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FIELD MEASUREMENTS OF THE HEATING EFFICIENCY OF ELECTRIC FORCED-AIR SYSTEMS IN 24 HOMES

RCDP Cycle III Heating System Investigations

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EXECUTIVE SUMMARY

This report presents the results of field measurements of heating efficiency for 24 all-electric homes with central forced-air distribution systems. The homes were not selected randomly; it was primarily a sample of convenience. Homes with less than 50% of the ductwork in unconditioned spaces were excluded, as were homes with complex systems (i.e., multiple air handlers). The homes were generally measured under typical mid-winter weather conditions.

The base sample consisted of 22 homes. Two additional homes were chosen with the furnace located in the conditioned space and all ductwork in interior partitions. These provide a valuable comparison with the base sample, as well as a validity check on the coheat efficiency method. The efficiency tests for homes with heat pumps were done in resistance mode only. A separate one-time test was made to determine the heat pump COP.

Six of the homes underwent a duct leakage retrofit, with complete efficiency tests done before and after retrofit. The retrofits and post-retrofit test for five of these homes were funded under a separate contract with the Electric Power Research Institute. This report contains only the only the pre-retrofit results for these homes. The post-retrofit results and evaluation of the retrofits will be presented in a future report. The retrofit of one of these homes was funded under this study and the results are presented here.

The field tests were designed to provide two standard measures of heating efficiency, as defined in Chapter 29 of the *ASHRAE HVAC Systems and Equipment Handbook.* The heat delivery efficiency is the total useful heat delivered through the supply registers while the fan is on, divided by the power input to the furnace (including fan power); the system efficiency is the total useful heat delivered to the conditioned space during the entire period of furnace cycling, divided by the power input to the furnace (including fan power). Because the effects of increased infiltration during fan-off times and differential pressurization due to door closure are not included, the system efficiency given here should be taken as an upper limit on the actual efficiency under these weather conditions.

The results are summarized in the table below. The base sample is compared with the two homes with all interior ductwork. The temperature difference to outside which is a measure of the heating load averaged 33 F. The heat delivery efficiency averaged 56% for the base sample and 67% for the interior ductwork homes. Due to recovery of cycling losses and offset of loads due to heating of buffer zones, the system efficiency is higher.

The base sample averaged 71% system efficiency. This means the electric furnace used 1.41 times more heating energy than would have been required if the home with ducts in place had been heated by electric baseboards in such a way as to maintain the same temperatures as those maintained by the furnace. The homes with all interior ducts had a system efficiency of 98%, which means that almost all of the duct losses were recovered as useful heat. This is potentially a very important finding, which should be verified by measurements on additional homes. If this high efficiency is typical of these homes, it would not be cost efficient to retrofit such homes, or to place additional restrictions, such as air sealing or additional duct insulation, on new construction.

SUMMARY OF RESULTS

Variable	Base Sample (n=22)		All Interior Ductwork (n=2)	
	Average	Std. Deviation	Average	Std. Deviation
Delta T (in - out) [F]	33.2	7.7	40.8	3.7
Heat Delivery Efficiency	56.2	10.4	66.8	14.1
System Efficiency	71.0	7.6	97.9	1.6
Efficiency Loss	29.0	7.6	2.2	1.6
Power Loss [W]	1276.1	664.2	86.5	65.8
Percent Ontime	42.8	16.2	39.9	5.8
Duct Air Leakage				
Duct Leakage @ 50Pa [CFM]	435.6	278.9	20.5	24.7
Leakage Percent of Total	19.5	7.5	0.7	0.6
Heat Pump	(n=9)			
Heat Pump COP	2.47	0.79	-	-
Heat Pump Efficiency	165.8	41.7	-	-

The efficiency loss averaged 31% for the base homes and 2% for all interior ductwork. The power loss is the efficiency loss times the average cycle power of the furnace, it is an important measure because efficiencies can be misleading. For instance a moderately high efficiency in a home with a large load may have a power loss greater than that of a home with poorer efficiency but a small load. It is the power loss which determines the cost efficiency of duct retrofit or standards programs. The power loss averaged 1276 watts for the base sample and only 86 watts for interior ducts.

Air leakage is responsible for a major portion of the efficiency losses. The duct leakage to outdoors (not including duct leaks to the conditioned space) averaged 435 CFM for the base sample and 20 CFM for interior ducts. This leakage represented 20% of the total leakage of the home (including the duct system) for the base sample but only 1% for interior ducts.

Of the 11 homes with heat pumps, valid COP data was obtained for 9 homes. The COP measured at the supply plenum averaged 2.47. This corresponds to an efficiency of 247%. The heat pump system efficiency is the product of the COP and the resistance system efficiency. This measures the overall efficiency of the system which average 166%.

TABLE 1: SITE CHARACTERISTICS

Site ID	City	State	Year Built	Area [ft^2]	Volume [ft^3]	Altitude [ft]	Heating System Type [1]	Heating System Location [2]
Base Sample								
101	Lake Stevens	WA	1978	1973	15898	500	F	G
102	Spanaway	WA	1992	1601	13035	500	F	G
103	Seattle	WA	1960	791	6205	100	F	H
104	Tacoma	WA	1987	2310	20179	250	HP	G
105	Puyallup	WA	1984	1812	14226	400	F	G
107	Coeur d'Alene	ID	1989	1450	12538	2200	HP,g	C
108	Kalispell	MT	1986	1979	17041	3000	HP,gd	C
109	Kalispell	MT	1971	1983	14773	3000	HP	C
110	Spanaway	WA	1992	1601	13035	500	F	G
111	Spanaway	WA	1992	1419	11035	500	F	G
112a	Redmond	WA	1984	1665	15680	600	F	G
114a	Redmond	WA	1982	1017	8011	600	F	G
115	Nampa	ID	1991	1179	9166	2400	HP	G
116a	Eugene	OR	1987	2000	17371	360	HP	G
117	Eugene	OR	1989	1442	12111	350	HP	G
118	Eugene	OR	1978	1356	10685	400	F	G
119	Junction City	OR	1974	978	7464	365	F	G
120	Tigard	OR	1986	1762	14664	200	HP	H
121	Canby	OR	1983	1556	14474	400	HP	G
122a	Silverdale	WA	1991	1860	17980	100	HP	H
123a	Duvall	WA	1974	1712	15688	250	HP	H
124a	Kirkland	WA	1965	1964	18570	150	HP	C
Avg.	-	-	**1983**	**1610**	**13629**	**778**	-	-
Homes With Furnace and All Ducts Interior								
106	Genesee	ID	1988	2713	22808	2400	F	H
113	Edmonds	WA	1981	2058	15861	300	F	H
Avg.	-	-	**1985**	**2386**	**19335**	**1350**	-	-
Retrofit Sample								
116a/b	Eugene	OR	1987	2000	17371	360	HP	G

1 F = Electric furnace; HP = Heat pump, where 'g' indicates ground coupling and 'd' indicates desuperheater present.

2 C = Crawl space; G = Garage; H = Home / Conditioned Space

TABLE 2: HEATING EFFICIENCIES

Site ID	Heat Delivery Efficiency [1]	System Efficiency [2]	Adjusted System Efficiency [3]	Heat Pump COP [4]
Base Sample				
101	31.9	62.5	62.5	-
102	42.2	66.0	66.0	-
103	61.8	72.7	72.7	-
104	64.7	56.8	77.6	2.11
105	64.1	56.7	76.9	-
107	48.8	58.6	58.6	2.30
108	63.9	63.7	76.7	1.77 [5]
109	43.0	68.3	68.3	2.48
110	54.0	71.9	71.9	-
111	60.0	73.5	73.5	-
112a	56.6	70.9	70.9	-
114a	47.4	64.6	64.6	-
115	64.7	69.2	69.2	0.85 [6]
116a	69.6	79.6	79.6	1.40
117	49.5	71.2	71.2	1.91
118	68.7	88.8	82.4	-
119	56.8	74.8	74.8	-
120	58.5	65.7	65.7	3.03
121	65.6	62.3	78.7	-
122a	65.0	62.2	78.0	1.99
123a	60.1	64.5	72.2	3.45
124a	39.1	49.9	49.9	3.75
Avg.	**56.2**	**67.0**	**71.0**	**2.49**
Homes With Furnace and All Ducts Interior				
106	56.8	99.0	99.0	-
113	76.7	96.7	96.7	-
Avg.	**66.8**	**97.9**	**97.9**	-
Retrofit Comparison				
116a	69.6	79.6	79.6	1.40
116b	72.2	88.1	88.1	1.40

1 This efficiency is the heat delivered to the home through supply registers during the time the air handler fan is running divided by the energy output of the heating system. It does not account for factors such as supply leaks to the conditioned space, heat recovered from ducts during the off-cycle, or heat recovered from buffer zones.

2 System efficiency is the total heat delivered to the conditioned space divided by the energy output of the heating system, as measured by the coheat method.

3 For a variety of reasons, the coheat results are questionable for some homes. The heat delivery efficiency, being more robust, was used to adjust the system efficiency for these homes.

4 Ratio of heat output of compressor to power input, both input and output include fan power.

5 Excluded from average due to presence of desuperheater.

6 Excluded from average due to abnormally low temperatures during testing period.

TABLE 3: FURNACE POWER SUMMARY

Site ID	Full Power [1] [W]	AH Fan Power [W]	Fan-On Power [2] [W]	Fan-On as % of Full [3]	Percent Ontime [4]	Cycling Avg. Pwr. [5] [W]	Efficiency Loss [%] [6]	Efficiency Loss [W] [7]
Base Sample								
101	23844	790	14358	60	37.8	5421	37.5	2033
102	10860	450	9689	89	18.8	1822	34.0	619
103	11588	520	11588	100	32.5	3762	27.3	1027
104	10900	460	10528	97	74.5	7840	22.4	1757
105	14800	420	14590	99	41.2	6005	23.1	1384
107	10484	490	8793	84	19.7	1732	41.4	717
108	11209	500	9500	85	32.6	3099	23.3	723
109	25357	530	25301	100	13.7	3460	31.7	1097
110	10380	430	8879	86	33.9	3014	28.1	847
111	10400	460	8793	85	37.0	3257	26.5	863
112a	15313	300	13651	89	39.2	5348	29.1	1556
114a	15409	370	11441	74	34.5	3948	35.4	1398
115	10517	170	7686	73	62.6	4809	30.8	1481
116a	15268	580	10809	71	60.0	6485	20.4	1323
117	15596	500	9248	59	47.6	4405	28.8	1269
118	15660	500	11623	74	38.0	4415	17.6	776
119	12317 [8]	360	7622	62	48.9	3726	25.2	939
120	5463 [8]	170	5384	99	50.8	2737	34.3	939
121	15889	310	12086	76	42.6	5149	21.3	1098
122a	8772	340	6893	79	52.6	3625	22.0	799
123a	16010	740	13303	83	46.7	6215	27.8	1731
124a	10440	530	9617	92	76.8	7384	50.1	3699
Avg.	**13476**	**451**	**10972**	**82**	**42.8**	**4439**	**29.0**	**1276**
Homes With Furnace and all Ducts Interior								
106	16000	470	11198	70	35.8	4009	1.0	40
113	15296	500	9133	60	44.0	4019	3.3	133
Avg.	**15648**	**485**	**10166**	**65**	**39.9**	**4014**	**2.2**	**87**
Retrofit Comparison								
116a	15268	580	10809	71	60.0	6485	20.4	1323
116b	15268	580	11340	74	63.0	7140	11.9	850

1 Total power consumption of all electric resistance elements. Heat pump compressor not included.
2 Average power consumption of elements and fan while fan is on.
3 Ratio of fan-on power to full power as percent.
4 Percent of time the air handler fan was on during a complete furnace cycle.
5 Fan-on power times percent ontime. This is the average power consumption during a complete furnace cycle.
6 100 minus Adjusted Heat Delivery Efficiency.
7 Efficiency loss (%) times Cycling Average Power
8 At Site 119, one 5kW element was connected to a 120V supply instead of 240V; At site 120, one 5kW element was non-operational.

TABLE 4: HOUSE LEAKAGE DIAGNOSTICS

	Blower Door		Tracer Decay [3] [ACH]		Delta Pressure [Pa]	
Site ID	Q50 [1] [SCFM]	ACH50 [2]	Fan On	Fan Off	Envelope [4]	Bedroom Door [5]
Base Sample						
101	3641	13.7	1.30	0.23	6.3	3.2
102	1445	6.7	0.41	0.18	–0.7	8.0
103	1362	13.2	0.74	0.19	–0.4	6.5
104	3298	9.8	0.49	0.22	–0.8	8.1
105	3114	13.1	0.34	0.26	–0.3	3.2
107	1399	6.7	0.37	0.08	3.4	–1.4
108	1014	3.6	0.30	0.04	1.8	6.5
109	3833	15.6	0.43	0.21	2.0	4.4
110	1113	5.1	0.64	0.15	–1.0	8.0
111	871	4.7	0.44	0.11	–1.5	6.5
112a	2304	8.8	0.57	0.28	1.0	5.4
114a	1394	10.4	0.88	0.21	1.2	6.3
115	1294	8.5	0.87	0.35	1.3	3.7
116a	2763	9.5	0.72	0.21	1.9	2.6
117	2224	11.0	0.76	0.32	1.7	1.6
118	2721	15.3	0.70	0.48	1.5	2.2
119	1053	8.5	0.82	0.26	–1.5	5.4
120	1762	7.2	0.30	0.16	–0.8	4.0
121	1908	7.9	0.34	0.16	–0.6	2.2
122a	2538	8.5	0.30	0.14	–0.3	4.7
123a	3075	11.8	0.55	0.36	0.3	12.3
124a	4851	15.7	1.62	0.39	2.2	4.5
Avg.	**2226**	**9.8**	**0.63**	**0.23**	**1.5**	**5.0**
Homes With Furnace and all Ducts Interior						
106	1099	2.9	0.12	0.10	–0.7	9.0
113	3322	12.6	0.84	0.49	0.0	9.3
Avg.	**2211**	**7.8**	**0.48**	**0.30**	**0.4**	**9.2**
Retrofit Comparison						
116a	2763	9.5	0.72	0.21	1.9	2.6
116b	2472	8.5	0.58	0.29	0.2	2.9

1 Total leakage in SCFM with ducts unsealed and house depressurized to 50 Pa. Air handler fan off.

2 Same conditions as above but leakage expressed in air changes per hour.

3 Total leakage expressed in air changes per hour based on tracer gas decay test.

4 Change in pressure across house envelope due to air handler fan (fan on - fan off). Positive values indicate that the house is pressurized with respect to outdoors and suggest that return leakage is dominant. The averages are of the absolute values of the differences.

5 Change in pressure across a closed bedroom door due to air handler fan (fan on - fan off). Positive values indicate that the bedroom is pressurized with respect to the rest of the house. The bedroom in site 107 had both supply and return registers. The averages are of the absolute values of the differences.

TABLE 5: DUCT LEAKAGE TO OUTDOORS

Site ID	Q50 [1] [SCFM]	Adj. Q50 [2] [SCFM]	% of Total [3]	Decay Test [4] [SCFM]	Decay Test On/Off Ratio [5]
Base Sample					
101	1008	1372	37.7	282	5.61
102	235	352	24.4	51	2.33
103	63	70	5.1	57	3.89
104	226	403	12.2	90	2.24
105	487	686	22.0	18	1.29
107	191	290	20.7	61	4.52
108	95	207	20.5	74	6.89
109	365	534	13.9	54	2.05
110	151	243	21.9	106	4.30
111	49	95	10.9	60	4.01
112a	447	695 [6]	30.2	75	2.02
114a	379	451 [6]	32.3	89	4.10
115	115	163	12.6	80	2.52
116a	262	425	15.4	149	3.47
117	336	473	21.3	88	2.34
118	412	559	20.5	40	1.46
119	189	243	23.1	69	3.14
120	87	404 [6]	22.9	33	1.83
121	156	240 [6]	12.6	44	2.17
122a	253	446 [6]	17.6	48	2.15
123a	352	528 [6]	17.2	49	1.52
124a	475	704 [6]	14.5	381	4.15
Avg.	**288**	**436**	**19.5**	**91**	**3.09**
Homes With Furnace and All Ducts Interior					
106	3	3	0.3	11	1.29
113	38	38	1.1	91	1.70
Avg.	**21**	**21**	**0.7**	**51**	**1.50**
Retrofit Comparison					
116a	262	425	15.4	149	3.47
116b	95	210	8.5	83	1.97

1 From 50 Pa blower door test. Difference between tests with registers unsealed and registers sealed. SCFM = measured CFM corrected to a standardized volumetric flow rate at a density of .075 lbs/cubic ft.
2 Blower door tests adjusted by correlation with more accurate Duct Blaster tests available for later homes.
3 Adjusted duct Q50 as a percentage of the whole-house Q50 with registers unsealed.
4 Difference between tracer decay tests with air handler fan on and fan off.
5 Ratio of tracer decay tests.
6 Actual Duct Blaster measurements.

TABLE 6: AVERAGE TEMPERATURES DURING CYCLING [1] (F)

Site ID	Outside	Crawl Space	Garage	Attic	Inside [2]	Delta House [3]
Base Sample						
101	35.9	53.1	45.4	52.2	67.7	31.8
102	39.2	48.1	53.8	45.5	71.1	31.9
103	49.4	61.2	-	51.0	73.9	24.5
104	39.8	55.6	62.2	-	74.5	34.7
105	46.8	56.7	62.1	-	74.8	28.0
107	39.6	57.7	46.5	-	67.9	28.3
108	36.2	52.8	47.5	-	70.7	34.5
109	47.6	60.8	57.2	-	72.7	25.1
110	44.4	57.4	62.9	-	75.3	30.9
111	44.7	54.5	54.0	-	75.2	30.6
112a	34.6	51.0	50.0	-	72.9	38.2
114a	42.7	-	45.6	50.5	71.9	29.2
115	11.3	62.8	41.3	32.4	71.2	59.9
116a	31.6	47.0	50.3	-	73.3	41.7
117	38.0	45.1	49.2	47.7	72.7	34.7
118	38.0	52.0	51.4	51.6	72.3	34.3
119	32.8	57.1	45.9	-	72.4	39.6
120	49.1	56.4	56.9	-	73.9	24.8
121	34.5	55.2	48.9	-	72.5	37.9
122a	41.6	49.9	-	44.4	71.0	29.4
123a	36.0	54.1	-	-	71.4	35.4
124a	49.0	56.5	-	-	75.0	26.0
Avg.	**39.2**	**54.5**	**51.7**	**46.9**	**72.5**	**33.2**
Homes With Furnace and All Ducts Interior						
106	26.2	-	-	-	69.6	43.4
113	32.3	-	-	-	70.4	38.2
Avg.	**29.3**	**-**	**-**	**-**	**70.0**	**40.8**
Retrofit Comparison						
116a	31.6	47.0	50.3	-	73.3	41.7
116b	28.4	48.9	48.9	-	73.5	45.1

1 Missing values indicate there were no ducts in these locations.
2 Average of 6 - 11 control temperature points.
3 Average control temperature minus outside. To a first approximation, this is proportional to the heating load.

TABLE 7: SYSTEM TEMPERATURES DURING CYCLING [1] (F)

Site ID	Supply Registers [2]	Return Registers [2]	Return Plenum [3]	Inside [4]	Delta Supply [5]
Base Sample					
101	85.6	67.0	58.8	67.7	18.0
102	85.1	70.8	69.6	71.1	14.0
103	105.4	76.7	76.7	73.9	31.5
104	95.2	70.6	71.4	74.5	20.7
105	108.1	77.5	71.9	74.8	33.3
107	84.7	69.2	67.3	67.9	16.8
108	92.3	72.2	71.5	70.7	21.6
109	109.8	73.1	70.0	72.7	37.2
110	92.7	75.6	74.2	75.3	17.5
111	84.6	74.3	74.1	75.2	9.3
112a	99.5	-	71.3	72.9	26.7
114a	100.0	-	68.8	71.9	28.1
115	98.6	-	68.9	71.2	27.3
116a	95.4	-	69.6	73.3	22.1
117	89.7	-	70.5	72.7	17.0
118	100.8	-	73.1	72.3	28.5
119	90.8	-	72.8	72.4	18.5
120	89.3	-	73.5	73.9	15.3
121	112.6	74.4	73.8	72.5	40.1
122a	87.1	71.6	70.2	71.0	16.1
123a	92.4	70.0	69.4	71.4	21.0
124a	87.3	72.4	63.7	75.0	12.2
Avg.	**94.9**	**72.5**	**70.5**	**72.5**	**22.4**
Homes With Furnace and All Ducts Interior					
106	92.9	70.2	71.3	69.6	23.3
113	99.9	-	72.1	70.4	29.4
Avg.	**96.4**	**-**	**71.7**	**70.0**	**26.4**
Retrofit Comparison					
116a	95.4	-	69.6	73.3	22.1
116b	98.6	-	71.8	73.5	25.1

1 Missing values indicate measurements not made due to equipment limitations.
2 Flow-weighted average of register temperatures.
3 Return plenum temperatures; the supply plenum temperatures were unreliable and have been omitted from this report.
4 Average of 6 - 11 control temperature points.
5 Average supply register temperature minus average inside temperature. When multiplied by the supply register flow, this gives the heat delivered to the home through the registers.

TABLE 8: SYSTEM FLOWS AND PRESSURES

Site ID	Plenum Pressures [Pa]		Register Flows [SCFM]	
	Supply [1]	Return [2]	Supply [3]	Return [4]
Base Sample				
101	47	202	778	310
102	49	49	901	945
103	62	-[5]	787	842
104	10	90	873	855
105	34	23	962	920
107	45	43	998	680
108	30	60	952	780
109	16	36	937	900
110	130	45	869	965
111	130	50	940	1100
112a	52	3	912	875
114a	41	10	617	700
115	26	35	573	700
116a	21	50	1070	1050
117	35	110	849	983
118	19	24	888	902
119	80	87	738	864
120	26	26	647	600
121	14	18	624	620
122a	25	34	876	1000
123a	55	155	1201	840
124a	96	81	968	460
Avg.	**47**	**59**	**862**	**813**
Homes With Furnace and all Ducts Interior				
106	35	48	885	650
113	38	47	750	875
Avg.	**37**	**48**	**818**	**763**
Retrofit Comparison				
116a	21	50	1070	1050
116b	23	59	1028	1188

1 Pressure in the supply plenum, measured downstream from heating coils.
2 Pressure in the return plenum, measured upstream of the filter.
3 Sum of supply register flows, measured in SCFM. These measurements are quite reliable.
4 Sum of return register flows, measured in SCFM. These measurements were subject to a variety of problems and are therefore not well determined.
5 Site 103 had no return duct system.

TABLE 9: FURNACE CYCLING SUMMARY

Site ID	Cycle Time [1] [sec]	Ontime [2] [sec]	Offtime [sec]	Cycles per hour	Percent Ontime
Base Sample					
101	588	222	366	6.1	38
102	1170	220	950	3.1	19
103	770	250	520	4.7	32
104	1410	1050	360	2.6	74
105	3110	1280	1830	1.2	41
107	2640	520	2120	1.4	20
108	1410	460	950	2.6	33
109	2340	320	2020	1.5	14
110	545	185	360	6.6	34
111	513	190	323	7.0	37
112a	485	190	295	7.4	39
114a	473	163	310	7.6	35
115	428	268	160	8.4	63
116a	517	310	207	7.0	60
117	352	167	184	10.2	48
118	520	198	322	6.9	38
119	558	272	285	6.5	49
120	498	253	245	7.2	51
121	710	302	408	5.1	43
122a	413	217	196	8.7	53
123a	610	285	325	5.9	47
124a	703	540	163	5.1	77
Avg.	**944**	**357**	**586**	**5.6**	**43**
Homes With Furnace and all Ducts Interior					
106	517	185	332	7.0	36
113	321	141	180	11.2	44
Avg.	**419**	**163**	**256**	**9.1**	**40**
Retrofit Comparison					
116a	517	310	207	7.0	60
116b	540	340	200	6.7	63

1 Average length of complete furnace cycle during testing.
2 Average length of time the air handler fan was on during each furnace cycle.