

# **Evaluation of Heating, Ventilation and Air Conditioning Systems (HVAC) Systems Available for Ohio Schools**

**Sponsored By**

**ASHRAE  
Cincinnati Chapter**

**Stephen Petty  
Energy & Environmental Solutions, Inc.**

**February 12, 2002**

Hi, my name is...



# INTRODUCTIONS

**Stephen Petty**

**EES, President**

**Education:**

**B.S. and M.S. Ch.E.**

**Univ. of Washington**

**M.B.A. - Univ. of Dayton**

**Work History:**

**Battelle - 1979 - 1989**

**Columbia Gas - 1989 -1997**

**EES - 1997**

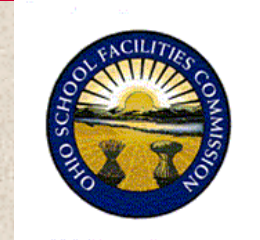
# SPECIAL THANKS

**ASHRAE – Cincinnati Chapter (Mr. Steve Donahugh)**

**Bill Manz: ODOD-OEE**  
**Sara Ward: ODOD-OEE**



**Franklin Brown: OSFC**



**Co-Author: Greg Hochstetler - Julian Speer**  
**Key Contributors: Mark Taylor - Limbach**  
**John Feters - Effective Lighting Solutions**

# LOCATION OF REPORT

- ◆ See <http://www.osfc.state.oh.us/Frequent..htm> for entire report. Final Report sent to ODOD-OEE and OSFC on November 10, 2000; issued January 2001

# REPORT/PRESENTATION OUTLINE

- ◆ **Background**
- ◆ **Topics and Results:**
  - **Annual energy use and costs**
  - **Life-cycle costs**
  - **Enthalpy heat recovery**
  - **Ventilation (IAQ)**
  - **Geothermal HP**
  - **Daylighting**

# **HISTORY – *The Buildings and Locations***

- ✦ **Started work in early March 1999. Worked delayed until receipt of architects drawings for first two schools designed under the new School Design Manual**
- ✦ **First two design manual school envelopes were modeled:**
  - **Uhrichsville High School - Claymont School District, Dennison, OH - 120,500 ft<sup>2</sup>**
  - **Katherine Thomas Elementary School - Windham Exempted Village Schools - Windham, Ohio (Portage County, OH) - 64,442 ft<sup>2</sup>**
- ✦ **Designs modeled in three locations (Cleveland, Cincinnati and Columbus) – Covers range of weather and utility rates in Ohio.**

# BACKGROUND - MODELING DETAILS

- ✦ **Model: Used Carrier's Hourly Analysis Program (HAP). Selected because it is an 8,760 model, is recognized by industry and is a less complex, but reasonable approximation to DOE 2.1.**
- ✦ **Each school divided into distinct spaces or zones:**
  - **Uhrichsville High School - 99 spaces/zones**
  - **Katherine Thomas Elementary School - 76 spaces/zones**

# BACKGROUND – MODELING DETAILS

- ✦ **36 Schedules needed for each building (e.g.,**
  - People 1- Classrooms**
  - Lights 1 – Classrooms**
- ✦ **Modeled actual construction materials for walls, roofs and windows**
- ✦ **Air Systems: Used the 4 systems outlined in the OSFC Design Manual (VAV Reheat, Dual Duct VAV, SFPVAV and WSHP)**

# MODELING – “BASELINE” CASES

- ◆ **Total: 40 HVAC combinations**

- **In three cities - Totals 120 combinations (40 \* 3)**

- **And with two buildings – Totals 240 combinations (120 \* 2)**

**240 configuration analyzed for annual building energy loads and energy costs. Known as “baseline” cases.**

# BACKGROUND – THE “KEY”

System Number	Air System	Boiler	Heating Fuel	Cooling Plant
1A1	VAV with Reheat	Atmospheric	Nat. Gas	Air Cooled Screw Chiller
1A2	VAV with Reheat	Atmospheric	Nat. Gas	Water Cooled Screw Chiller
1A3	VAV with Reheat	Atmospheric	Nat. Gas	Water Cooled Centrifugal Chiller
1B1	VAV with Reheat	Power	Nat. Gas	Air Cooled Screw Chiller
1B2	VAV with Reheat	Power	Nat. Gas	Water Cooled Screw Chiller
1B3	VAV with Reheat	Power	Nat. Gas	Water Cooled Centrifugal Chiller
1C1	VAV with Reheat	Power	Nat. Gas	Air Cooled Screw Chiller
1C2	VAV with Reheat	Power	Nat. Gas	Water Cooled Screw Chiller
1C3	VAV with Reheat	Power	Nat. Gas	Water Cooled Centrifugal Chiller

## System

System Number	Air System	Boiler	Heating Fuel	Cooling Plant
1A1	VAV with Reheat	Atmospheric	Nat. Gas	Air Cooled Screw Chiller
1A2	VAV with Reheat	Atmospheric	Nat. Gas	Water Cooled Screw Chiller

2D2	Series Fan Powered VAV Box	Power	Oil	Water Cooled Screw Chiller
2D3	Series Fan Powered VAV Box	Power	Oil	Water Cooled Centrifugal Chiller
3A1	Water Source Heat Pump	Atmospheric	Nat. Gas	
3B1	Water Source Heat Pump	Power	Nat. Gas	
3C1	Water Source Heat Pump	Electric	Electric	
3D1	Water Source Heat Pump	Power	Oil	
4A1	Dual Duct VAV	Atmospheric	Nat. Gas	Air Cooled Screw Chiller
4A2	Dual Duct VAV	Atmospheric	Nat. Gas	Water Cooled Screw Chiller
4A3	Dual Duct VAV	Atmospheric	Nat. Gas	Water Cooled Centrifugal Chiller
4B1	Dual Duct VAV	Power	Nat. Gas	Air Cooled Screw Chiller
4B2	Dual Duct VAV	Power	Nat. Gas	Water Cooled Screw Chiller
4B3	Dual Duct VAV	Power	Nat. Gas	Water Cooled Centrifugal Chiller
4C1	Dual Duct VAV	Electric	Electric	Air Cooled Screw Chiller
4C2	Dual Duct VAV	Electric	Electric	Water Cooled Screw Chiller
4C3	Dual Duct VAV	Electric	Electric	Water Cooled Centrifugal Chiller
4D1	Dual Duct VAV	Power	Oil	Air Cooled Screw Chiller
4D2	Dual Duct VAV	Power	Oil	Water Cooled Screw Chiller
4D3	Dual Duct VAV	Power	Oil	Water Cooled Centrifugal Chiller

# BACKGROUND – THE “KEY” Continued

Key: XYZ where:

**X:** is the air system

- “1” is a VAV with reheat
- “2” is a Series fan powered VAV box
- “3” is a Water-source heat pump
- “4” is a Dual-duct VAV

**Y:** is the heating plant system

- “A” is an atmospheric natural gas boiler
- “B” is a powered natural gas boiler
- “C” is an electric boiler
- “D” is a powered oil boiler

**Z:** is the cooling plant system

- “1” is an air-cooled screw chiller; except HP for HP cases
- “2” is a water-cooled screw chiller
- “3” is a water-cooled centrifugal chiller

Thus “1A1” is a VAV with reheat air system using an atmospheric natural gas boiler for heating and an air-cooled screw chiller for cooling.

# BACKGROUND – Utility/Energy Rates Used

## ◆ Electric:

Cleveland - CEI -- SS

Columbus - CSP -- GS-3

Cincinnati - CG&E -- GS

## ◆ Gas:

Cleveland and Columbus - Columbia Gas -- GS

Cincinnati - CG&E – DS

## ◆ Oil:

All cities - \$0.80 per gallon

# BACKGROUND – BASELINE MODEL OUTPUT

- ◆ Hourly electric (kW and kWh), natural gas (BTU) and oil consumption (BTU) determined by system

Then

- ◆ Combined hourly energy consumption with energy rates in an Excel spreadsheet to determine annual energy costs.
- ◆ Presented as both site and source annual energy consumption.

# BASELINE ANNUAL ENERGY USE

## – Site Energy Consumption

HVAC OPTION	Elec. (kWH)	Nat. Gas (MCF)	Fuel Oil (gallons)	Site Energy (MBTU)	Max. (kW)
1A1	476,059	916	0	2,568	432
1A2	430,333	916	0	2,412	358
1A3	443,414	916	0	2,456	329
1B1	477,825	905	0	2,562	432
1B2	432,099	905	0	2,406	358
1B3	445,179	905	0	2,451	329
1C1	693,900	0	0	2,368	469
1C2	648,174	0	0	2,212	469
1C3	661,254	0	0	2,256	469
1D1	479,000	0	6,628	2,554	432
1D2	433,274	0	6,628	2,398	358
1D3	446,355	0	6,628	2,442	329
2A1	499,372	939	0	2,671	452
2A2	448,525	939	0	2,498	358
2A3	463,985	939	0	2,550	341
2B1	501,193	930	0	2,667	452
2B2	450,345	930	0	2,494	358
2B3	465,806	930	0	2,547	341
2C1	723,913	0	0	2,470	492
2C2	673,066	0	0	2,297	492
2C3	688,526	0	0	2,349	492
2D1	502,406	0	6,788	2,656	452
2D2	451,559	0	6,788	2,482	358
2D3	467,019	0	6,788	2,535	341
3A1	734,648	1,817	0	4,378	455
3B1	735,670	1,771	0	4,334	456
3C1	1,155,353	0	0	3,942	1,077
3D1	736,353	0	13,158	4,337	457
4A1	508,948	1,614	0	3,399	422
4A2	464,659	1,614	0	3,248	354
4A3	478,114	1,614	0	3,294	325
4B1	509,858	1,574	0	3,361	422
4B2	465,570	1,574	0	3,210	354
4B3	479,024	1,574	0	3,256	325
4C1	883,341	0	0	3,014	954
4C2	839,052	0	0	2,863	954
4C3	852,507	0	0	2,909	954
4D1	510,465	0	11,689	3,363	422
4D2	466,177	0	11,689	3,212	354
4D3	479,632	0	11,529	3,235	325

HVAC OPTION	Elec. (kWH)	Nat. Gas (MCF)	Fuel Oil (gallons)	Site Energy (MBTU)	Max. (kW)
1A1	476,059	916	0	2,568	432
1A2	430,333	916	0	2,412	358
1A3	443,414	916	0	2,456	329

Raw Model output for Elementary School in Columbus.

First three line items pulled out.

# BASELINE ANNUAL ENERGY USE – Site Energy Consumption

HVAC System Option	Elementary School			High School		
	Cincinnati	Cleveland	Columbus	Cincinnati	Cleveland	Columbus
1A1	2,430	2,762	2,568	7,091	8,011	7,429
1A2	2,249	2,624	2,412	6,904	7,862	7,263
1A3	2,290	2,656	2,456	7,026	7,967	7,384
1B1	2,424	2,758	2,562	7,022	7,932	7,354
1B2	2,244	2,620	2,406	6,835	7,783	7,187
1B3	2,285	2,652	2,451	6,957	7,889	7,309
1C1	2,270	2,519	2,368	6,264	6,972	6,513
1C2	2,090	2,381	2,212	6,077	6,823	6,346
1C3	2,131	2,413	2,256	6,199	6,929	6,468
1D1	2,419	2,744	2,554	7,011	7,907	7,339
1D2	2,238	2,606	2,396	6,824	7,758	7,172
1D3	2,279	2,638	2,442	6,946	7,863	7,293
2A1	2,622	2,931	2,671	7,757	7,938	7,335
2A2	2,414	2,773	2,498	6,823	7,783	7,165
2A3	2,471	2,814	2,550	6,954	7,833	7,292
2B1	2,618	2,927	2,667	6,952	7,860	7,260
2B2	2,410	2,769	2,494	6,754	7,704	7,090
2B3	2,466	2,811	2,547	6,884	7,815	7,272
2C1	2,448	2,673	2,470	6,223	6,924	6,449
2C2	2,239	2,515	2,297	6,025	6,769	6,279
2C3	2,296	2,557	2,349	6,156	6,879	6,406
2D1	2,609	2,909	2,656	6,944	7,838	7,249
2D2	2,401	2,751	2,482	6,746	7,683	7,079
2D3	2,457	2,792	2,535	6,877	7,793	7,206
3A1	4,124	4,820	4,378	6,622	7,605	7,000
3B1	4,084	4,771	4,334	6,564	7,533	6,935
3C1	3,741	4,307	3,942	6,086	6,891	6,389
3D1	4,087	4,772	4,337	6,569	7,537	6,941
4A1	3,245	3,805	3,399	7,382	8,407	7,751
4A2	3,071	3,671	3,248	7,196	8,260	7,585
4A3	3,115	3,704	3,294	7,319	8,366	7,707
4B1	3,210	3,761	3,361	7,312	8,329	7,676
4B2	3,037	3,627	3,210	7,127	8,182	7,510
4B3	3,081	3,660	3,256	7,249	8,288	7,632
4C1	2,908	3,328	3,014	6,510	7,307	6,785
4C2	2,734	3,194	2,863	6,325	7,160	6,620
4C3	2,778	3,227	2,909	6,447	7,266	6,742
4D1	3,212	3,759	3,363	7,296	8,295	7,654
4D2	3,038	3,625	3,212	7,111	8,148	7,489
4D3	3,082	3,658	3,235	7,233	8,254	7,610

**Basis:**

**Electricity:**

**3,412 BTU per kW-hr**

**Natural Gas:**

**1,030 BTU per cubic foot**

**Fuel Oil:**

**138,690 BTU per gallon.**

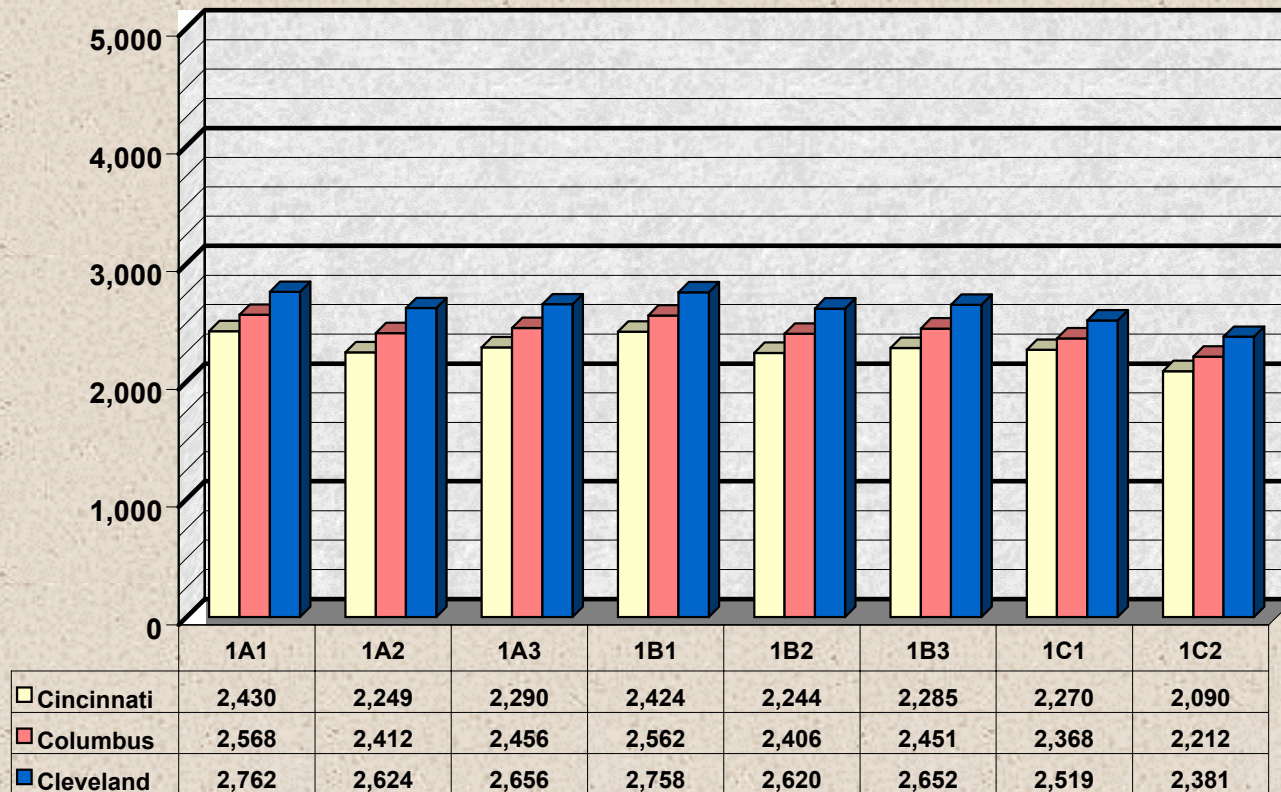
HVAC System Option	Elementary School		
	Cincinnati	Cleveland	Columbus
1A1	2,430	2,762	2,568
1A2	2,249	2,624	2,412
1A3	2,290	2,656	2,456
1B1	2,424	2,758	2,562
1B2	2,244	2,620	2,406
1B3	2,285	2,652	2,451
1C1	2,270	2,519	2,368

Table 3-1: Baseline Annual Site Energy Consumption (MMBTU/Year) by HVAC System Option, School Type and Location

# BASELINE ANNUAL ENERGY USE

## – Example of Model Output

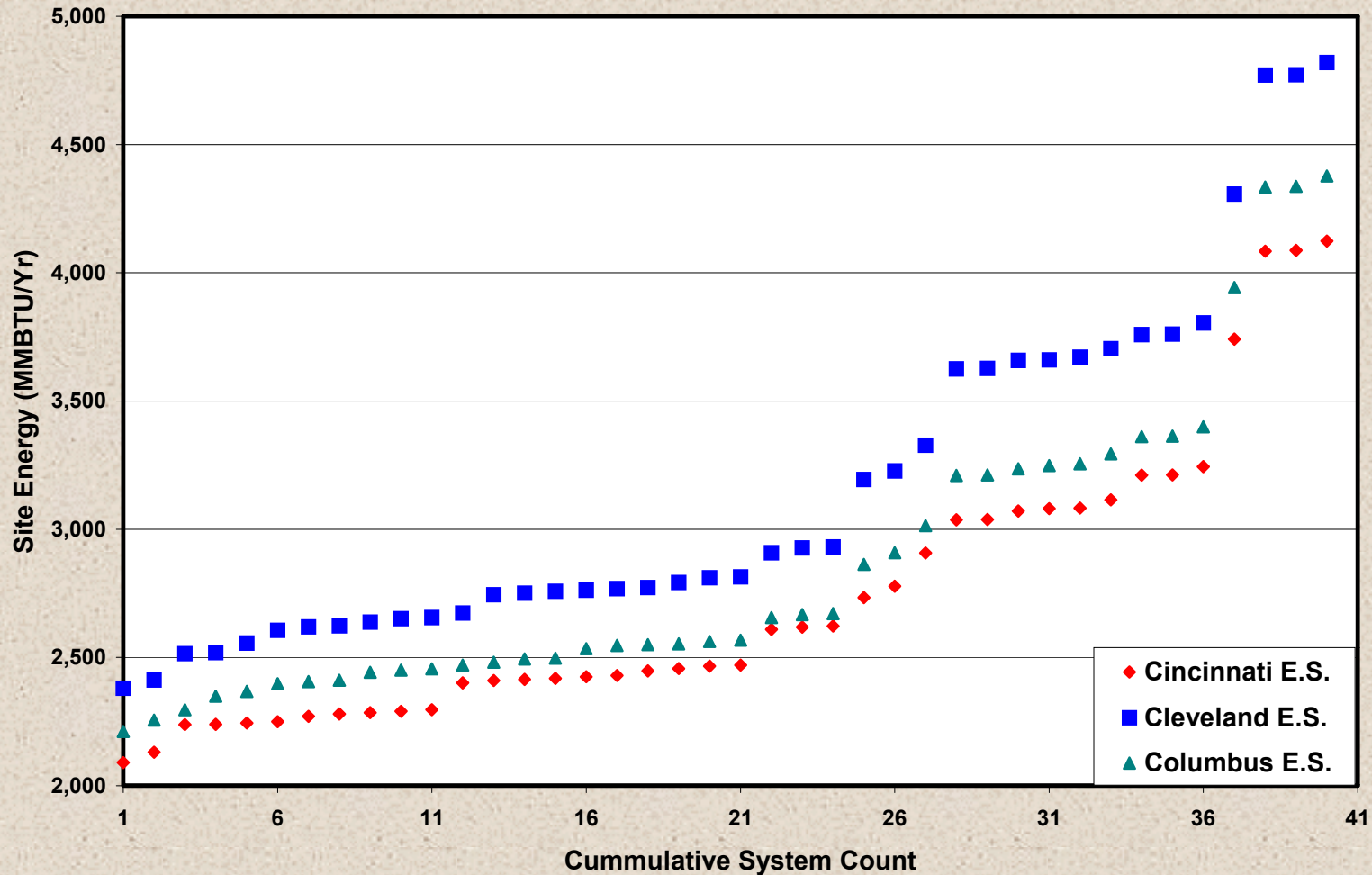
Figure 3-1: OSFC Elementary School  
Base Annual Site Energy Consumption (MMBTU/Year)  
(HVAC Systems 1A1 - 1C2)



HVAC System Types

# ANNUAL SITE ENERGY CONSUMPTION – Cumulative Plot by HVAC System Option

Elementary School Site Energy (MMBTU/Yr)



# BASELINE ANNUAL ENERGY USE – Source Energy Consumption

HVAC System Option	Elementary School			High School		
	Cincinnati	Cleveland	Columbus	Cincinnati	Cleveland	Columbus
1A1	6,440	6,610	6,463	15,473	16,282	15,679
1A2	5,840	6,149	5,943	14,849	15,785	15,124
1A3	5,976	6,257	6,091	15,255	16,137	15,529
1B1	6,445	6,622	6,470	15,413	16,216	15,614
1B2	5,845	6,161	5,950	14,789	15,719	15,058
1B3	5,981	6,268	6,098	15,195	16,070	15,464
1C1	7,566	8,396	7,892	20,880	23,241	21,710
1C2	6,966	7,935	7,372	20,256	22,744	21,154
1C3	7,102	8,042	7,521	20,662	23,096	21,559
1D1	6,547	6,776	6,597	15,907	16,831	16,159
1D2	5,946	6,316	6,077	15,282	16,335	15,603
1D3	6,083	6,423	6,226	15,689	16,686	16,008
2A1	6,891	6,978	6,754	15,568	16,332	15,707
2A2	6,197	6,451	6,176	14,907	15,814	15,141
2A3	6,384	6,590	6,352	15,342	16,182	15,564
2B1	6,898	6,992	6,764	15,507	16,265	15,641
2B2	6,204	6,465	6,186	14,846	15,746	15,075
2B3	6,392	6,604	6,362	15,281	16,115	15,498
2C1	8,159	8,910	8,233	20,744	23,081	21,498
2C2	7,465	8,383	7,655	20,084	22,563	20,931
2C3	7,653	8,522	7,831	20,518	22,931	21,354
2D1	7,008	7,153	6,891	15,983	16,867	16,169
2D2	6,314	6,626	6,313	15,323	16,349	15,603
2D3	6,502	6,765	6,488	15,758	16,717	16,026
3A1	10,105	11,128	10,434	16,997	18,516	17,534
3B1	10,068	11,083	10,393	16,938	18,445	17,469
3C1	12,471	14,357	13,140	20,286	22,971	21,295
3D1	10,298	11,391	10,656	17,258	18,872	17,834
4A1	7,591	8,053	7,636	15,932	16,882	16,183
4A2	7,011	7,608	7,132	15,314	16,391	15,631
4A3	7,159	7,718	7,285	15,723	16,745	16,037
4B1	7,559	8,012	7,600	15,875	16,819	16,121
4B2	6,980	7,567	7,097	15,257	16,328	15,569
4B3	7,127	7,677	7,250	15,665	16,682	15,975
4C1	9,692	11,093	10,047	21,700	24,357	22,618
4C2	9,113	10,648	9,543	21,082	23,866	22,066
4C3	9,260	10,758	9,696	21,491	24,220	22,472
4D1	7,761	8,298	7,832	16,393	17,470	16,694
4D2	7,182	7,853	7,328	15,775	16,979	16,142
4D3	7,329	7,963	7,454	16,184	17,333	16,548



HVAC System Option	Elementary School			High School		
	Cincinnati	Cleveland	Columbus	Cincinnati	Cleveland	Columbus
1A1	6,440	6,610	6,463	15,473	16,282	15,679
1A2	5,840	6,149	5,943	14,849	15,785	15,124
1A3	5,976	6,257	6,091	15,255	16,137	15,529

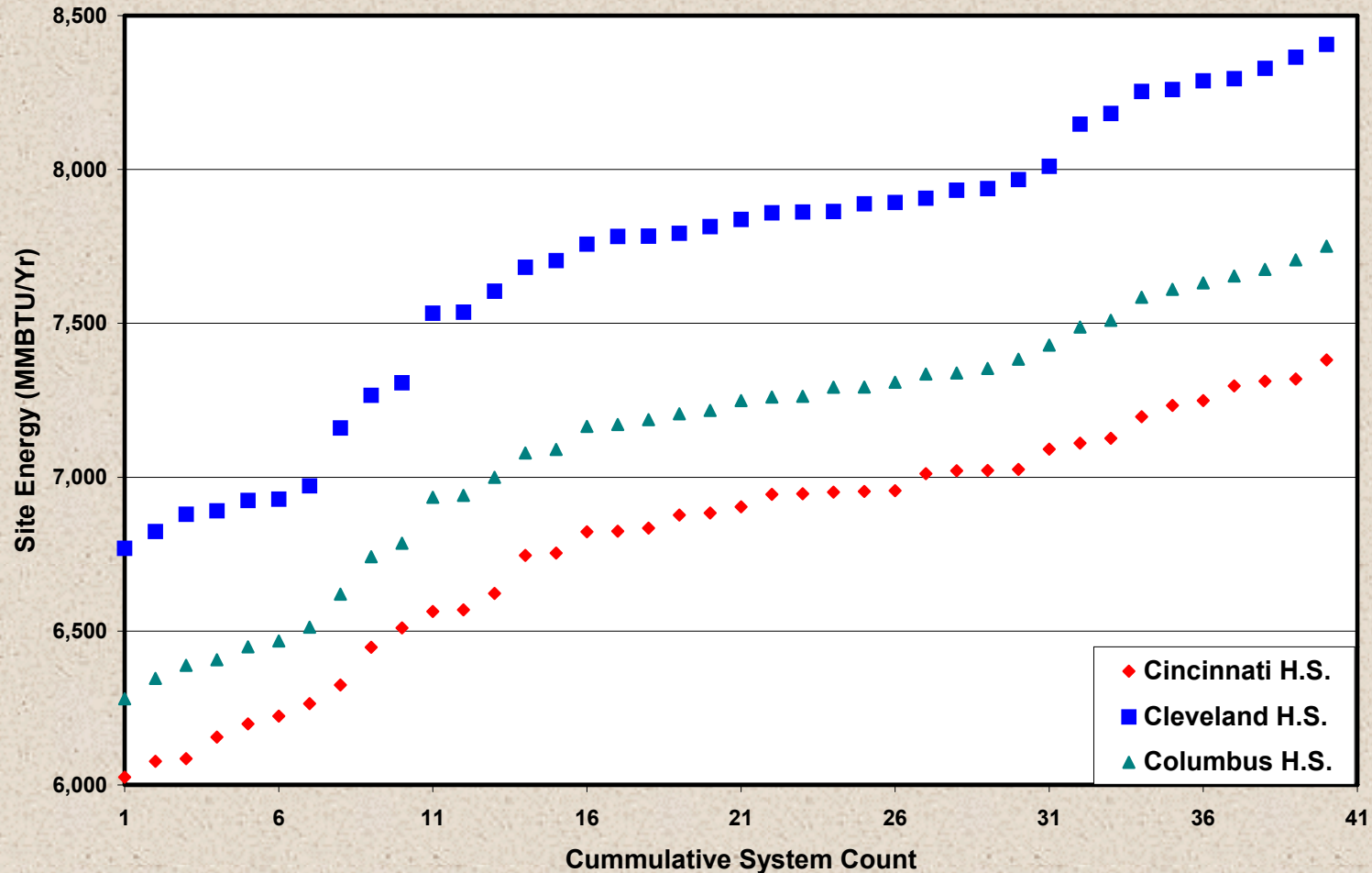
## Basis:

- Electricity: 30% of source BTUs converted to site BTUs
- Natural Gas: 90% of source BTUs converted to site BTUs
- Fuel Oil: 80% of source BTUs converted to site BTUs

Table 3-6: Baseline Annual Source Energy Consumption (MMBTU/Year) by HVAC System Option, School Type and Location

# ANNUAL SOURCE ENERGY CONSUMPTION – Cumulative Plot by HVAC System Option

High School Site Energy (MMBTU/Yr)



# BASELINE ANNUAL ENERGY COSTS

\$

H V A C System Option	Elementary School			High School		
	Cincinnati	Cleveland	Columbus	Cincinnati	Cleveland	Columbus
1A1	\$87,169	\$78,352	\$65,656	\$150,390	\$161,542	\$120,884
1A2	\$66,349	\$70,705	\$57,092	\$135,594	\$154,039	\$114,784
1A3	\$65,195	\$70,678	\$54,783	\$127,977	\$155,961	\$114,999
1B1	\$87,166	\$78,602	\$65,634	\$150,102	\$161,370	\$120,476

H V A C System Option	Elementary School			High School		
	Cincinnati	Cleveland	Columbus	Cincinnati	Cleveland	Columbus
1A1	\$87,169	\$78,352	\$65,656	\$150,390	\$161,542	\$120,884
1A2	\$66,349	\$70,705	\$57,092	\$135,594	\$154,039	\$114,784
1A3	\$65,195	\$70,678	\$54,783	\$127,977	\$155,961	\$114,999
1B1	\$87,166	\$78,602	\$65,634	\$150,102	\$161,370	\$120,476
1B2	\$66,347	\$70,954	\$57,071	\$135,306	\$153,866	\$114,503
1B3	\$65,192	\$70,925	\$54,763	\$127,689	\$155,788	\$114,718
1C1	\$89,427	\$110,225	\$77,472	\$193,683	\$281,848	\$218,221
1C2	\$74,708	\$102,588	\$73,858	\$186,206	\$275,502	\$216,979
1C3	\$74,086	\$102,543	\$73,174	\$183,552	\$277,801	\$217,885
1D1	\$87,884	\$78,789	\$65,659	\$153,906	\$161,767	\$120,742
1D2	\$67,066	\$71,147	\$57,095	\$139,110	\$154,263	\$114,844
1D3	\$65,911	\$71,120	\$54,789	\$131,493	\$156,184	\$115,058
2A1	\$89,457	\$83,248	\$68,928	\$152,450	\$163,705	\$123,030
2A2	\$68,656	\$74,277	\$58,520	\$136,799	\$156,075	\$116,193
2A3	\$67,265	\$74,624	\$57,690	\$129,290	\$157,890	\$116,542
2B1	\$89,461	\$83,490	\$68,919	\$152,158	\$163,507	\$122,620
2B2	\$68,661	\$74,139	\$58,510	\$136,507	\$155,885	\$115,896
2B3	\$67,269	\$74,866	\$57,680	\$128,997	\$157,693	\$116,244
2C1	\$92,196	\$115,418	\$80,535	\$193,087	\$279,580	\$215,423
2C2	\$77,072	\$106,311	\$75,998	\$184,590	\$272,330	\$214,157
2C3	\$76,454	\$107,030	\$75,826	\$182,118	\$274,737	\$215,102
2D1	\$90,256	\$83,663	\$68,926	\$155,819	\$163,912	\$122,894
2D2	\$69,456	\$74,312	\$58,518	\$140,169	\$156,283	\$116,240
2D3	\$68,065	\$75,040	\$57,688	\$132,659	\$158,097	\$116,588
3A1	\$90,051	\$120,475	\$88,973	\$144,017	\$196,519	\$140,739
3B1	\$89,938	\$120,354	\$88,830	\$143,814	\$196,383	\$140,477
3C1	\$124,060	\$182,459	\$149,204	\$190,656	\$284,280	\$225,636
3D1	\$91,678	\$120,629	\$89,075	\$146,250	\$196,755	\$142,002
4A1	\$88,793	\$88,495	\$69,675	\$150,065	\$165,214	\$121,845
4A2	\$70,525	\$81,235	\$61,870	\$136,064	\$157,883	\$116,721
4A3	\$68,508	\$81,222	\$60,607	\$128,554	\$159,872	\$117,082
4B1	\$88,646	\$88,401	\$69,465	\$149,780	\$165,075	\$121,441
4B2	\$70,378	\$81,142	\$61,703	\$135,780	\$157,744	\$116,443
4B3	\$68,361	\$81,128	\$60,488	\$128,272	\$159,733	\$116,805
4C1	\$111,054	\$150,870	\$125,405	\$199,590	\$295,197	\$232,238
4C2	\$99,623	\$143,608	\$124,280	\$192,663	\$289,156	\$231,004
4C3	\$98,536	\$143,586	\$124,622	\$190,180	\$291,485	\$231,912
4D1	\$90,138	\$88,660	\$69,609	\$153,802	\$165,443	\$121,695
4D2	\$71,870	\$81,400	\$61,877	\$139,801	\$158,119	\$116,772
4D3	\$69,854	\$81,386	\$60,564	\$132,293	\$160,108	\$117,135

Table 3-11: Baseline Annual Site Energy Cost (\$/Year) by HVAC System Option, School Type and Location



# BASELINE ANNUAL ENERGY COSTS

## - \$/Ft<sup>2</sup>

H V A C System Option	Elementary School			High School		
	Cincinnati	Cleveland	Columbus	Cincinnati	Cleveland	Columbus
1A1	\$1.35	\$1.22	\$1.02	\$1.25	\$1.34	\$1.00
1A2	\$1.03	\$1.10	\$0.89	\$1.13	\$1.28	\$0.95
1A3	\$1.01	\$1.10	\$0.85	\$1.06	\$1.29	\$0.95
1B1	\$1.35	\$1.22	\$1.02	\$1.25	\$1.34	\$1.00
1B2	\$1.03	\$1.10	\$0.89	\$1.12	\$1.28	\$0.95

H V A C System Option	Elementary School			High School		
	Cincinnati	Cleveland	Columbus	Cincinnati	Cleveland	Columbus
1A1	\$1.35	\$1.22	\$1.02	\$1.25	\$1.34	\$1.00
1A2	\$1.03	\$1.10	\$0.89	\$1.13	\$1.28	\$0.95
1A3	\$1.01	\$1.10	\$0.85	\$1.06	\$1.29	\$0.95
1B1	\$1.35	\$1.22	\$1.02	\$1.25	\$1.34	\$1.00
1B2	\$1.03	\$1.10	\$0.89	\$1.12	\$1.28	\$0.95
1B3	\$1.01	\$1.10	\$0.85	\$1.06	\$1.29	\$0.95
1C1	\$1.39	\$1.71	\$1.20	\$1.61	\$2.34	\$1.81
1C2	\$1.16	\$1.59	\$1.05	\$1.55	\$2.29	\$1.80
1C3	\$1.15	\$1.59	\$1.14	\$1.52	\$2.31	\$1.81
1D1	\$1.36	\$1.22	\$1.02	\$1.28	\$1.34	\$1.00
1D2	\$1.04	\$1.10	\$0.89	\$1.15	\$1.28	\$0.95
1D3	\$1.02	\$1.10	\$0.85	\$1.09	\$1.30	\$0.95
2A1	\$1.39	\$1.29	\$1.07	\$1.27	\$1.36	\$1.02
2A2	\$1.07	\$1.15	\$0.91	\$1.14	\$1.30	\$0.96
2A3	\$1.04	\$1.16	\$0.90	\$1.07	\$1.31	\$0.97
2B1	\$1.39	\$1.30	\$1.07	\$1.26	\$1.36	\$1.02
2B2	\$1.07	\$1.15	\$0.91	\$1.13	\$1.29	\$0.96
2B3	\$1.04	\$1.16	\$0.90	\$1.07	\$1.31	\$0.96
2C1	\$1.43	\$1.79	\$1.25	\$1.60	\$2.32	\$1.79
2C2	\$1.20	\$1.65	\$1.18	\$1.53	\$2.26	\$1.78
2C3	\$1.19	\$1.66	\$1.18	\$1.51	\$2.28	\$1.79
2D1	\$1.40	\$1.30	\$1.07	\$1.29	\$1.36	\$1.02
2D2	\$1.08	\$1.15	\$0.91	\$1.16	\$1.30	\$0.96
2D3	\$1.06	\$1.16	\$0.90	\$1.10	\$1.31	\$0.97
3A1	\$1.40	\$1.87	\$1.38	\$1.20	\$1.63	\$1.17
3B1	\$1.40	\$1.87	\$1.38	\$1.19	\$1.63	\$1.17
3C1	\$1.93	\$2.83	\$2.32	\$1.58	\$2.36	\$1.87
3D1	\$1.42	\$1.87	\$1.38	\$1.21	\$1.63	\$1.18
4A1	\$1.38	\$1.37	\$1.08	\$1.25	\$1.37	\$1.01
4A2	\$1.09	\$1.26	\$0.96	\$1.13	\$1.31	\$0.97
4A3	\$1.06	\$1.26	\$0.94	\$1.07	\$1.33	\$0.97
4B1	\$1.38	\$1.37	\$1.08	\$1.24	\$1.37	\$1.01
4B2	\$1.09	\$1.26	\$0.96	\$1.13	\$1.31	\$0.97
4B3	\$1.06	\$1.26	\$0.94	\$1.06	\$1.33	\$0.97
4C1	\$1.72	\$2.34	\$1.95	\$1.66	\$2.45	\$1.93
4C2	\$1.55	\$2.23	\$1.93	\$1.60	\$2.40	\$1.92
4C3	\$1.53	\$2.23	\$1.93	\$1.58	\$2.42	\$1.92
4D1	\$1.40	\$1.38	\$1.08	\$1.28	\$1.37	\$1.01
4D2	\$1.12	\$1.26	\$0.96	\$1.16	\$1.31	\$0.97
4D3	\$1.08	\$1.26	\$0.94	\$1.10	\$1.33	\$0.97

Table 3-12: Baseline Annual Site Energy Cost (\$/Ft<sup>2</sup>/Year) by HVAC System Option, School Type and Location

# BASELINE ANNUAL ENERGY COSTS - Elementary School/Sorted

HVAC OPTION	Cincinnati E.S.	HVAC OPTION	Cleveland E.S.	HVAC OPTION	Columbus E.S.
1B3	\$65,192	1A3	\$70,678	1B3	\$54,763
1A3	\$65,195	1A2	\$70,705	1A3	\$54,783
1D3	\$65,911	1B3	\$70,925	1D3	\$54,789
1B2	\$66,347	1B2	\$70,954	1B2	\$57,071
1A2	\$66,349	1D3	\$71,120	1A2	\$57,092

2C1	\$92,196	3D1	\$120,629	3D1	\$89,075
4C3	\$98,536	4C3	\$143,586	4C2	\$124,280
4C2	\$99,623	4C2	\$143,608	4C3	\$124,622
4C1	\$111,054	4C1	\$150,870	4C1	\$125,405
3C1	\$124,060	3C1	\$182,459	3C1	\$149,204

**Table 3-13: Baseline Site Energy Cost (\$/Year) for the Elen School Case – Sorted from Smallest to Largest**

# BASELINE ANNUAL ENERGY COSTS - High School/Sorted

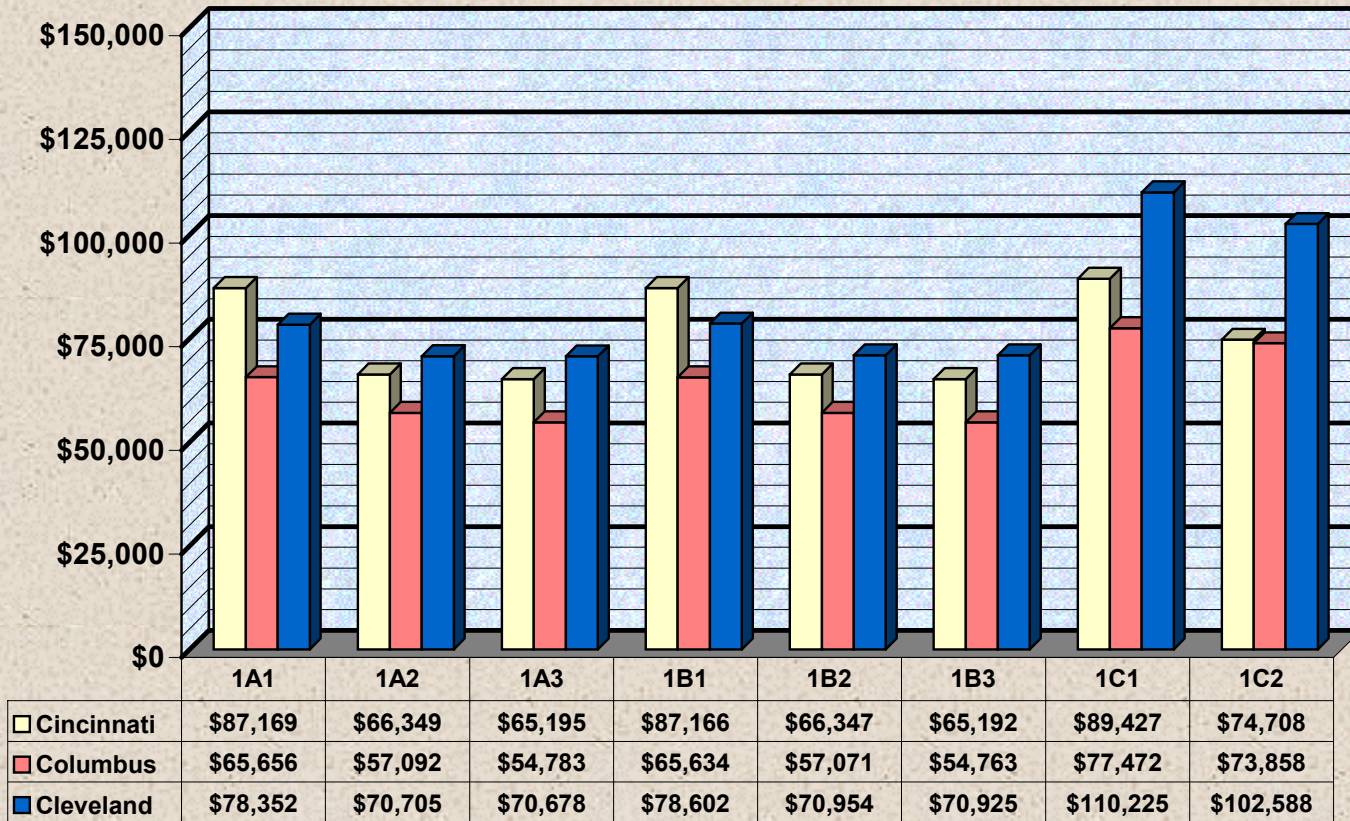
H V A C O P T I O N	Cincinnati H.S.	H V A C O P T I O N	Cleveland H.S.	H V A C O P T I O N	Columbus H.S.
1B3	\$127,689	1B2	\$153,866	1B2	\$114,503
1A3	\$127,977	1A2	\$154,039	1B3	\$114,718
4B3	\$128,272	1D2	\$154,263	1A2	\$114,784
4A3	\$128,554	1B3	\$155,788	1D2	\$114,844
2B3	\$128,997	2B2	\$155,885	1A3	\$114,999
2A3	\$129,290	1A3	\$155,961	1D3	\$115,058
1D3	\$131,493	2A2	\$156,075	2B2	\$115,896

4C3	\$190,180	2C1	\$279,580	1C3	\$217,885
3C1	\$190,656	1C1	\$281,848	1C1	\$218,221
4C2	\$192,663	3C1	\$284,280	3C1	\$225,636
2C1	\$193,087	4C2	\$289,156	4C2	\$231,004
1C1	\$193,683	4C3	\$291,485	4C3	\$231,912
4C1	\$199,590	4C1	\$295,197	4C1	\$232,238

**Table 3-14**      **Baseline Site Energy Cost (\$/Year) for the High School Case – Sorted from Smallest to Largest**

# BASELINE ANNUAL ENERGY COSTS

Figure 3-11: OSFC Elementary School  
Baseline Annual Energy Costs (\$/Year)  
(HVAC Systems 1A1 - 1C2)

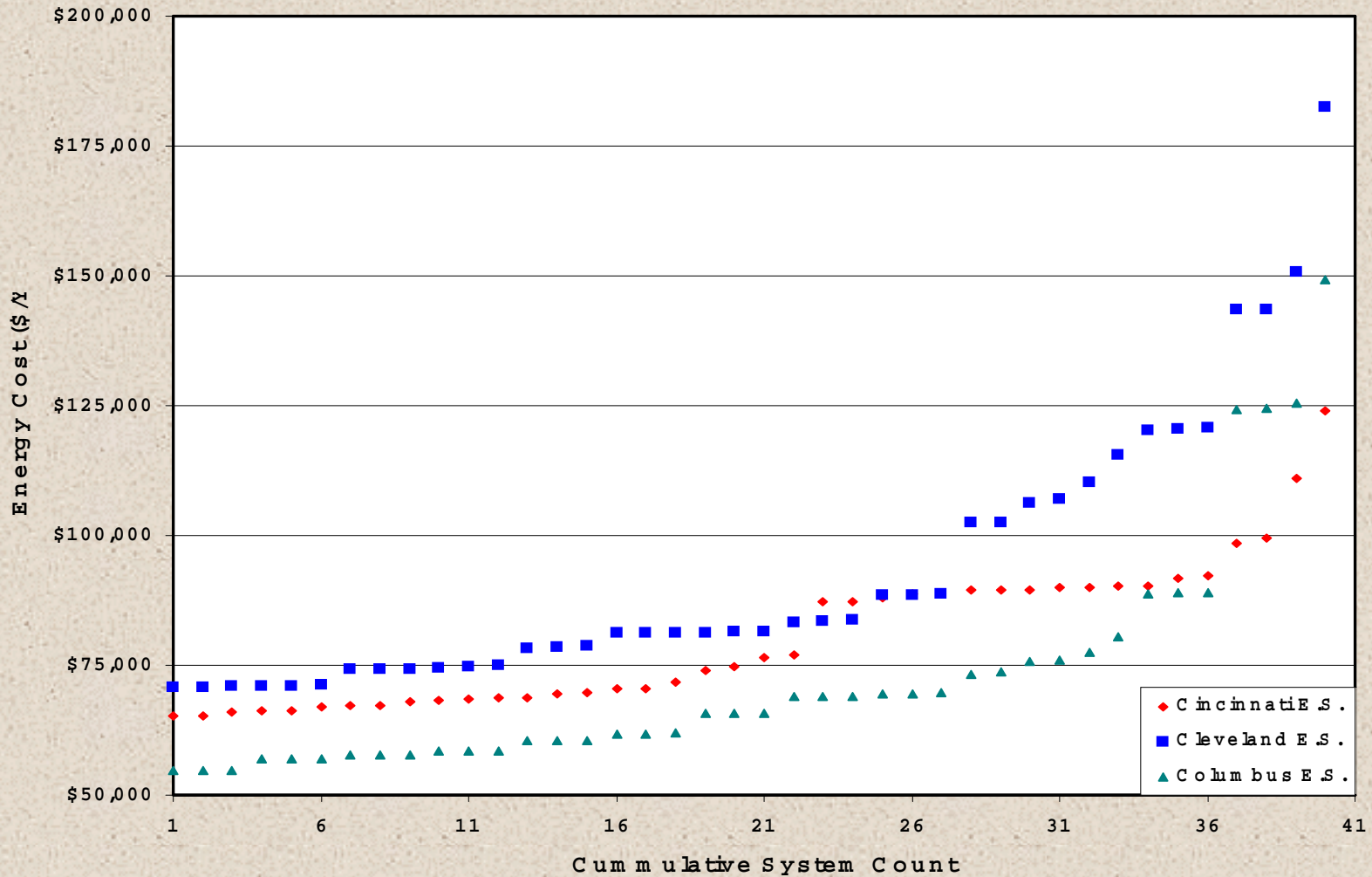


HVAC System Types

# ANNUAL ENERGY COSTS

## – Cumulative Plot by HVAC System Option

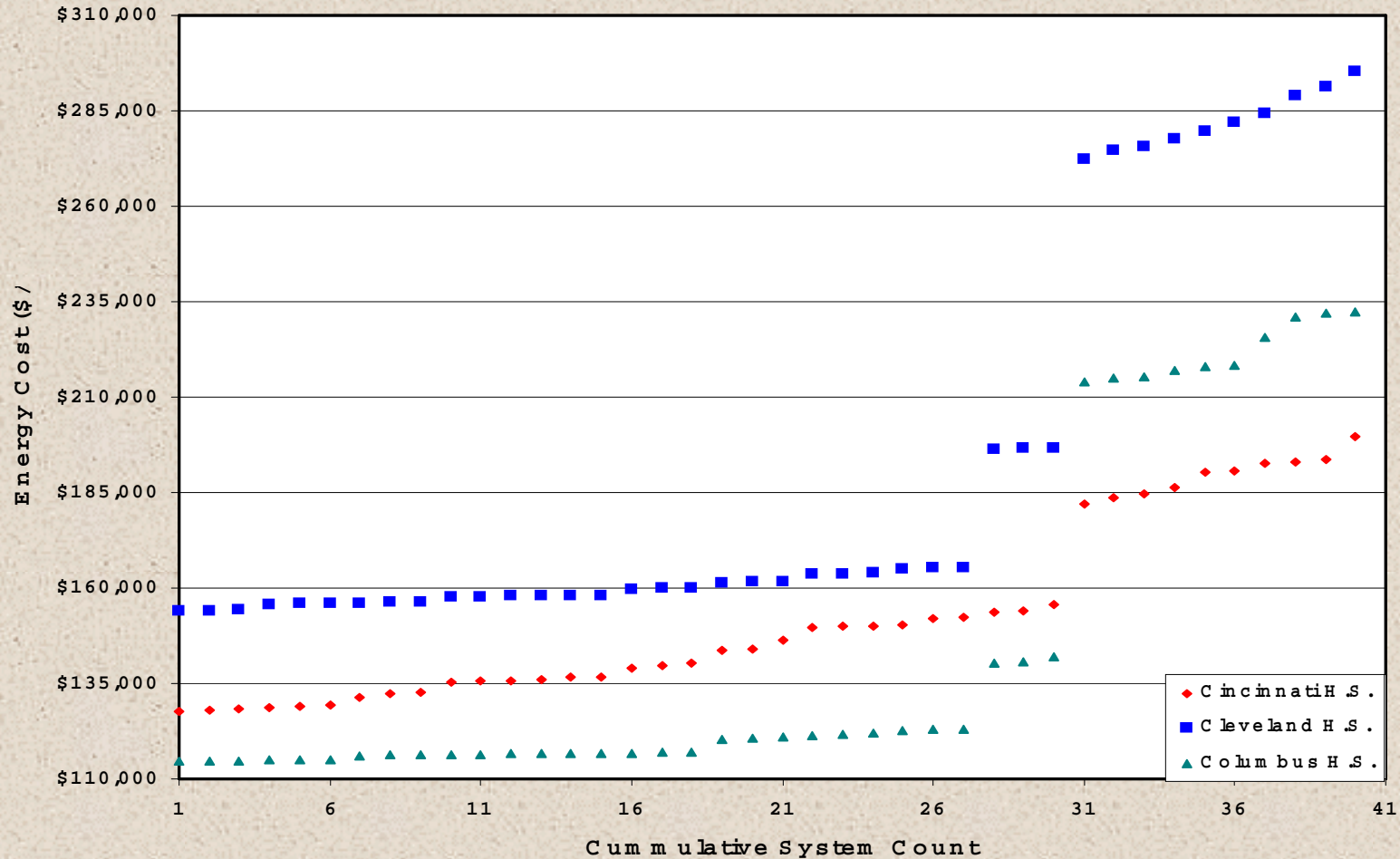
Elementary School Energy Cost (\$/Yr)



# ANNUAL ENERGY COSTS

## – Cumulative Plot by HVAC System Option

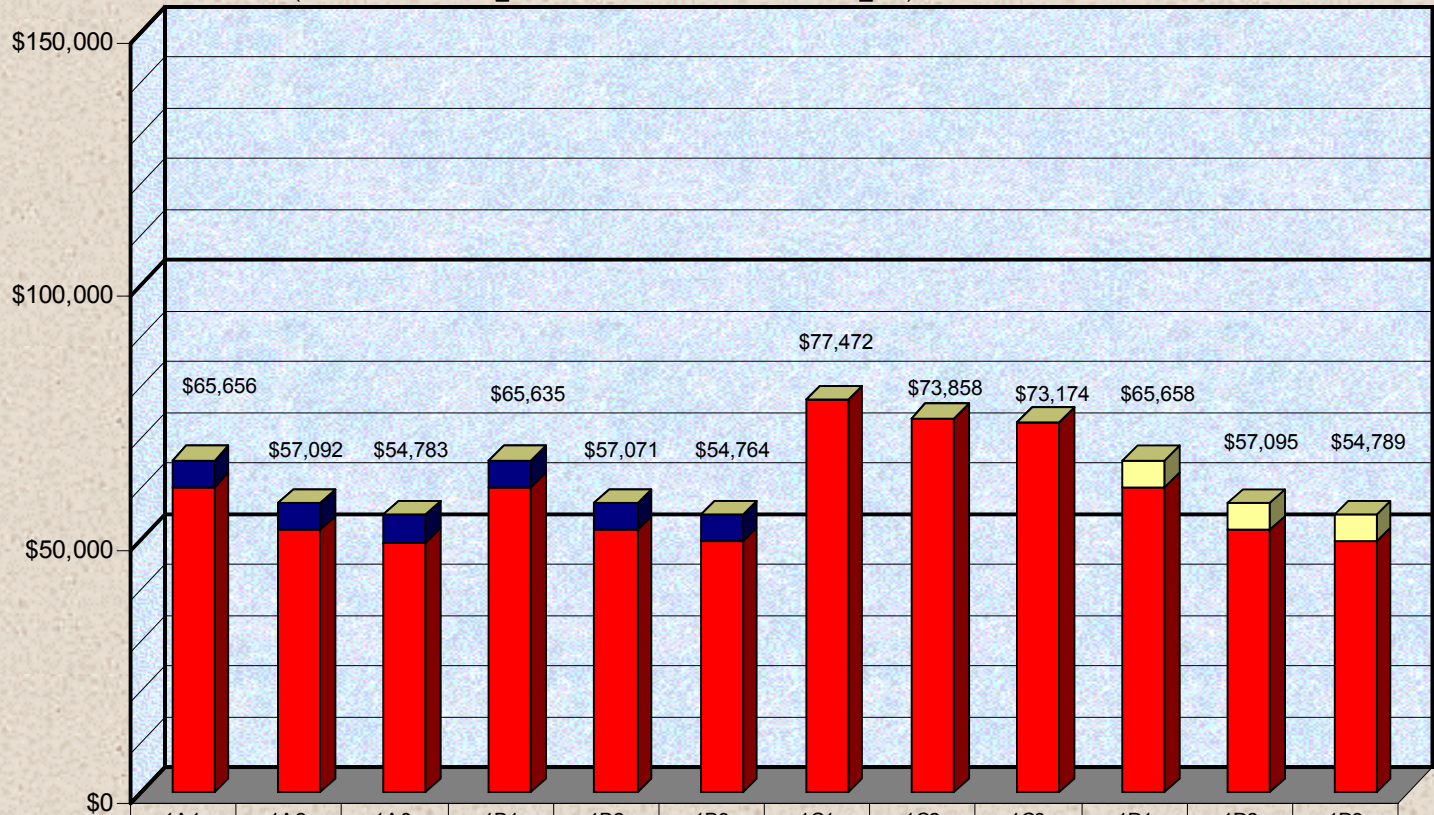
High School Energy Cost (\$/Yr)



# BASELINE ANNUAL ENERGY COSTS

## OSFC Elementary School Energy Simulation - Columbus VAV w/ Reheat

(Electric Rate - AEP\_GS3 and Natural Gas Rate - COH\_GS)



	1A1	1A2	1A3	1B1	1B2	1B3	1C1	1C2	1C3	1D1	1D2	1D3
■ Fuel Oil Cost (\$0.80/gallon)	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$5,302	\$5,302	\$5,302
■ Natural Gas Cost (COH_GS Rate)	\$5,374	\$5,374	\$5,374	\$5,308	\$5,308	\$5,308	\$0	\$0	\$0	\$0	\$0	\$0
■ Electric Cost (AEP_GS3 Rate)	\$60,282	\$51,718	\$49,409	\$60,327	\$51,763	\$49,456	\$77,472	\$73,858	\$73,174	\$60,356	\$51,793	\$49,487

System Type

# LIFE-CYCLE COST ANALYSES

# LIFE-CYCLE COST ANALYSES

HVAC decisions not based only on annual energy costs !

- ◆ Life-cycle analyses based on:
  - Equipment first costs
  - Annual energy costs
  - Annualized service and maintenance costs.
  
- ◆ Equipment first costs included three major elements:
  - Plant (heating and cooling plant equipment)
  - Ductwork
  - Terminal units.
  
- ◆ Service and Maintenance costs included:
  - Preventive (Scheduled) Maintenance Costs - Annual
  - Repair and Replacement Service and Maintenance - Annualized.

# OTHER INPUTS USED FOR LIFE-CYCLE COST CALCULATIONS

- ✦ Means CostWorks 2000 for Costs - See next page for an example
- ✦ 6% discount factor
- ✦ Added first cost to 20 years of annual energy and S/M costs – discounted.

# USE OF MEANS COSTWORKS 2000 DATA

<b><u>HEATING EQUIPMENT - Boiler Systems</u></b>						
Installed, including system components						
<b>A: Electric Boiler - Hot Water/Steam Data Source: 2000 Means Mechanical Cost Index</b>						
<b>Hot Water</b>			<b>Non-linear fits fared no better based on R<sup>2</sup></b>			
<u>Capacity</u>		<u>Cost (\$)</u>	<u>Cost = Slope * MMBtu + Intercept</u>			<u>Pred. Cost</u>
kW	Million BTU		<u>Slope</u>	<u>Intercept</u>		(linear)
60	0.205	\$8,050	9,836.77	15,102.61	Linear	\$17,119.15
120	0.410	\$11,400				\$19,135.69
150	0.510	\$20,000				\$20,119.36
210	0.716	\$23,350				\$22,145.74
270	0.922	\$27,025				\$24,172.11
480	1.636	\$35,375				\$31,195.57
630	2.148	\$40,350				\$36,231.99
900	3.071	\$52,500				\$45,311.33
1320	4.505	\$63,600				\$59,417.26
2100	7.167	\$82,400				\$85,602.74
2610	8.905	\$99,100				\$102,699.05
<i>Used for Electric Boiler</i>						

Similar curves developed for all plant equipment and for service and maintenance costs.

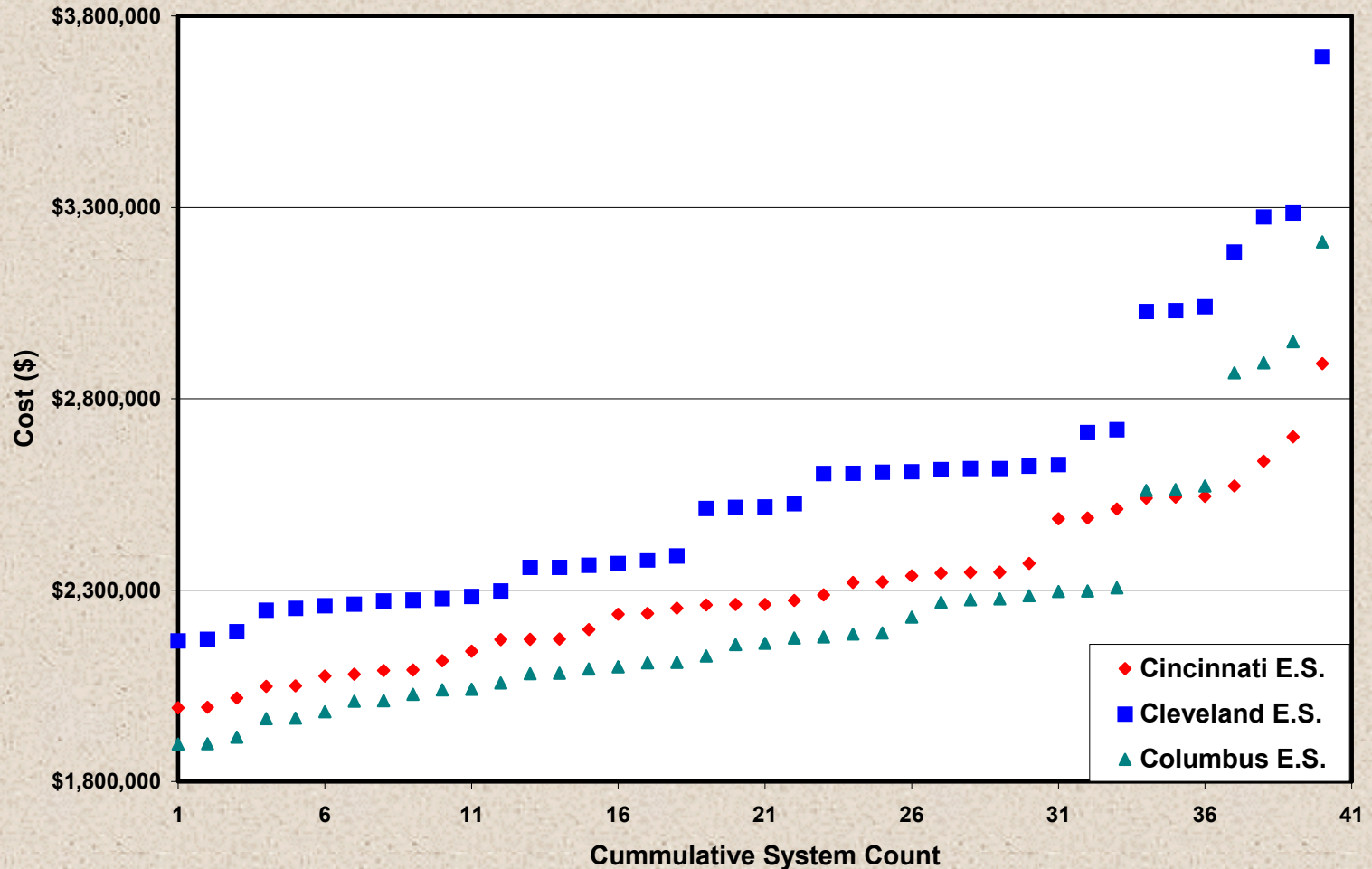
# ROLL-UP OF LIFE-CYCLE COSTS

Elementary School Life-Cycle Sorts					
H V A C System	Cincinnati	H V A C System	Cleveland	H V A C System	Columbus
1 A 3	\$1,992,541	1 A 3	\$2,167,169	1 A 3	\$1,897,806
1 B 3	\$1,993,885	1 B 3	\$2,171,512	1 B 3	\$1,898,981
1 D 3	\$2,018,368	1 D 3	\$2,191,439	1 D 3	\$1,915,842
2 A 3	\$2,048,769	2 A 3	\$2,247,842	2 A 3	\$1,964,275
2 B 3	\$2,050,196	2 B 3	\$2,252,116	2 B 3	\$1,965,565
2 D 3	\$2,075,560	1 A 2	\$2,259,071	2 D 3	\$1,982,220
1 C 3	\$2,080,509	1 B 2	\$2,263,431	1 A 2	\$2,009,998
1 A 2	\$2,089,820	2 D 3	\$2,271,805	1 B 2	\$2,011,158
1 B 2	\$2,091,178	1 A 1	\$2,272,507	1 D 2	\$2,028,004
4 C 3	\$2,540,251	3 A 1	\$3,027,582	3 A 1	\$2,560,640
3 A 1	\$2,543,046	3 B 1	\$3,030,219	3 B 1	\$2,562,762
3 B 1	\$2,545,447	3 D 1	\$3,040,369	3 D 1	\$2,572,124
3 D 1	\$2,571,823	4 C 3	\$3,183,553	4 C 3	\$2,867,422
4 C 2	\$2,636,775	4 C 2	\$3,275,394	4 C 1	\$2,893,625
4 C 1	\$2,700,720	4 C 1	\$3,285,501	4 C 2	\$2,949,214
3 C 1	\$2,891,908	3 C 1	\$3,693,610	3 C 1	\$3,209,445

**Table 4-11: Elementary School Life Cycle Costs for all B**

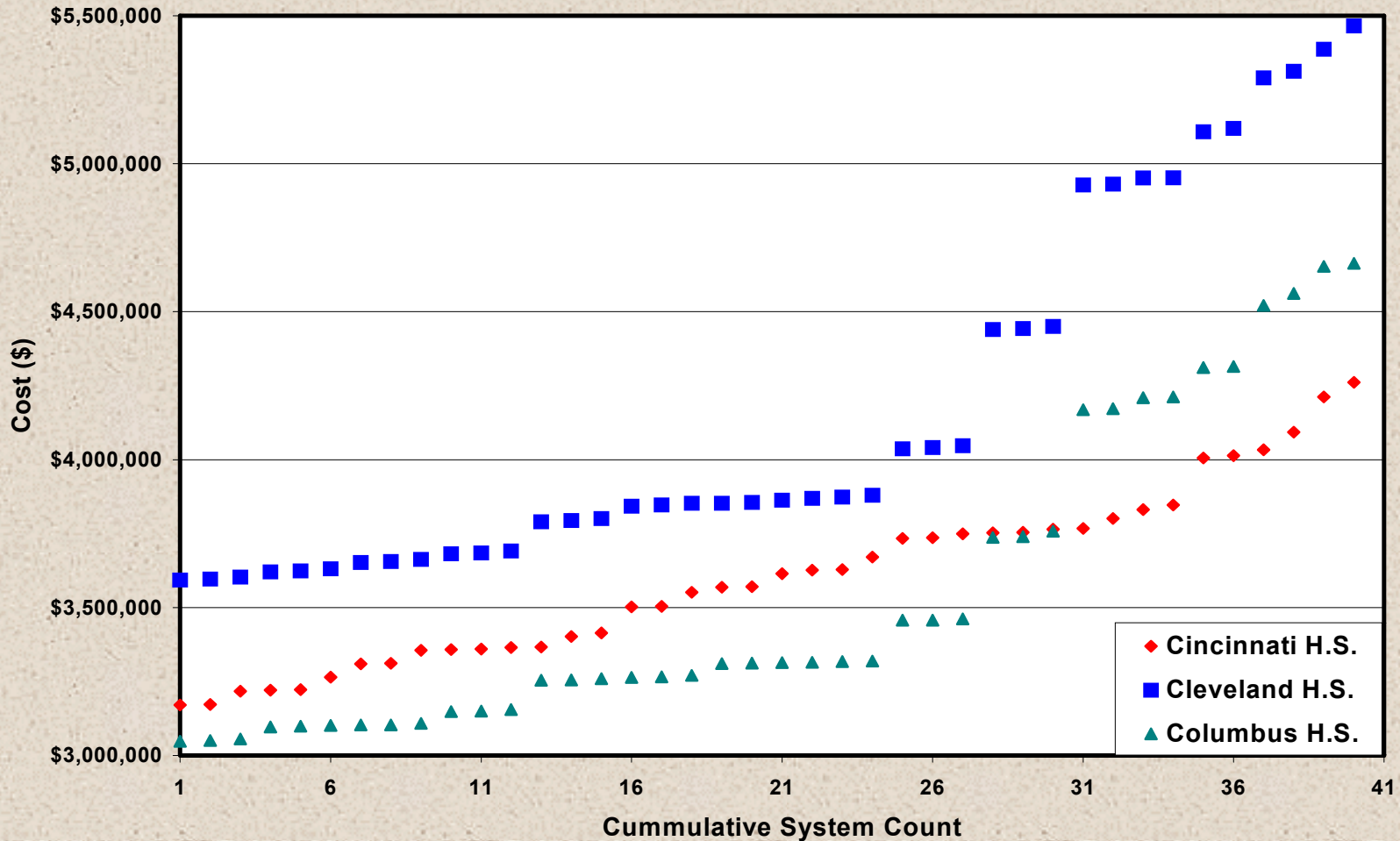
# LIFE CYCLE COSTS – Cumulative Plot by HVAC System Option

Elementary School Life Cycle Costs (\$)



# LIFE CYCLE COSTS – Cumulative Plot by HVAC System Option

High School Life Cycle Costs (\$)



# ENTHALPY HEAT RECOVERY COST ANALYSES

# ENTHALPY HEAT RECOVERY APPROACH

- ✦ **Energy Costs** - Models re-run for *both buildings in all three cities* assuming all heat recovery equipment options available were installed.
- ✦ **Capital Costs** - Incremental equipment costs for both building types computed based on smaller plant sizes and cost of enthalpy equipment.
- ✦ **Differential annual energy costs and S&M costs** were combined with incremental equipment first costs, to calculate NPVs and PBs.

# AREAS INCLUDED FOR ENTHALPY HEAT RECOVERY

School Building	Alternative ID	Equipment	CFM
Elementary School	Area A: Admin, Art, Music and Media Rooms		4,000
	Area B: Gym, Cafateria, Mech. Room		4,000
	Area C: Pre-K, K Classrooms		3,500
	Area D: 1 <sup>st</sup> and 2 <sup>nd</sup> Grade Classrooms		3,500
	Area E: 3 <sup>rd</sup> Grade, Special Ed. Classrooms		3,500
		TOTAL	
High School	M-2: Classrooms in Areas A, C and D – Drawings M4.1A, M4.2A and M4.3A	HRU-1A	6,000
		HRU-2A	6,000
		HRU-4A	8,000
	M-3: Auditoria – Drawing M4.2A.	HRU-3A	6,000
		HRU for AHU-5	28,000
	TOTAL		<b>54,000</b>

**OSFC cost: \$8.55/CFM**

**Supplier (Means, Carrier, Trane, and FAS) costs: \$4.50/CFM**

**Used supplier costs for enthalpy first costs.....**

# ENTHALPY NPV AND PB RESULTS

## Elementary School

Enthalpy Cost-Benefit Analysis - Elementary School						
System	E. S. School - Enthalpy-NPV			E. S. School - Enthalpy-PB		
Number	Cleveland	Cincinnati	Columbus	Cleveland	Cincinnati	Columbus
1A1	\$49,696	\$156,109	\$76,650	6.2	3.0	4.8
1A2	-\$65,045	-\$43,606	-\$33,300	104.5	32.8	22.4
1A3	-\$41,962	\$4,548	-\$24,535	30.4	10.7	18.8
1B1	\$52,763	\$157,603	\$78,110	6.0	2.9	4.7
1B2	-\$61,967	-\$42,099	-\$31,855	85.5	32.0	21.9
1B3	-\$38,908	\$6,028	-\$23,603	28.0	10.4	18.6
1C1	\$240,853	\$170,586	\$174,763	2.4	2.9	2.9
4C2	\$591,096	\$348,712	\$703,908	0.9	1.3	0.7
4C3	\$615,188	\$381,727	\$738,169	0.8	1.1	0.6
4D1	\$176,770	\$229,807	\$153,765	0.7	0.5	0.8
4D2	\$75,720	\$69,445	\$67,599	2.9	2.9	3.0
4D3	\$99,899	\$98,665	\$85,792	1.9	1.8	2.1

For the elementary school, NPVs ranged from -\$65,045 (Cleveland, 1A2) to \$887,794 (Columbus, 3C1)

Paybacks ranged from nearly instantaneous (Columbus, 3C1) to 104.5 years (Cleveland, 1A2). However, most of the paybacks were less than 25 years and over half were less than six years.

Consistently, systems based on water-cooled screw chillers produce the poorest NPVs and PBs. This is tied directly back to the smallest equipment size reductions

# ENTHALPY NPV AND PB RESULTS

## High School

Enthalpy Cost-Benefit Analysis - High School						
System	H . S . School - Enthalpy-NPV			H . S . School - Enthalpy-PB		
Number	Cleveland	Cincinnati	Columbus	Cleveland	Cincinnati	Columbus
1A1	\$40,330	\$187,674	\$60,670	9.4	5.5	8.5
1A2	-\$64,727	\$24,226	-\$50,985	17.6	10.0	16.2
1A3	-\$74,955	-\$17,693	-\$60,513	18.5	12.7	17.1
1B1	\$45,452	\$191,189	\$62,950	9.2	5.3	8.4
1B2	-\$59,610	\$27,740	-\$47,243	17.1	9.8	15.9
1B3	\$118,878	\$118,898	\$52,723	18.8	12.5	16.2
4C1	\$912,750	\$527,213	\$961,230	2.1	3.1	1.9
4C2	\$822,334	\$431,419	\$891,861	2.3	3.5	2.1
4C3	\$819,093	\$415,707	\$894,565	2.4	3.8	2.2
4D1	\$25,838	\$179,090	\$45,576	10.1	5.6	9.1
4D2	-\$73,614	\$45,111	-\$52,636	19.0	9.1	16.4
4D3	-\$83,915	\$4,045	-\$61,708	20.0	11.2	17.3

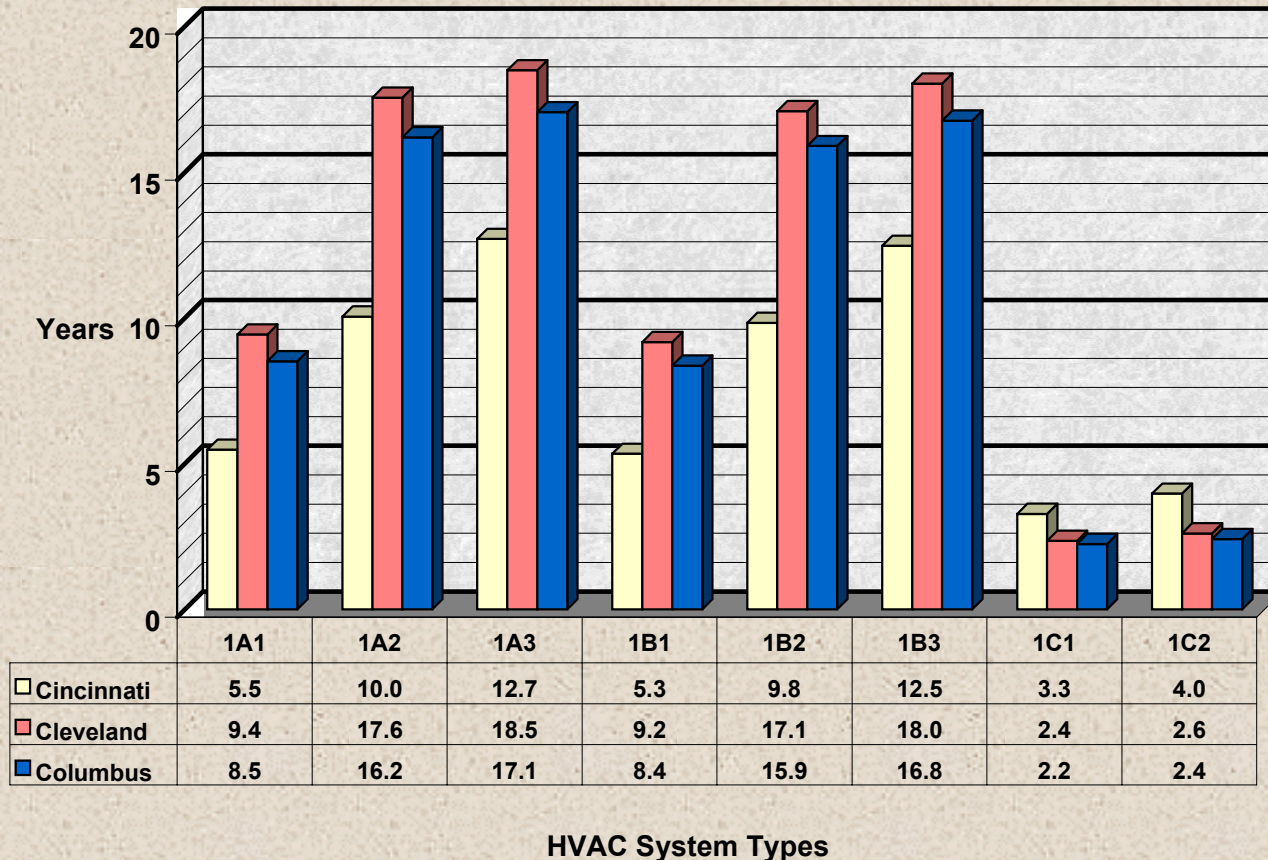
For the high school, NPVs ranged from -\$83,915 (Cleveland, 4D3) to \$1,166,479 (Columbus, 3C1)

Paybacks ranged from nearly instantaneous (Columbus, 3C1) to 20.0 years (Cleveland, 1A2).

In all cases the benefits would be lower if only a portion of the building systems used enthalpy heat recovery.

# H.S. ENTHALPY HEAT RECOVERY PAYBACKS (Years)

Figure 7-6: OSFC High School  
Paybacks with Enthalpy Heat Recovery (Years)  
(HVAC Systems 1A1- 1C2)



# ENTHALPY HX CONCLUSIONS

- ◆ *In general, the overall economics for use of enthalpy heat recovery appear to be quite positive; the technology has maximum benefits for the all-electric cases.*
- ◆ For the elementary school, NPVs ranged from -\$65,045 (Cleveland, 1A2) to \$887,794 (Columbus, 3C1) and paybacks ranged from nearly instantaneous (Columbus, 3C1) to 104.5 years (Cleveland, 1A2). However, over 75% of the cases have positive NPVs and paybacks of less than 11 years. Consistently, systems based on water-cooled screw chillers produce the poorest NPVs and PBs while all-electric systems produce the best NPVs and PBs.
- ◆ For the high school, NPVs ranged from -\$83,915 (Cleveland, 4D3) to \$1,166,479 (Columbus, 3C1) and paybacks ranged from nearly instantaneous (Columbus, 3C1) to 20.0 years (Cleveland, 1A2).
- ◆ Given building lives in excess of 20 years, it would appear that enthalpy heat recovery should be considered in all high school cases and the majority of elementary school cases.

# OCCUPANCY-BASED VENTILATION ANALYSES

# OCCUPANCY-BASED VENTILATION (IAQ) APPROACH

- ✦ **Energy Costs** - Models re-run for high school in Columbus. Ran two cases: i) reduced ventilation air from 15 to 10 CFM/person and ii) increased air from 15 to 20 CFM/person.
- ✦ **Capital Costs** - Incremental equipment costs for both options computed based on smaller/larger plant sizes.
- ✦ **Differential annual energy costs and S&M costs** were combined with incremental equipment first costs, to calculate NPVs.

# COOLING EQUIPMENT SIZE CHANGES

HVAC System Option	Cooling Plant	HS Cooling Equipment (RT)		
		Base Case	10 CFM	20 CFM
1A1	Air Cooled Screw Chiller	340	325	370
1A2	Water Cooled Screw Chiller	340	325	370
1A3	Water Cooled Centrifugal Chiller	340	325	400
1B1	Air Cooled Screw Chiller	340	325	370
1B2	Water Cooled Screw Chiller	340	325	370
4C1	Air Cooled Screw Chiller	340	325	370
4C2	Water Cooled Screw Chiller	340	325	370
4C3	Water Cooled Centrifugal Chiller	340	325	400
4D1	Air Cooled Screw Chiller	340	325	370
4D2	Water Cooled Screw Chiller	340	325	370
4D3	Water Cooled Centrifugal Chiller	340	325	400

**Table 8-1: Cooling Equipment Chiller Sizes (RT) for Three Fresh Air Ventilation Rates (High School - Columbus)**

**10 CFM/Person Cooling Equipment Size: Reductions: 15 RT**

**20 CFM/Person Cooling Equipment Size: Increase: 30 to 60 RT**

**Heat Pump Cases: Baseline Case - 423 RT, 10 CFM/Person Case - 362 RT, 20 CFM/Person Case - 485 RT**

# HEATING EQUIPMENT SIZE CHANGES

HVAC System Option	Heating Plant	HS Cooling Equipment (MBTUH)		
		Base Case	10 CFM	20 CFM
1A1	NG Boiler - Atmospheric Burner	7,000	4,500	7,000
1A2	NG Boiler - Atmospheric Burner	7,000	4,500	7,000
1A3	NG Boiler - Atmospheric Burner	7,000	4,500	7,000
1B1	NG Boiler - Power Burner	7,000	4,500	7,000
1B2	NG Boiler - Power Burner	7,000	4,500	7,000
1B3	NG Boiler - Power Burner	7,000	4,500	7,000
4C1	Electric Boiler	5,734	4,200	7,000
4C2	Electric Boiler	5,734	4,200	7,000
4C3	Electric Boiler	5,734	4,200	7,000
4D1	Oil Boiler - Power Burner	7,000	5,000	8,500
4D2	Oil Boiler - Power Burner	7,000	5,000	8,500
4D3	Oil Boiler - Power Burner	7,000	5,000	8,500

**Table 8-2: Heating Equipment Boiler Sizes (MBTUH) for Three Fresh Air Ventilation Rates (High School – Columbus,**

**10 CFM/Person Heating Equipment Size: Reductions: 1,534 to 2,500 MBTUH**

**20 CFM/Person Heating Equipment Size: Increase: 0 to 1,500 MBTUH**

# H.S. DIFFERENTIAL ENERGY USAGE

HVAC System Option	Columbus - 20 vs 15 CFM			Columbus - 10 vs 15 CFM		
	Baseline Energy	20 CFM Energy	Increased Energy Use	Baseline Energy	10 CFM Energy	Decreased Energy Use
1A1	7,429	8,694	1,265	7,429	6,329	1,101
1A2	7,263	8,518	1,256	7,263	6,167	1,095
1A3	7,384	8,670	1,286	7,384	6,289	1,096
1B1	7,354	8,622	1,268	7,354	6,285	1,069
1B2	7,187	8,446	1,259	7,187	6,123	1,064
1B3	7,309	8,598	1,289	7,309	6,244	1,064
1C1	6,513	7,569	1,057	6,513	5,647	866

Comparing the 10 vs 15 CFM/person cases, annual energy savings ranged a low of 825 million BTUH per year (2C3) to a high of 1,532 million BTUH per year (3A1).

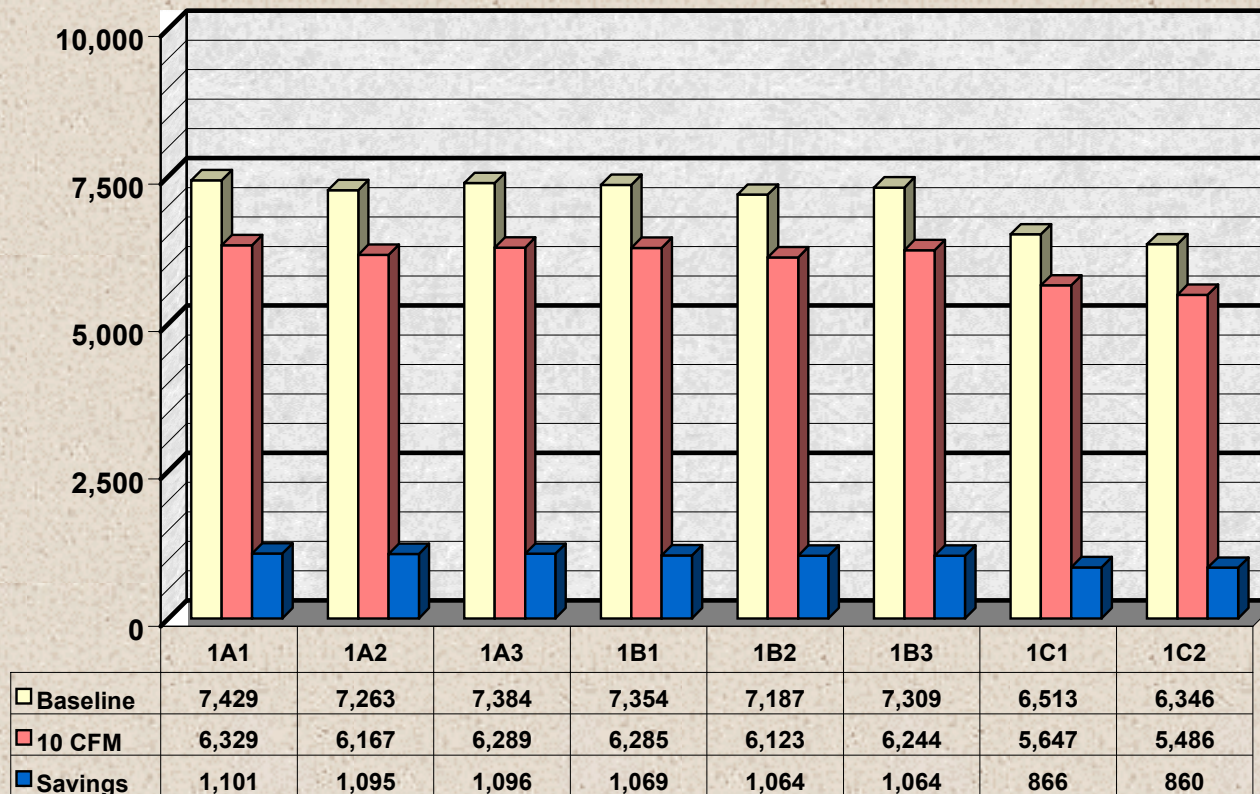
On a per square foot basis, this ranged from a low of 6.8 thousand BTUH per square foot per year (2C3) to a high of 12.7 thousand BTUH per square foot per year (3A1).

Comparing the 20 vs 15 CFM/person cases, annual site energy increased from a low of 1,048 million BTUH per year (1C2) to a high of 1,565 per year (3A1).

On a per square foot basis, this ranged from a low of 8.7 thousand BTUH per square foot per year (1C2) to a high of 13.0 BTUH per square foot per year (3A1).

# H.S. VENTILATION ENERGY SAVINGS (MMBTUH/Year)

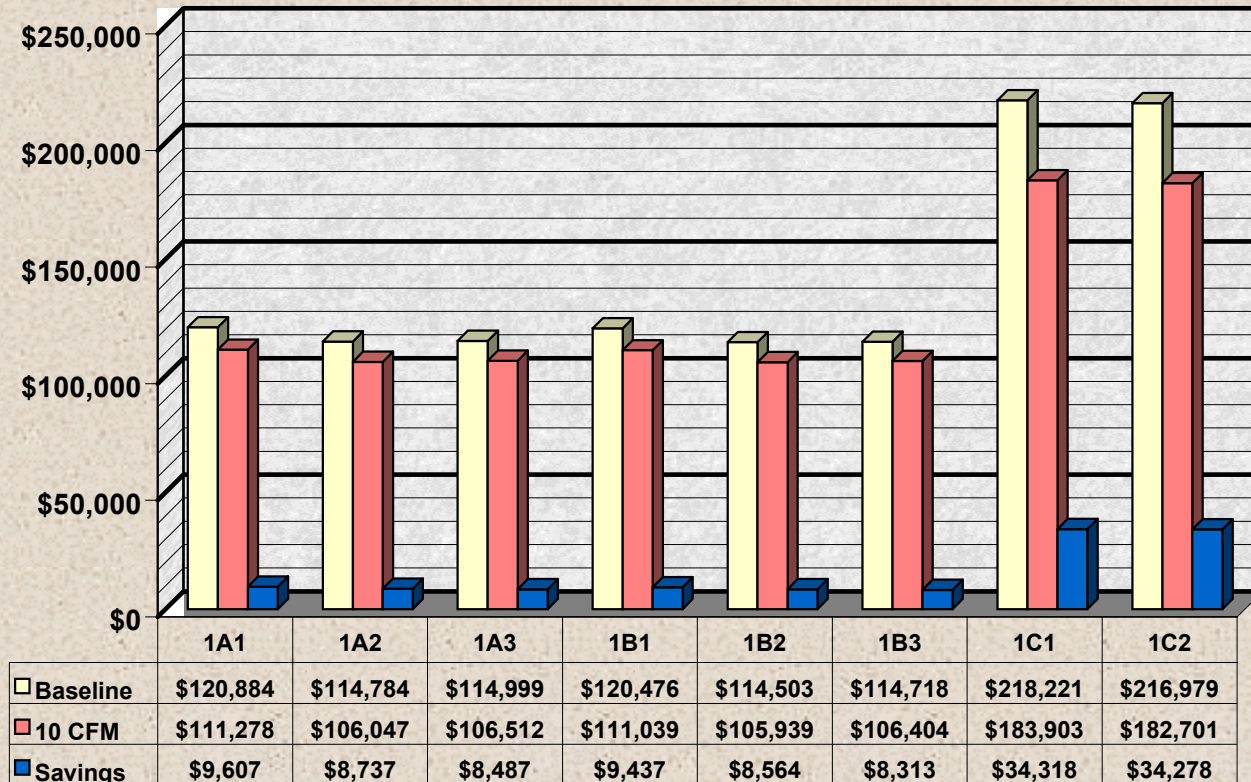
Figure 8-1: OSFC Columbus High School  
Annual Site Energy Use for 15 vs 10 SCFM/Person (MMBTU/Year)  
(HVAC Systems 1A1 - 1C2)



HVAC System Types

# H.S. VENTILATION ENERGY SAVINGS (\$/Year)

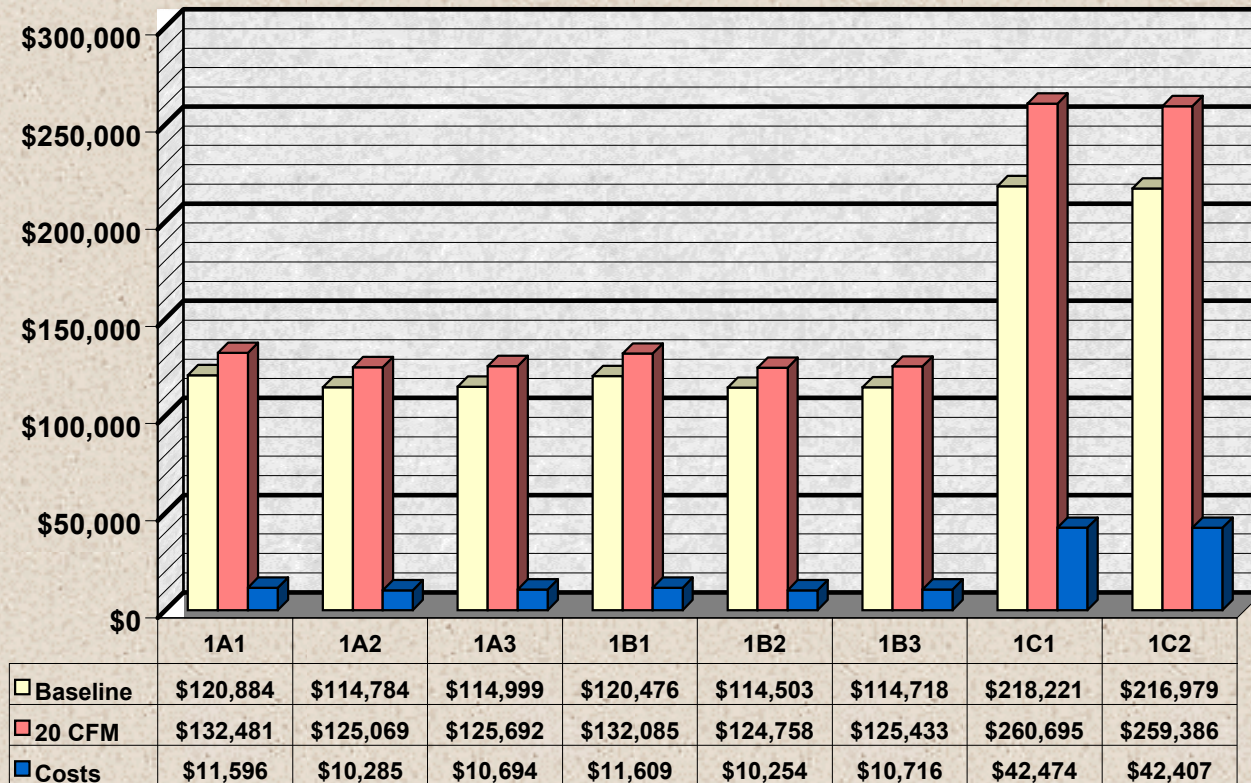
Figure 8-3: OSFC Columbus High School  
Annual Site Energy Savings for 15 vs 10 SCFM/Person (MBTU/Year)  
(HVAC Systems 1A1 - 1C2)



HVAC System Types

# H.S. VENTILATION ENERGY COSTS (\$/Year)

Figure 8-4: OSFC Columbus High School  
Annual Site Energy Cost for 15 vs 20 SCFM/Person (MBTU/Year)  
(HVAC Systems 1A1 - 1C2)



HVAC System Types

# VENTILATION NPV RESULTS

System Number	High School	
	10 CFM	20 CFM
1A 1	-\$193,849	\$194,240
1A 2	-\$164,410	\$140,254
1A 3	-\$167,529	\$191,218
1B 1	-\$191,905	\$194,387
1B 2	-\$162,421	\$139,909
1B 3	-\$165,540	\$191,471
1C 1	-\$454,764	\$548,398
1C 2	-\$434,837	\$508,696
1C 3	-\$440,867	\$557,542
4B 1	-\$188,884	\$261,268
4B 2	-\$162,593	\$195,631
4B 3	-\$166,105	\$245,840
4C 1	-\$567,880	\$553,526
4C 2	-\$547,941	\$513,819
4C 3	-\$553,984	\$562,667
4D 1	-\$185,023	\$251,558
4D 2	-\$159,109	\$185,498
4D 3	-\$162,621	\$236,220

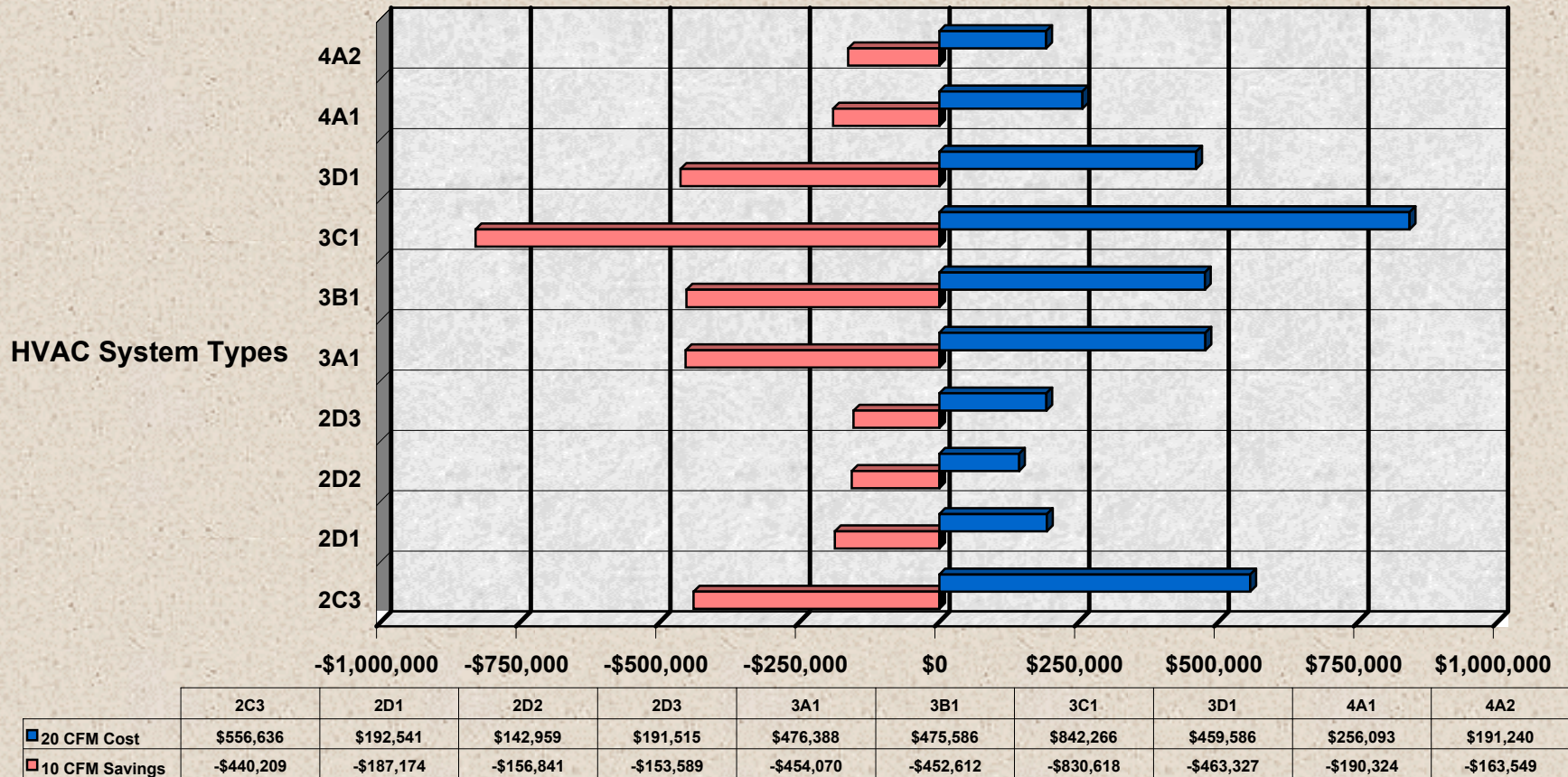
For the 10 vs 15 CFM/person cases (reduced ventilation or fresh air), the minimum savings calculated were \$153,589 (2D3) and the maximum savings were \$830,618 (3C1).

For the 20 vs 15 CFM/person cases (increased ventilation or fresh air), the minimum savings calculated were \$139,120 (1D2) and the maximum savings were \$842,266 (3C1).

The least impacted cases use water-cooled chillers and the highest impacted case is the all-electric heat pump case.

# VENTILATION LIFE CYCLE RESULTS

Figure 8-7: OSFC Columbus High School  
Differential Life Cycle Costs (\$)  
(HVAC Systems 2C3 - 4A2)



# VENTILATION (IAQ) CONCLUSIONS

- ◆ From a life-cycle perspective, decreasing ventilation air to school spaces saves \$153,589 (2D3) to \$830,618 (3C1), or 4.9% to 17.9% of baseline life cycle costs. Typical savings were about 5.2%.
- ◆ From a life-cycle perspective, increasing ventilation air to school spaces costs \$139,120 (1D2) to \$842,266 (3C1) or 4.5% to 18.1% of baseline life cycle costs. Typical increased costs were about 5.8%.
- ◆ Reduced equipment first costs for the 10 CFM/person cases ranged from a low of \$21,361 (4C1) to a high of \$106,530 (3D1).
- ◆ Increased equipment first costs for the 20 CFM/person cases ranged from a low of \$13,236 (multiple cases) to a high of \$113,496 (3D1).

# GEOHERMAL HEAT PUMP ANALYSES

# GEOHERMAL HEAT PUMP APPROACH

- ✦ **Energy Costs** - Models re-run for six cases. *These cases were both building types in all three cities.*
- ✦ **Capital Costs** - Equipment costs for both building types were computed based on an average of three sources of cost data.
- ✦ **Annual energy costs and S&M costs** were combined with equipment first costs to calculate life cycle costs.
- ✦ **Ground-loop temperatures critical to sizing and costing systems ... and to the resultant energy and economic analyses.**

# GEOHERMAL HEAT PUMP GROUND LOOP TEMPERATURE ISSUE

**ISSUE:** NEED OPTIMAL DESIGN LOOP TEMPERATURES ON AN HOUR BY HOUR BASIS TO RUN HAP!...DON'T EXIST.

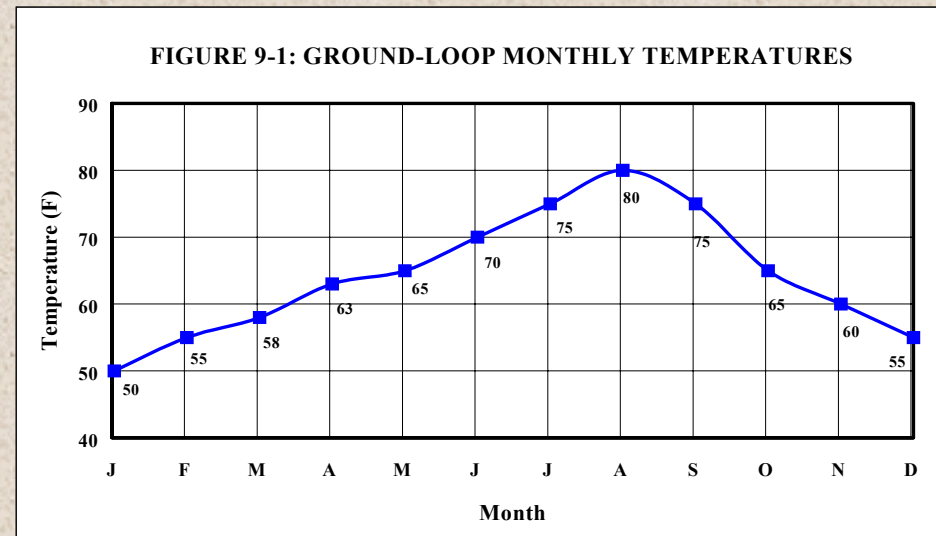
Evaluated series of DOE raw data (NB and KY), but sub optimum...down-hole temperature profiles flat.

Decided to determine /use monthly averages as best alternative.

**Keys:** Profile must reflect Ohio subsurface conditions and must optimize down hole costs (steep profile would be best) against system performance and delivered comfort (flat profile would be best).

Again, little hard design guidance available.

**Decision:** Profile reflects ARI test standards for geothermal heat pumps.



# GEOHERMAL ENERGY MODELING RESULTS

<b>Building Type &amp; Location</b>	<b>Elec. (kWH)</b>	<b>Nat. Gas (MCF)</b>	<b>Fuel Oil (Gallons)</b>	<b>Site Energy (MMBTU)</b>	<b>Source Energy (MMBTU)</b>	<b>Max. (kW)</b>
<u>Elem. School</u>						
Cincinnati	854,446	0	0	2,915	9,718	443
Cleveland	896,719	0	0	3,060	10,199	539
Columbus	865,200	0	0	2,952	9,840	503
<u>High School</u>						
Cincinnati	1,499,019	0	0	5,115	17,049	682
Cleveland	1,571,865	0	0	5,363	17,877	805
Columbus	1,523,422	0	0	5,198	17,326	771

**Table 9-2: Annual Site and Source Energy Consumption for Geothermal Cases**

# GEOHERMAL ANNUAL ENERGY COST RESULTS

<b>Building Type &amp; Location</b>	<b>Annual Energy Cost</b>
<u>Elem. School</u>	
Cincinnati	\$87,982
Cleveland	\$121,427
Columbus	\$85,400
<u>High School</u>	
Cincinnati	\$141,193
Cleveland	\$201,972
Columbus	\$136,106

# GEOHERMAL LIFE-CYCLE ASSUMPTIONS

## Geothermal well field costs:

<u>Source</u>	<u>\$/RT</u>	
Jim Kish	\$1,200.00	Ohio - installs 5 per systems per year
Charley Hill	\$750.00	Ohio installer
Maxey - ORNL	<u>\$948.80</u>	Lincoln, NB installation
	\$966.27 Avg.	Used average value for wellfield costs!

## Service and Maintenance Costs:

<u>Cost Item</u>	<u>Value and Basis</u>
PM	\$400/year for ES and \$600/year for HS
Repair	\$4,053 and \$5,653 annually for the ES and HS respectively (1/20th of first cost every five years)
Replacement	1/20 of first cost per year.

# GEOHERMAL LIFE CYCLE COSTS

HVAC System Number	Elementary School			High School		
	Cincinnati	Cleveland	Columbus	Cincinnati	Cleveland	Columbus
3A1 - Geo	\$3,285,977	\$3,739,791	\$3,296,783	\$4,474,558	\$5,225,838	\$4,469,900

## Comparable Baseline Life Cycle Results:

**Elementary School:            \$1,897,806 to \$3,693,690**

**High School:                    \$3,048,756 to \$5,465,692**

# SUMMARY – GEOTHERMAL H.P.



- ◆ Annual energy costs for Geothermal H.P. are low.
- ◆ Life-cycle costs are relatively high.
- ◆ Key is below-ground costs (i.e., drilling) which make first costs high.
- ◆ Technology is relatively new; first costs are likely to drop with time.
- ◆ Design basis (e.g., loop temperature curve vs heat exchange area) for below-ground conditions still evolving.

# DAYLIGHTING ANALYSES



# SUMMARY – DAYLIGHTING

- ◆ **Net annual energy costs for daylighting are essentially neutral. This is quite positive since non-energy benefits are positive (e.g., increased test scores).**
- ◆ **The two new buildings appear to be over lit (100 vs 60 foot-candles). Need to determine why.**
- ◆ **Key to daylighting is alternative architectural considerations – See detailed recommendations.**

# *Thank You*



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