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AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF WET AND DRY COIL CONDITIONS ON CYCLIC PERFORMANCE IN THE SEER PROCEDURE

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ABSTRACT

In the Unites States, residential air conditioners (ACs) and heat pumps (HPs) are rated by a test procedure that estimates seasonal efficiency, or SEER. One part of the test procedure -- the cyclic test -- determines the efficiency degradation when the AC system cycles ON and OFF. The cyclic test is presently conducted at dry coil conditions, even though most systems operate the majority of the time at wet coil conditions.

In this paper, cyclic test results are presented for two AC systems -- one constant-speed (CS) and one variable-speed (VS) -- at both wet and dry coil conditions. The results indicate that wet and dry cyclic tests are not equivalent, as had been assumed [5]. The wet coil cyclic test results in a 9% smaller SEER than the dry coil cyclic test for the CS system, and 4% smaller SEER for the VS system. A new method for conducting the cyclic test at wet coil conditions is presented.

INTRODUCTION

In the late 1970's, the United States Department of Energy (DOE) developed and implemented a rating procedure to determine the efficiency of residential air conditioners (ACs) and heat pumps (HPs) in the cooling mode. This procedure consists of a series of laboratory tests that manufacturers are required to perform to determine the Seasonal Energy Efficiency Ratio (SEER).

The purpose of this paper is to examine one particular aspect of the test procedure: the cyclic test. Presently, the cyclic test is performed at dry coil conditions (sensible only, no moisture removal), even though most systems operate at wet coil conditions in the majority of applications. The cyclic performance of two AC systems is experimentally examined; one constant-speed (CS) system and one variable-speed (VS) system are tested. Tests are run at both wet and dry coil conditions and the results are compared.

Overview of SEER Test Procedure

The SEER procedure consists of a series of steady-state and cyclic laboratory tests, which are specified in detail in the Federal Register [1], as well as ARI and ASHRAE Standards [2,3]. The required tests for a conventional, CS systems are listed in Table 1.

TABLE 1
Tests Required for SEER Determination:
Constant-Speed (CS) Systems

Test	Operation	Indoor DB/WB	Outdoor DB
A	Steady-State	80°F / 67°F	95°F
B	Steady-State	80°F / 67°F	82°F
C	Steady-State	80°F / 57°F*	82°F
D	Cyclic**	80°F / 57°F*	82°F

Notes:
* - such that no condensate forms on indoor coil
** - 6 minutes ON; 24 minutes OFF

Tests A and B are steady-state tests which are used to determine the effect of outdoor temperature on steady-state cooling capacity and electrical energy use. Tests C and D are used to determine the degradation coefficient (C_D); C_D is the rate at which part load efficiency decreases as the building load decreases (see Figure 1). The results of these tests are combined with a simple linear building load model and bin weather data to determine the SEER.

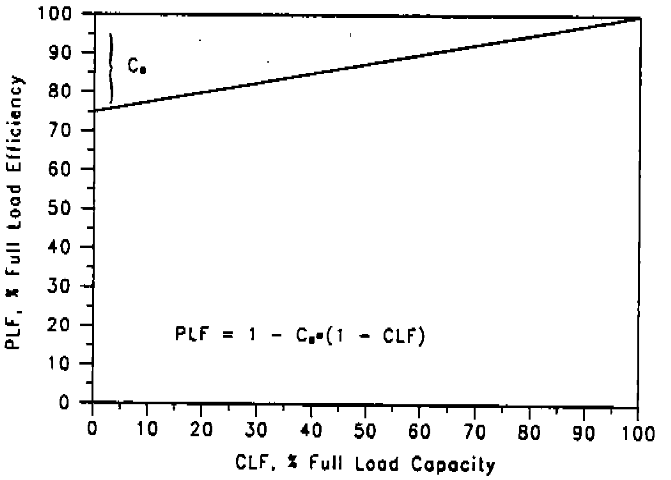

Figure 1 - Definition of C_D: PLF verses CLF

Recently, variable-speed systems have been introduced and the SEER procedure has been modified to include them [4]. Since VS systems vary compressor speed to meet the building load, five steady-state tests are required: tests A and B at the highest speed (95°F & 82°F outdoors); tests a and b at the lowest speed (82°F & 67°F outdoors); and an intermediate speed test (87°F outdoors). Tests C and D are still required, since the system will cycle ON and OFF when the building load is less than the system capacity at the lowest speed. However, tests C and D are performed at the minimum compressor speed and at an outdoor temperature of 67 °F for VS systems.

<u>Determining Part Load Degradation (C_D)</u>

The cyclic test for both VS and CS systems (test D) is performed at dry coil conditions (i.e., low humidity) such that no moisture condenses on the evaporator. Test C is the steady-state test, to which test D is compared. For the cyclic test, the cooling capacity (q_{cyc}) is determined by integrating the temperature difference across the evaporator from unit startup until 2 minutes after compressor shutdown (8 minutes total). The calculations required to determine C_D are given in the Appendix.

Most of the original development work for the SEER test procedure was done by Kelley and Parken [5] at the National Institute of Standards and Technology (NIST; formerly NBS). They noted that performing the cyclic tests at wet coil conditions (80°F DB and 67°F WB) was most representative of actual operation. However, they found that measuring total capacity (both latent and sensible) was difficult at wet coil conditions. Therefore, they proposed performing the cyclic test at dry coil conditions as a simpler, more accurate alternative. They justified the use of the dry coil test with the following assumption:

$$\frac{EER_{cyclic,\ dry}}{EER_{ss,\ dry}} = \frac{EER_{cyclic,\ wet}}{EER_{ss,\ wet}} \qquad (1)$$

Though they reported to have experimental evidence to validate equation (1), this author and others [6] have found none reported in the open literature. The ratio of cyclic and steady-state EER is used to determine C_D, and therefore has an important impact on the calculation of SEER.

The Effect of C_D on SEER

Once the degradation factor C_D has been determined, it is used to determine the part-load efficiency when the AC system cycles ON and OFF to meet the load (see Figure 1). In Figure 2, the variation of SEER with C_D is shown for typical CS and VS systems. Note that C_D has a much smaller impact on the SEER of the VS system. This is because the VS system modulates to meet the building load, and therefore cycles ON and OFF much less. Therefore, an error in determining C_D will impact the SEER of CS systems more than VS systems.

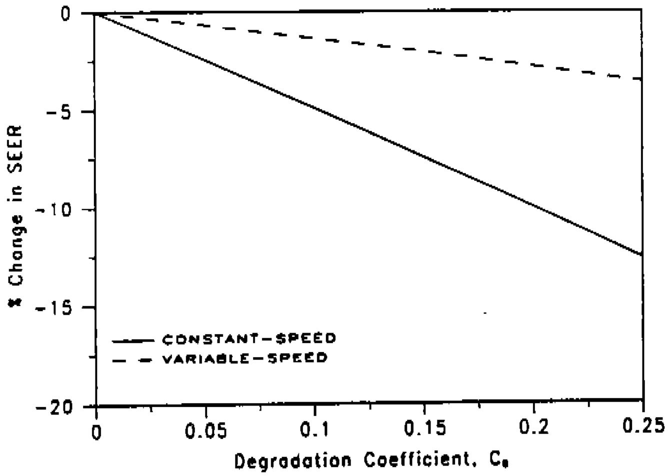

Figure 2 - The Effect of C_D on SEER

EXPERIMENTAL METHOD

Two AC systems, a constant-speed (CS) and variable-speed (VS), were tested according to the standard SEER test procedure. The cyclic test was also repeated at wet coil conditions. The systems, instrumentation, and data analysis are discussed below.

Description of Tested AC Systems

The CS system discussed in this paper was a conventional, commercially available "split-system" heat pump. Its nominal capacity was 2 tons (7 kW) and its rated SEER was 9.0. This system was chosen as typical of many AC systems in use today.

The VS unit was a modified, cooling only, variable-speed, "split-system" air-conditioner. The factory controls were removed, and new controls installed so that the tests required for the SEER procedure could be more easily performed. Off-the-shelf fan motors and inverters were added to the system, and a new inverter was added to the existing three-phase scroll compressor. The fans, compressor, and expansion device were independently controlled by a microcomputer.

Both systems used "fixed, short-orifice" expansion devices.

Instrumentation and Test Chambers

All testing took place in a laboratory with two environmental chambers capable of maintaining indoor and outdoor conditions. The indoor unit was installed in one chamber, and the outdoor unit was installed in the other. The conditions in both chambers were independently controlled to the desired condition by an automatic data acquisition and control system. The minimum dew point obtainable for the dry coil tests was 43°F for steady-state tests, and 47°F for transient tests. This resulted in no less than 99% sensible capacity and was considered adequate for these tests.

The instrumentation was designed to measure both the "air-side" and the "refrigerant-side" performance of the system. In Figure 3, the location and type of instrumentation are shown schematically.

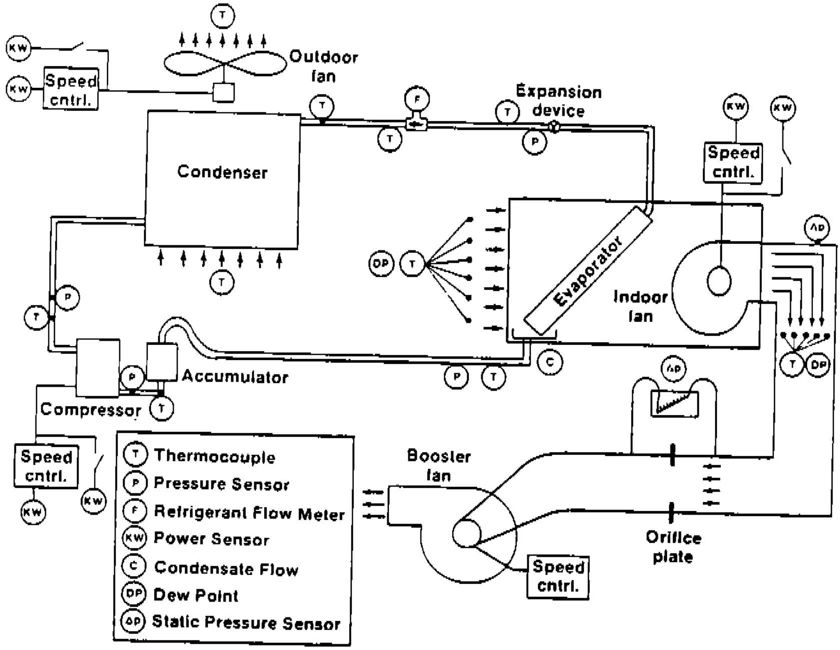

Figure 3 - Schematic of Test Setup and Instrumentation

Refrigerant Temperatures were measured with 22 gauge, type-T thermocouples (TCs). Each TC was attached to the outside of the refrigerant tubing with thermally-conductive epoxy and insulated from the air with "tar-tape" and foam insulation.

Air Temperatures were also measured with 22 gauge, type-T TCs. The evaporator entering and leaving air temperatures were measured with grids of TC junctions connected in parallel. For the constant-speed system, a grid of 5 junctions was used; for the variable-speed system, a grid of 9 junctions was used. The size of each junction was minimized to ensure a time constant of 2.5 seconds or less.

Dew Point temperatures entering and leaving the evaporator were measured with chilled-mirror hygrometers. A pump pulled air from a sampling tree in the duct to the hygrometer at a rate of 3 SCFH. The entering and leaving hygrometer were calibrated with respect to each other to within ±0.1 °F.

At 3 SCFH, the dew point hygrometer was stable at steady-state conditions and responded quickly to sudden changes in dew point. The hygrometers time constant of response was measured to be 5-10 seconds. Using an analytical analysis similar to that used by Lamb and Tree [7] for TCs, the expected error due to sensor lag in the cyclic latent capacity test is expected to be less than 3% (based on 60 second AC time constant; 10 second sensor time constant; 360 second integration time).

Pressure Sensors were used at various point around the refrigerant system. They were calibrated using a dead-weight tester.

Electrical Power Sensors measured the "true power" consumption of the compressor, indoor fan, and outdoor fan.

Condensate Flow from the evaporator was measured with a modified "tipping bucket" rain gauge. Each cycle, or tip, corresponded to a known quantity of water (0.021 lbs.).

Refrigerant Flow was measured with a turbine flow meter (volumetric). A thermocouple measured the temperature of the liquid refrigerant at the flow meter; from the temperature, the density was calculated and the mass flowrate was determined.

Air Flow Rate was determined by measuring the static pressure drop across a square-edged orifice plate. A booster fan with a speed control made up for the static pressure loss through the orifice plate. In a thermal calibration test, the measured and predicted air flow were within 3% across the range of operation.

Data Acquisition and Analysis

An automatic data acquisition system monitored all measured points approximately every 15 seconds. Data were saved on a minicomputer for later analysis and reduction. The total, sensible, and latent cooling capacity of the system were calculated by the "air-enthalpy" method described in ASHRAE [8]. The enthalpy and specific volume of air were calculated from the temperature and dew point at each scan using psychrometric routines on a minicomputer.

To check total capacity, the measured refrigerant mass flow rate was compared to mass flow rate calculated from the total "air-side" capacity, fan heat, and refrigerant enthalpy change across the evaporator. The refrigerant enthalpy was calculated from the measured temperatures and pressures using property routines for R-22.

To check latent capacity, the measured mass flow rate of condensate from the evaporator was compared to the calculated condensate flow rate based on the air flowrate and the dew point change across the evaporator.

For each steady-state test, the measured and calculated refrigerant flow and condensate flow were compared. For all steady-state tests, the measured and calculated values agreed to within 3%.

RESULTS

Both the constant-speed and variable-speed systems were tested to determine the SEER using the standard test procedure. The cyclic tests were then repeated at wet coil conditions for both systems.

Standard SEER Tests

The SEER was calculated for both systems using the standard procedure. The results for the constant-speed and variable-speed systems are given in Table 2 and 3, respectively.

TABLE 2
Results of Standard SEER Test Procedure:
Constant-Speed (CS)

Test	Capacity, Btuh			EER
A	21410			7.87
B	23474			9.48
C	21292*			8.88
D	q_{cyc}	=	2064 Btu*	
	EER_{cyc}	=	8.25	
	C_D	=	0.088	
	SEER	=	9.00	

Notes: * - sensible cooling only
Air flow = 700 cfm; static pressure = 0.37 inches H_2O

TABLE 3
Results of Standard SEER Test Procedure:
Variable-Speed (VS)

Test	Capacity, Btuh			EER
A (90 hz)	29016			6.22
B (90 hz)	28177			7.18
a (30 hz)	12840			12.03
b (30 hz)	14723			16.17
i (41.7 hz)	18493			11.51
C (30 hz)	11867*			13.17
D (30 hz)	q_{cyc}	=	1042 Btu*	
	EER_{cyc}	=	11.86	
	C_D	=	0.120	
	SEER	=	11.50	

Notes: * - sensible cooling only
Maximum (90 hz) air flow = 900 cfm; static pressure = 0.62 inches H_2O
Minimum (30 hz) air flow = 300 cfm

Wet and Dry Coil Cyclic Tests

The cyclic test was repeated for both systems at wet coil conditions and total capacity was measured. In Figures 4 through 7, the measured transient total capacity for each AC system is shown at both wet and dry coil conditions. In Table 4, the wet and dry tests are compared for both CS and VS systems.

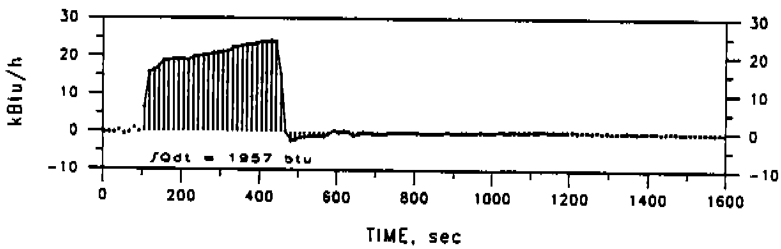

Figure 4 - Total Capacity at Wet Coil Conditions: CS system

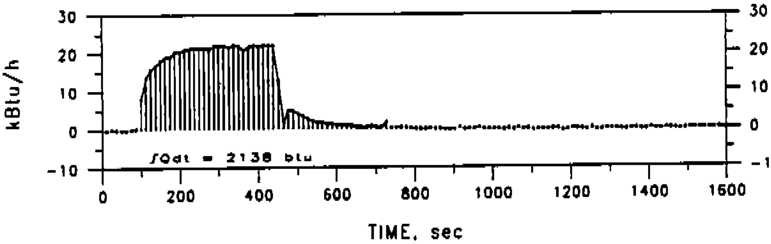

Figure 5 - Total Capacity at Dry Coil Conditions: CS system

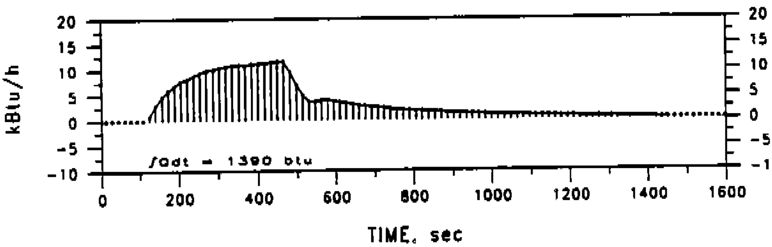

Figure 6 - Total Capacity at Dry Coil Conditions: VS system

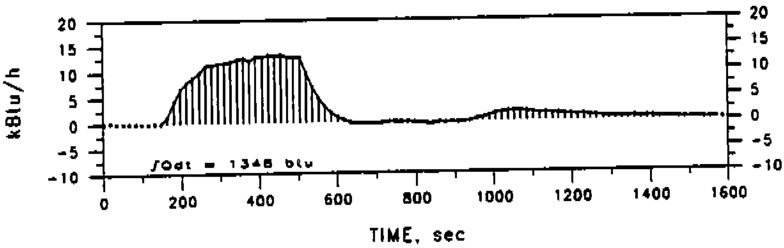

Figure 7 - Total Capacity at Wet Coil Conditions: VS system

TABLE 4
Comparison of Wet and Dry Coil Tests

	Constant-Speed (CS)			Variable-Speed (VS)		
	Wet <u>Coil</u>		Dry <u>Coil</u>	Wet <u>Coil</u>		Dry <u>Coil</u>
EER_{ss}	9.49		8.79	16.17		13.17
Integration Time, sec	1103		641	1438		1344
q_{cyc}, Btu*	1958		2138	1348		1390
EER_{cyc}**	7.88		8.54	14.63		15.80
EER_{cyc}/EER_{ss}	0.830	≠	0.972	0.905	≠	1.148
C_D***	0.204		0.035	0.116		-.191
SEER	8.45		9.25	11.51		11.95

Notes:
* Total capacity integrated until within 3% of zero.
** All EER_{cyc} are based on integrated instantaneous total capacity; fan heat is <u>not</u> added to q_{cyc} as specified in Appendix.
*** See equation (A3), Appendix for definition of C_D.

Note that the wet and dry EER ratios (EER_{cyclic}/EER_{ss}) are not equal for either the CS or the VS system. This runs counter to the assumption given by equation (1), which is the basis for the use of the dry coil cyclic test. These results indicate that C_D based on the dry coil cyclic test under-estimates the efficiency degradation at wet conditions. Since systems operate much of the time at wet coil conditions, the dry coil cyclic test is not representative of "real life" operating conditions.

The effect of C_D on SEER is shown in Table 4. Though the difference in wet and dry EER ratios are of similar magnitude for the CS and VS systems, the corresponding difference in SEERs is not. The SEER of the CS system based on the wet coil cyclic test is 9% less than the SEER based on the dry coil cyclic test. However, the wet SEER for the VS system is only 4% smaller.

No satisfactory reason could be found for the why the EER ratio was larger than zero for the VS system at dry coil conditions (which gives a negative C_D). Note that the integration time (to reach 3% of zero) was much longer for both tests with the VS system. In general, integrating small capacities over long intervals increases the amount of error.

Comparing Total and Sensible Capacity

In Figure 8, the total, sensible and latent capacity are shown for the VS system at wet coil conditions. Note that the integrated latent capacity is nearly zero over the entire cycle and the following is true:

$$\int_0^{\text{ON + OFF Cycle}} Q_{total}\,dt \approx \int_0^{\text{ON + OFF Cycle}} Q_{sensible}\,dt \qquad (2)$$

Equation (2) is also true for the CS system. For both systems total and sensible capacity are equal to within 2%

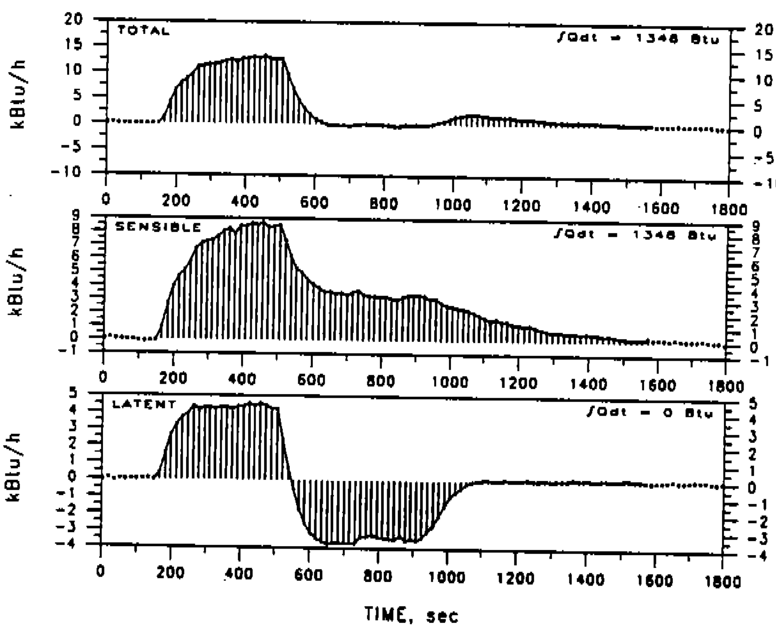

Figure 8 - Total, Sensible, and Latent Capacity at Wet Coil: VS system

Proposing a New Cyclic Test

The main reason given by Kelley and Parken [5] for using the dry coil cyclic test was the difficulty in measuring transient total capacity at wet coil conditions. One solution is to measure sensible capacity over the entire ON and OFF cycle at wet coil conditions. Besides providing a cyclic test at more realistic conditions, this change to the test procedure eliminates the need for test C. The results of a test D at wet coil conditions would be compared to test B to determine C_D.

Though only two systems have been tested here, it seems likely that equation (2) would hold for any system at the cyclic test conditions. Since the fan runs for the entire 24 minute OFF period, all condensate that forms on the coil during the ON period is adiabatically reabsorbed into the air during the OFF period. Equation (2) would not be valid if condensate drained from the unit during the compressor ON period. However, due to the nature of the cyclic test conditions (i.e., starting with a dry coil), this does not seem likely.

CONCLUSIONS

Presently, the cyclic test (i.e., test D) in the SEER test procedure is performed at dry coil conditions, even though most AC systems operate the majority of the time at wet coil conditions. The use of the dry coil cyclic test has been based on the assumption that the wet and dry coil cyclic test are equivalent (equation (1)).

The cyclic performance of two systems -- a variable-speed (VS) and a constant-speed (CS) -- was measured at both wet and dry coil conditions. The results indicate that cyclic performance at wet and dry coil conditions are not equivalent. The EER ratio at dry coil conditions was higher than at wet coil conditions for both the VS and CS systems. The EER ratio is used to calculate C_D, which in turn is used to determine SEER. Therefore, the SEER based on the wet coil cyclic test is lower than the SEER based on the dry coil cyclic test (lower by 9% for the CS and 4% for the VS).

This discrepancy in calculating SEER probably does not impact the ranking among CS systems. However, the SEER of VS systems is much less dependent on C_D (see Figure 2). Therefore, any error in determining C_D will have a larger effect on the SEER of CS systems than on VS systems. This may effect the relative ranking among CS and VS systems.

To correct for this deficiency, it is proposed that sensible capacity be measured at wet coil conditions over the entire ON and OFF cycle. Since the net latent capacity over the ON and OFF cycle is zero, sensible capacity and total capacity will be equivalent. This method provides an easy means of determining the cyclic capacity at wet coil conditions -- which is more typical of actual operating conditions. This method also eliminates the need for test C, the steady-state dry coil test, and reduces the testing burden on manufacturers.

ACKNOWLEDGMENTS

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APPENDIX

Cyclic Test in SEER Test Procedure

Compressor ON Time:	6 minutes
Compressor OFF Time:	24 minutes
Integration Time:	8 minutes

Indoor Fan on for complete test

$$q_{cyc} = \frac{60*CFM*c_{pa}}{V_{ma}} \int_0^{8\ min} (T_{in} - T_{out})\ dt + 3.412* \int_{6\ min}^{8\ min} W_{IDF}\ dt \quad ,\ \text{Btu} \tag{A1}$$

where:

c_{pa}	-	specific heat of moist air, Btu/lb-°F
CFM	-	flow through cooling coil, ft^3/min
V_{ma}	-	specific volume of moist air, ft^3/lb
T_{in}, T_{out}	-	temperature in and out of coil, °F
W_{IDF}	-	indoor fan motor power, Watts

$$EER_{cyc} = q_{cyc}/p_{cyc} \tag{A2}$$

where:

p_{cyc}	-	total electric usage during ON time plus parasitics for complete test, Wh

$$C_D = \frac{(1 - EER_{cyc}/EER_{ss,dry})}{(1 - q_{cyc}/(Q_{ss,dry}*0.5)\ )} \tag{A3}$$

where:

$Q_{ss,dry}$	-	steady-state capacity, Test C, Btuh
$EER_{ss,dry}$	-	EER from steady-state Test C
0.5	-	total duration for Test D, hrs.