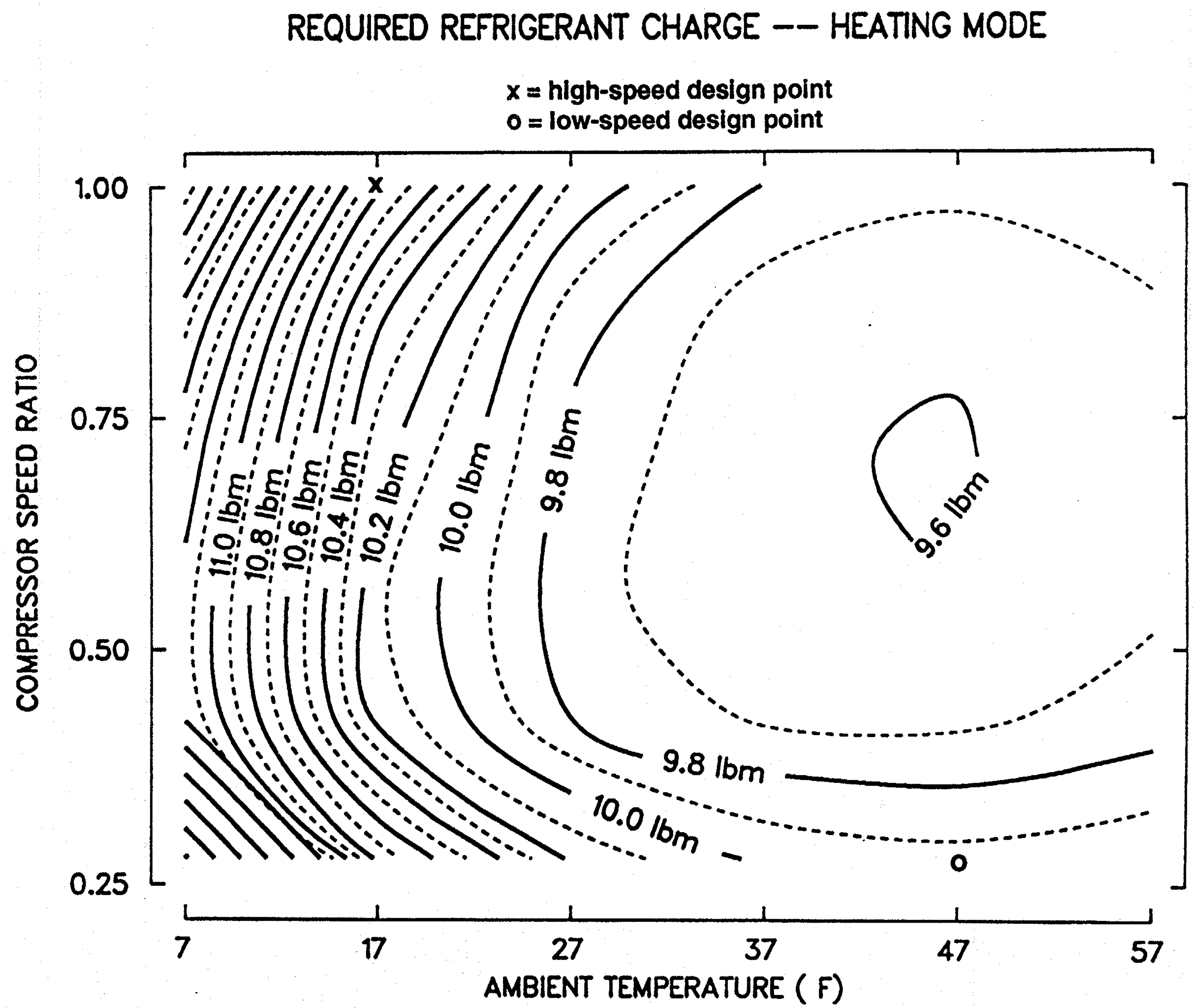


COMPARISON OF STEADY-STATE RESULTS





HEATING COP
x = high-speed design point
o = low-speed design point
COMPRESSOR SPEED RATIO
1.00
0.75
0.50
0.25
COPH = 2.8
COPH = 3.2
COPH = 3.6
COPH = 4.0
COPH = 4.4
COPH = 4.8
7
17
27
37
47
57
AMBIENT TEMPERATURE (F)


REQUIRED REFRIGERANT CHARGE -- HEATING MODE
x = high-speed design point
o = low-speed design point
COMPRESSOR SPEED RATIO
1.00
0.75
0.50
0.25
AMBIENT TEMPERATURE (F)
7
17
27
37
47
57
11.0 lbm
10.8 lbm
10.6 lbm
10.4 lbm
10.2 lbm
10.0 lbm
9.8 lbm
9.6 lbm
9.8 lbm
10.0 lbm

SEASONAL PERFORMANCE RESULTS

House-Loads-Based Seasonal Model

- Binned Weather For DOE Region IV City
  - Columbus, Ohio
- 1800 ft^2 House
  - HUD minimum insulation
- Nominal Unit Sizing Per DOE Procedure
  - Scaled unit capacity as needed
- Full Speed vs Ambient SS Performance Mapping
- Default C_D's of 0.25

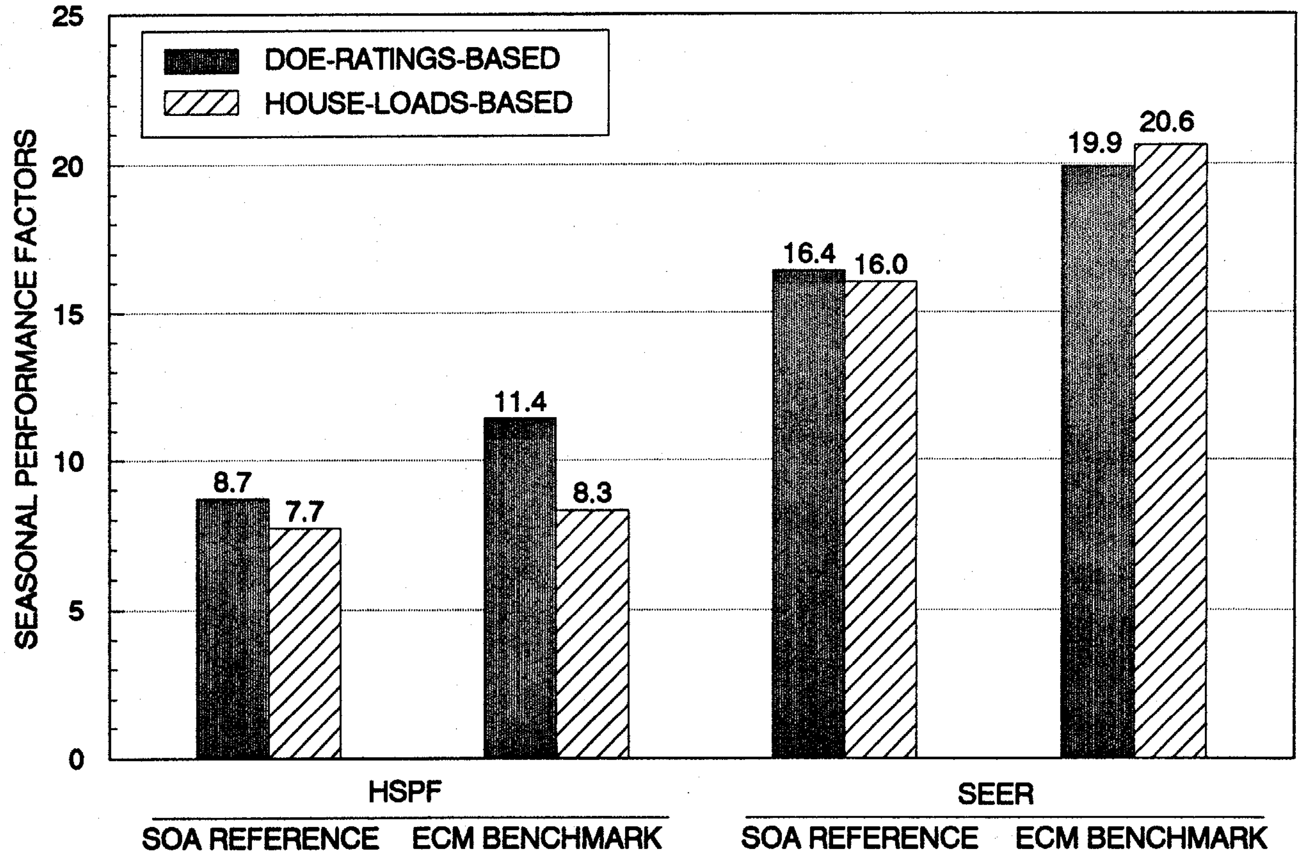
SEASONAL PERFORMANCE RESULTS

DOE Ratings Analysis

- Normalized Region IV Weather Profile
- Minimum DHR
- DOE Unit Performance Specification
  - Min, max, and intermediate speeds
  - At selected ambients
- Default C_D's of 0.25

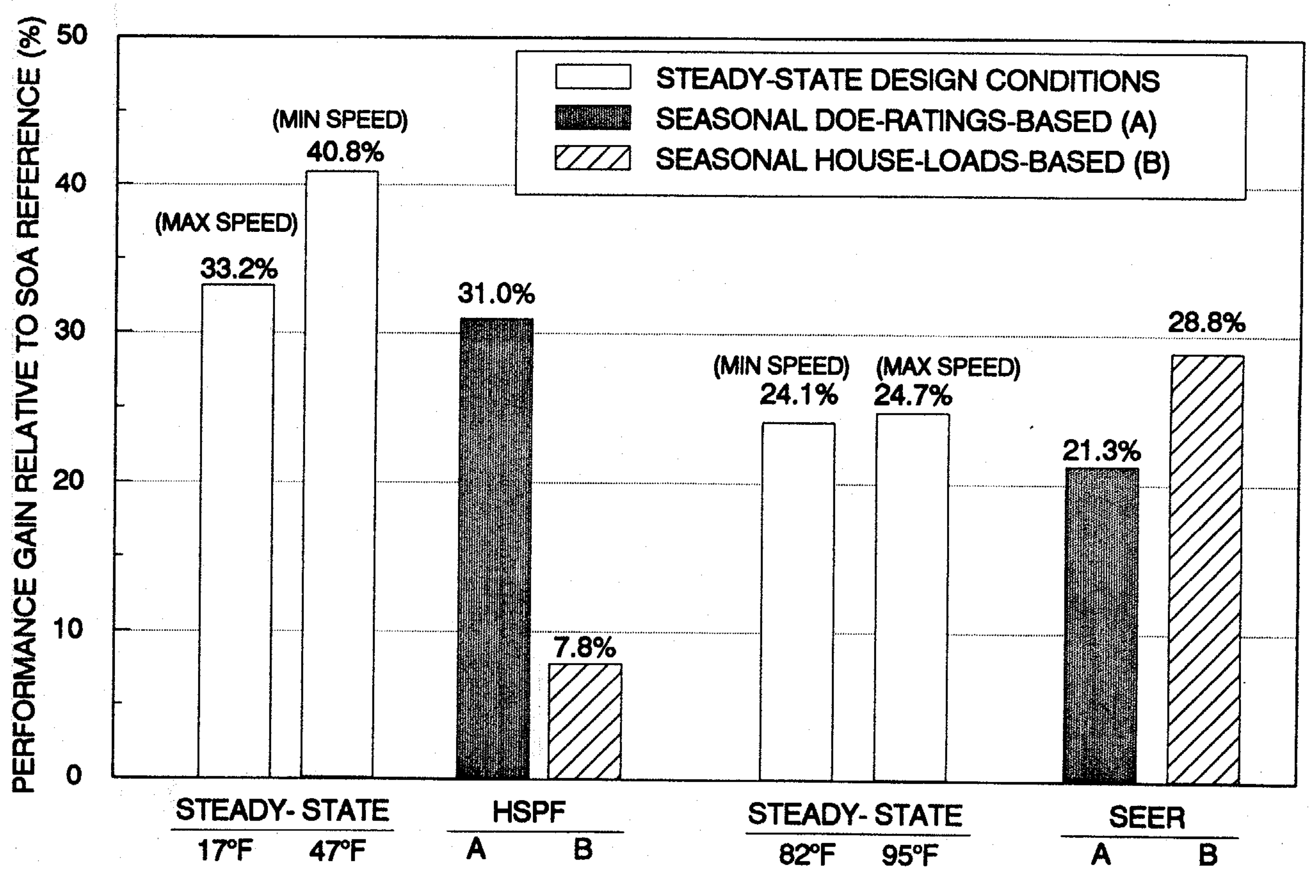
Predicted Seasonal Performance Factors For SOA Reference and ECM Benchmark

(DOE Region IV--Nominal Unit Sizing)



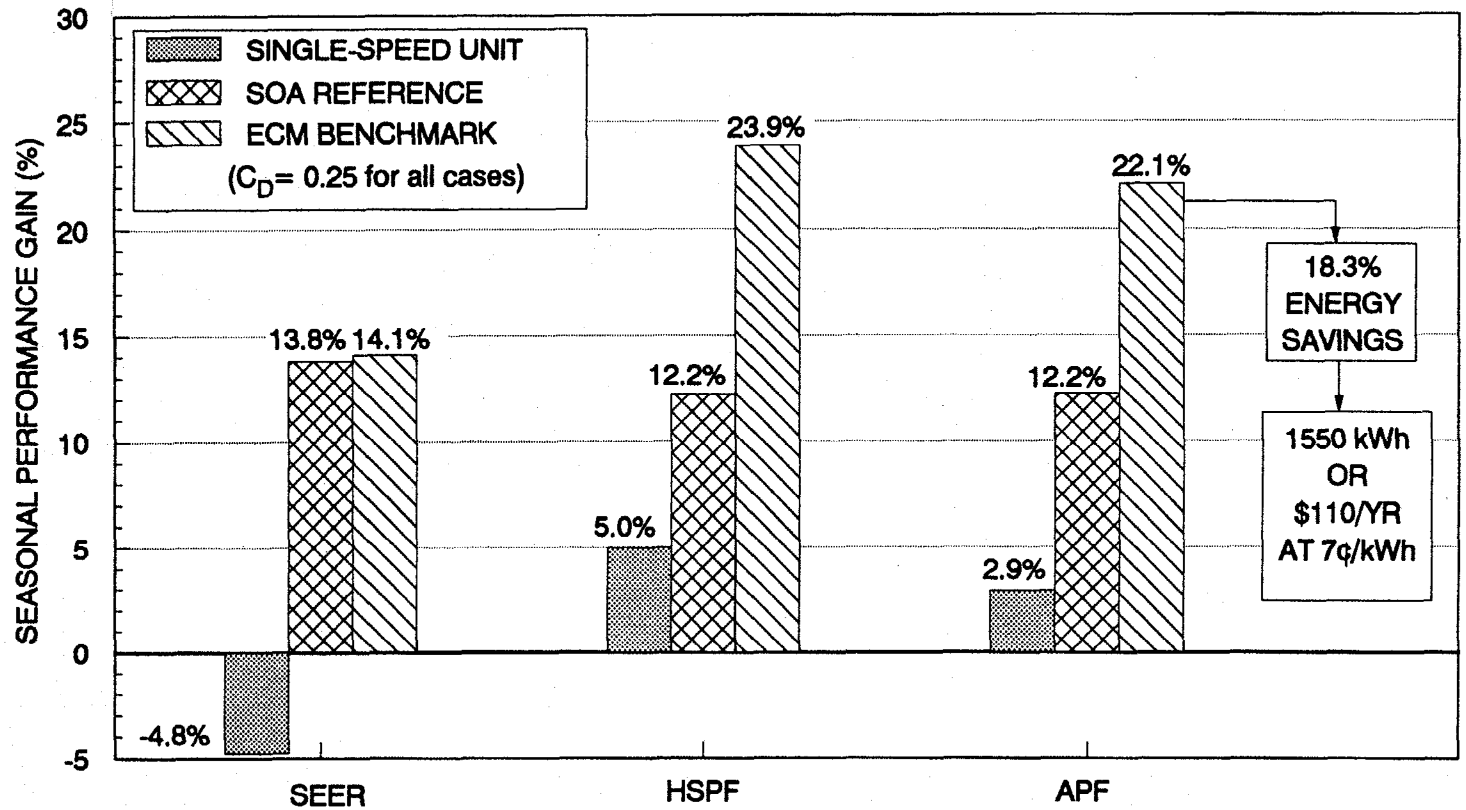
HSPF Gain for ECM Benchmark Is Overpredicted By DOE Rating Procedure

(DOE Region IV -- Nominal Unit Sizing)



50% Oversizing Gives A Large Boost To Region IV Heating and Annual Performance For High-Efficiency Modulating Units

(House-Loads-Based)



CONCLUSIONS

- For a Best-Case Optimized Design
  - Upper limit SEER of 20 with relaxed S/T ratios
  - Steady-state heating gains greater than cooling
  - Only 8% HSPF gains vs 29% SEER increase
    - for standard unit sizing
- Oversizing More Beneficial For Modulating Heat Pumps
- Lower-Cost Alternatives To Oversizing Need Evaluation
  - More compressor overspeed in heating mode
  - Use of a scroll compressor
- DOE Ratings Overestimate Typical HSPFs

CONCLUSIONS (continued)

- An Optimized Modulating Design Can Be Obtained
  - With 4-point approach
- Decisions Remain With Design Engineer
  - Rather than with black-box routines
- Modulating Design Model Is A Viable Desktop Tool
  - For optimizing air-to-air heat pumps
    - using built-in parametrics
    - and available contour plotting software
- Program Is Available To HVAC Industry
  - Can be used to optimize designs for pure refrigerant alternatives
    - e.g., Spatz -- 1991 CFC Alternatives Conference

UNRESOLVED ISSUES

Estimated Contributors To Predicted COP Gains

- ✦ First Level
  - Relaxed S/T ratios at lower speeds (cooling only)
  - Optimal air flow control
  - Internal and external H.T. augmentation
- ✦ Second Level
  - Closer motor sizing
    - fans -- especially indoor
  - Optimal refrigerant flow control
- ✦ Third Level
  - No line or reversing valve losses
  - No filters/chokes on ECM drives
  - Ideal circuiting and flow arrangement assumptions