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Comparative Analysis of HVAC Systems That Minimize the Risk of Airborne Infectious Disease Transmission

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ABSTRACT

According to published statistical data, most TB contamination occurs from unknown and unsuspected TB carriers. It can be found in many areas of a health care facility where, based on the building code requirements, the air is not exhausted to the outside but recirculated to other areas of the facility.

Although any system exhausting instead of recirculating the air greatly minimizes the risk of contamination, all-exhaust systems are not used because of their increased energy consumption. As an alternative method, recirculated air is HEPA filtered.

To assess the economic impact of these systems, a life-cycle cost analysis is performed for a health care facility using five alternatives, recirculation, HEPA filtration, or 100% exhaust applied to the waiting rooms and HEPA filtration and 100% exhaust applied to the entire building, for three locations: Los Angeles, New York, and Atlanta. The results show that the HEPA filtration system costs more than the 100% exhaust system, but the supplementary annual costs and life-cycle costs of any of the alternatives studied versus using the recirculation system are insignificant if compared to the cost of medical treatment for one TB patient—approximately $100,000.

INTRODUCTION

Health care facilities are characterized by both the presence of areas of high contamination (Cole and Cook 1998) and the increased sensitivity of some occupants. According to published statistical data, most TB contamination occurs from unknown and unsuspected TB carriers and can be found in many areas of health care facilities. Moreover, in many cases, the transmission of tuberculosis occurred when the patients were incorrectly diagnosed and were not isolated (Adal et al. 1994). This risk is higher in the outpatient clinics during the first visit of a patient "before a history has been taken that suggests tuberculosis" (Adal et al. 1994). This places the waiting rooms in health care clinics at the top of the list for high risk contamination.

The increased awareness regarding the risk of contamination with airborne disease in health care facilities, particularly TB contamination, was followed only partially by engineering controls code changes. For example, until recently the California mechanical code required only the isolation and some treatment rooms in the health clinics to be exhausted directly to the outside, but they allow recirculation of air for other areas of the facility, including waiting rooms.

Although any system exhausting instead of recirculating the air greatly minimizes the risk of contamination, all-exhaust systems are not used because of their increased energy consumption.

As an alternative method for control of airborne disease transmission, the recirculated air is HEPA filtered. The codes allow the use of HEPA filters as a method of air cleaning that either supplements other ventilation measures or replaces some of them.

According to CDC guidelines (CDC 1994), HEPA filters can be placed in three positions: (1) in the exhaust duct, to remove droplet nuclei from air being discharged to the outside; (2) in ducts discharging air from TB-contaminated rooms into the general air-conditioning system; (3) in fixed or portable room air cleaners.

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In the first case, there is no need for HEPA filtration if the ductwork is extended 7 feet above the roof and the air is discharged upstream at high velocity (CMC 1998).

In the second case, the addition of high-pressure HEPA filters on branches serving the contaminated rooms to the general return air system is impractical. It would need either the "artificial" increase of pressure drop through dampers on the other duct branches or the addition of in-line fans for the branches with HEPA filters. Both methods increase the energy cost and the maintenance cost in addition to the cost of the HEPA filters and fan. A dedicated system for the selected rooms is a more practical solution and a less costly one.

In the third case, the CDC guidelines (CDC 1994) state that "the effectiveness of portable HEPA room-air cleaning units has not been adequately evaluated, and there is probably considerable variation in their effectiveness." Also, a portable piece of equipment that may be removed at any time from its designated place should not be part of the equipment that ensures code compliance.

Fixed HEPA filters can be installed along with adequate fans and ductwork to recirculate the air locally in rooms where the required air movement cannot be achieved through the central air system. Again, this involves an increase in energy and maintenance costs.

HEPA filtration presents two main disadvantages: (1) it has a high pressure drop that increases fan energy consumption and (2) it has a high maintenance cost exacerbated by the need for bag-in, bag-out replacement procedures and hazardous material disposal. Also, an eventual puncture of the filter or a gap between the filter and its casing could annihilate its effectiveness.

The risk of contamination cannot be entirely removed but it can be further reduced by exhausting the air from the entire facility to the outside. A 100% exhaust, i.e., a 100% outside air system, would transform the entire facility into an isolation room, reducing substantially the risk of transmission of TB and other airborne disease. The method is especially valuable in AIDS treatment facilities where every patient is at high risk. However, the 100% outside air systems cannot be readily prescribed because they are not traditionally used owing to their higher energy cost. The replacement of a less than 100% outside air system with a 100% outside air system entails an increase in energy for the cooling and heating of the supplementary air, but it also results in a reduction of the construction cost because it would eliminate the return air duct, the return fan, and the air economizer with its dampers and controls.

In the past, saving energy at any cost dictated the selection of the HVAC systems. This trend continues today. Design above code requirements that would increase energy consumption would not be considered by designers. However, when the health of the occupants is at risk, the train of thought must change gear. In this specific case, minimizing the risk of contamination with TB or another airborne disease should be the major concern, and an economic comparison must stand at the basis of any design decision.

This paper proposes to do such an economic evaluation: to establish the energy cost differential of several system alternatives that minimize the risk of contamination versus the recirculating air system (allowed by codes) and to compare this cost with the cost of treatment of one TB patient, evaluated now at approximately $100,000.

HVAC ALTERNATIVES SELECTED FOR ANALYSIS

The analysis includes five HVAC alternatives as follows:

- Alternative 1—Isolation rooms, X-ray suite, and toilet rooms have the air exhausted to the outside; the rest of the building, including the waiting rooms, has the air recirculated to the rest of the building.
- Alternative 2—Same as Alternative 1, except a HEPA filter is added on the return air from the waiting rooms.
- Alternative 3—Same as Alternative 1, except the air from the waiting rooms is exhausted to the outside.
- Alternative 4—Same as Alternative 1, except a HEPA filter is added on the return air from the entire building.
- Alternative 5—The air from the entire building is exhausted to the outside.

To assess the economic impact of these five system alternatives, they were applied to a simplified version of a real building, "Mid-Valley Comprehensive Health Center," a 52,540 ft^2 health care facility located in Los Angeles. Since the energy consumption of the HVAC systems is climate dependent, the analysis was extended to two other extreme climatic locations, New York and Atlanta.

METHODOLOGY

A meaningful cost comparison should include all the cost elements that differ from one alternative to the other. The elements of this life-cycle cost analysis are the investment cost, the annual energy cost (electricity and gas), and the annual operation/maintenance cost. For ease of calculation, only the differential costs have been input.

For the investment cost, it was estimated that the cost of the HEPA filter installation for the waiting rooms is $3430 (of which $2520 represents the filter) and the total cost of HEPA filtration for the entire building is $7980 (of which $5880 represents the filter). Adding an exhaust fan for the waiting rooms and reducing the size of the return fan in Alternative 3 would add approximately $1000; the elimination of the return duct and return fan in Alternative 5 would save $3000.

The annual energy consumption for each alternative is estimated with a commercially available energy computer program. Figure 1 shows the layout, size, and zoning of the building, and the results of the energy computer simulation are presented in Table 1 for Los Angeles, Table 2 for New York, and Table 3 for Atlanta.

The cost of energy varies between locations in the U.S. However, to eliminate other than climatic factors, the energy rates and the rate structure of energy in Los Angeles were also

TABLE 1
Annual Energy Consumption and Cost for Building Located in Los Angeles

ENERGY CATEGORY	RATE	ALTERNATIVE 1 Waiting Rm Recirculation		ALTERNATIVE 2 Waiting Rm HEPA		ALTERNATIVE 3 Waiting Rm 100% Exhaust		ALTERNATIVE 4 Building HEPA		ALTERNATIVE 5 Building 100% Exhaust	
		Consumption	COST	Consumption	COST	Consumption	COST	Consumption	COST	Consumption	COST
		kW or kWh	$	kW or kWh	$	kW or kWh	$	kW or kWh	$	kW or kWh	$
ELECTRICITY											
DEMAND	**$/kW**										
on peak											
summer	10.88	1531	16,657	1543	16,788	1579	17,180	1574	17,125	1658	18,039
winter	10.15	2000	20,300	2026	20,564	2033	20,635	2057	20,879	2085	21,163
mid peak											
summer	6.46	1482	9574	1497	9671	1520	9819	1523	9839	1575	10,175
winter	6.10	1938	11,822	1971	12,023	1961	11,962	1997	12,182	2005	12,231
off peak											
all	3.65	3007	10,976	3022	11,030	3048	11,125	3070	11,206	3089	11,275
ENERGY	**$/kWh**										
on peak											
all	0.04966	257,413	12,783	258,820	12,853	262,241	13,023	262,327	13,027	270,429	13,430
mid peak											
all	0.04920	321,055	15,796	322,941	15,889	328,336	16,154	326,772	16,077	339,732	16,715
off peak											
all	0.03668	208,561	7650	209,264	7676	213,517	7832	211,164	7745	221,449	8123
TOTAL ELEC.			**105,557**		**106,493**		**107,730**		**108,079**		**111,149**

GAS	$/therm	Therms	$	Therms	$	Therms	$	Therms	$	Therms	$
TOTAL	0.45	3516	1582	3516	1582	3533	1590	3516	1582	4524	2036

TOTAL ENERGY COST	**107,140**	**108,075**	**109,320**	**109,661**	**113,185**

TABLE 2
Annual Energy Consumption and Cost for Building Located in New York

ENERGY CATEGORY	RATE	ALTERNATIVE 1 Waiting Rm Recirculation Consumption kW or kWh	COST $	ALTERNATIVE 2 Waiting Rm HEPA Consumption kW or kWh	COST $	ALTERNATIVE 3 Waiting Rm 100% Exhaust Consumption kW or kWh	COST $	ALTERNATIVE 4 Building HEPA Consumption kW or kWh	COST $	ALTERNATIVE 5 Building 100% Exhaust Consumption kW or kWh	COST $
ELECTRICITY											
DEMAND	**$/kW**										
on peak											
summer	10.88	1587	17,267	1602	17,430	1653	17,985	1628	17,713	1790	19,475
winter	10.15	1595	16,189.25	1618	16,423	1612	16,362	1634	16,585	1647	16,717
mid peak											
summer	6.46	1576	10,181	1593	10,291	1643	10,614	1615	10,433	1768	11,421
winter	6.10	1564	9540	1589	9693	1578	9626	1602	9772	1616	9858
off peak											
all	3.65	2724	9943	2731	9968	2786	10,169	2768	10,103	2925	10,676
ENERGY	**$/kWh**										
on peak											
all	0.04966	230,080	11,426	231,168	11,480	235,328	11,686	233,600	11,601	244,745	12,154
mid peak											
all	0.04920	286,529	14,097	287,869	14,163	293,431	14,437	290,487	14,292	303,715	14,943
off peak											
all	0.03668	192,161	7048	192,724	7069	197,584	7247	194,097	7119	207,057	7595
TOTAL ELEC.		**708,770**	**95,691**		**96,516**		**98,125**		**97,618**		**102,839**
GAS	**$/therm**	**Therms**	**$**	**Therms**	**$**	**Therms**	**$**	**Therms**	**$**	**Therms**	**$**
TOTAL	0.45	9352	4208	9349	4207	9955	4480	9322	4195	12,940	5823
TOTAL ENERGY COST			**99,900**		**100,723**		**102,605**		**101,813**		**108,662**

TABLE 3
Annual Energy Consumption and Cost for Building Located in Atlanta

ENERGY CATEGORY	RATE	ALTERNATIVE 1 Waiting Rm Recirculation		ALTERNATIVE 2 Waiting Rm HEPA		ALTERNATIVE 3 Waiting Rm 100% Exhaust		ALTERNATIVE 4 Building HEPA		ALTERNATIVE 5 Building 100% Exhaust	
		Consumption	COST	Consumption	COST	Consumption	COST	Consumption	COST	Consumption	COST
		kW or kWh	$	kW or kWh	$	kW or kWh	$	kW or kWh	$	kW or kWh	$
ELECTRICITY											
DEMAND	**$/kW**										
on peak											
summer	10.88	1616	17,582	1629	17,724	1682	18,300	1657	18,028	1832	19,932
winter	10.15	1921	19,498.15	1946	19,752	1941	19,701	1975	20,046	2006	20,361
mid peak											
summer	6.46	1592	10,284	1608	10,388	1658	10,711	1632	10,543	1814	11,718
winter	6.10	1891	11,535	1918	11,700	1902	11,602	1934	11,797	1972	12,029
off peak											
all	3.65	3003	10,961	3017	11,012	3057	11,158	3063	11,180	3161	11,538
ENERGY	**$/kWh**										
on peak											
all	0.04966	250,720	12,451	251,877	12,508	256,767	12,751	254,951	12,661	271,643	13,490
mid peak											
all	0.04920	303,129	14,914	304,639	14,988	309,815	15,243	307,564	15,132	327,968	16,136
off peak											
all	0.03668	203,036	7447	203,633	7469	208,266	7639	205,305	7531	219,060	8035
TOTAL ELEC.			**104,673**		**105,541**		**107,105**		**106,918**		**113,239**

GAS	$/therm	Therms	$	Therms	$	Therms	$	Therms	$	Therms	$
TOTAL	0.45	5294	2382	5294	2382	5416	2437	5287	2379	6880	3096

TOTAL ENERGY COST		**107,055**		**107,923**		**109,543**		**109,297**		**116,335**

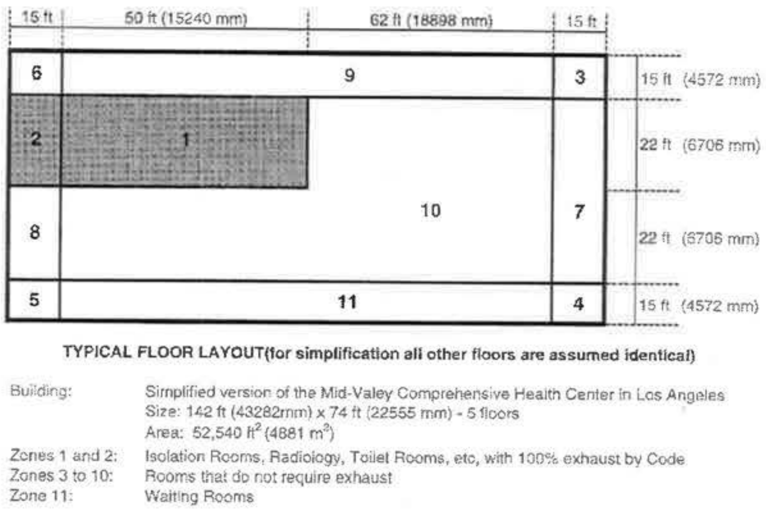

Figure 1 *Building configuration and zoning for computer energy analysis.*

applied to the other locations. The results are shown in Table 4 and Figure 2.

For the maintenance cost, it was estimated that the replacement of HEPA filters would be done once a year and would cost approximately $2640 for Alternative 2 and $6120 for Alternative 4. The addition of one exhaust fan in Alternative 3 would increase the maintenance cost by $600. The elimination of the return fan in Alternative 4 and the reduction of the total number of fans (the building may have one system instead of two) would save approximately $1000 annually.

The life-cycle cost (LCC) analysis (Figure 3) is performed with an original simplified method based on NIST Handbook 135, *Life-Cycle Costing Manual*, issued by the National Institute of Standards and Technology. The present value of both alternatives for a period of 25 years has been calculated based on the annual supplement to this handbook, "Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis—April 1999" (NIST 1999), at the DOE discount rate.

The life-cycle cost analysis is condensed in Tables 5, 6, and 7 for Los Angeles, New York, and Atlanta.

RESULTS

The analysis shows that the annual energy cost, as expected, is lower in Alternative 1, and it increases gradually from Alternative 1 to Alternative 5. The variation of the energy cost between locations depends on the type of system: the energy cost is higher in Los Angeles for Alternatives 1 and 2 and higher in Atlanta for Alternative 5.

The 25-year life-cycle cost is higher for the HEPA system alternatives than for the 100% exhaust alternatives in both cases (applied to the waiting rooms only or to the entire building).

TABLE 4
Comparative Energy Cost Analysis

ALTERNATIVES		ENERGY COST—$		
		Los Angeles	New York	Atlanta
Alternative 1	Air Recirculation for Waiting Rooms	107,140	99,900	107,055
Alternative 2	HEPA Filtration for Waiting Rooms	108,075	100,723	107,923
Alternative 3	100% Exhaust for Waiting Rooms	109,320	102,605	109,543
Alternative 4	HEPA Filtration for Entire Building	109,661	101,813	109,297
Alternative 5	100% Exhaust for Entire Building	113,185	108,662	116,335
Comparison of Alternatives	Alternative 2 versus Alternative 1	935	823	868
	Alternative 3 versus Alternative 1	2180	2705	2488
	Alternative 3 versus Alternative 2	1245	1882	1620
	Alternative 4 versus Alternative 2	1586	1090	1374
	Alternative 5 versus Alternative 1	6045	8762	9280

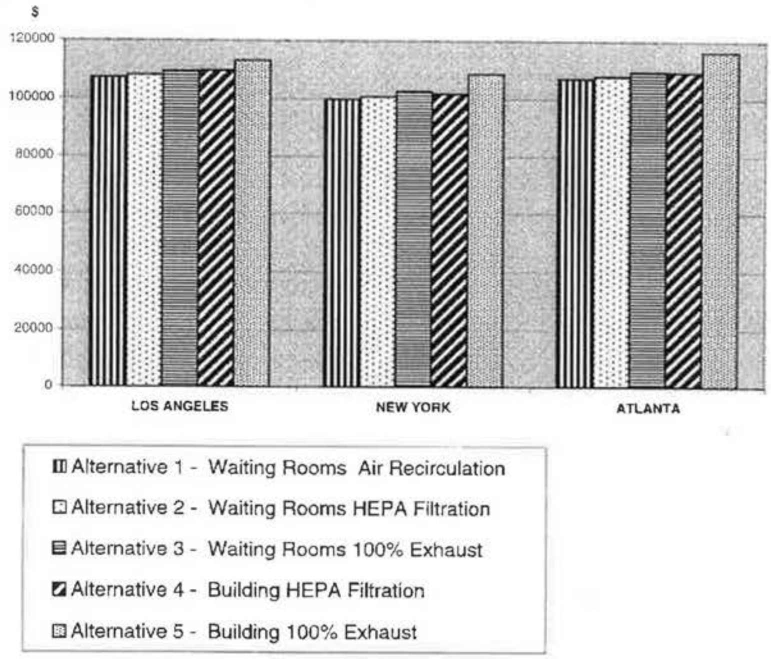

Figure 2 *Annual energy cost.*

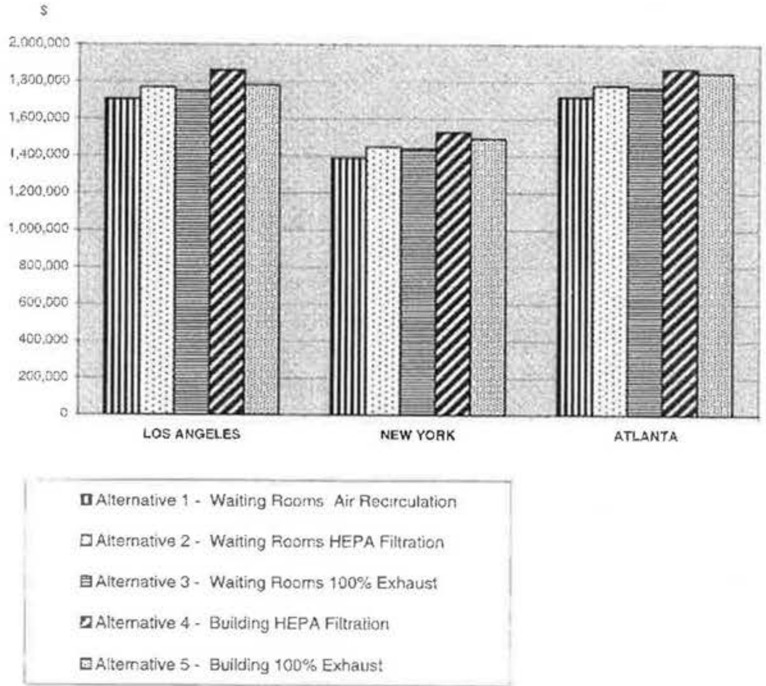

Figure 3 *Life cycle cost analysis.*

TABLE 5

Life Cycle Cost Analysis for 25 Years—Los Angeles Location*

ITEM	ALT 1 Waiting rooms air recirculation	ALT 2 Waiting rooms HEPA on return air	ALT 3 Waiting rooms 100% exhaust	ALT 4 Building HEPA on return air	ALT 5 Building 100% exhaust
INVESTMENT COST—$		3430	1000	7980	–3000
ELECTRIC ENERGY COST					
Annual Cost	105,557	106,493	107,730	108,079	111,149
FEMP UPV Factor	15.92	15.92	15.92	15.92	15.92
Present Value—$	1,680,467	1,695,369	1,715,062	1,720,618	1,769,492
COST OF GAS					
Annual Cost	1582	1582	1590	1582	2036
FEMP UPV Factor	17.03	17.03	17.03	17.03	17.03
Present Value—$	26,941	26,941	27,078	26,941	34,673
MAINTENANCE COST (labor and parts)					
Annual Cost	0	2640	600	6120	–1000
UPV Factor	17.22	17.22	17.22	17.22	17.22
Present Value—$	0	45,461	10,332	105,386	–17,220
TOTAL PRESENT VALUE	**1,707,409**	**1,771,201**	**1,753,471**	**1,860,926**	**1,783,945**

* Based on NISTIR 85-3273-14r (Rev. 4/99) *Energy Price Indices and Discount Factors for Life Cycle Cost Analysis* (1999).

TABLE 6

Life Cycle Cost Analysis for 25 Years—New York Location*

ITEM	ALT 1 Waiting rooms air recirculation	ALT 2 Waiting rooms HEPA on return air	ALT 3 Waiting rooms 100% exhaust	ALT 4 Building HEPA on return air	ALT 5 Building 100% exhaust
INVESTMENT COST—$		3430	1000	7980	–3000
ELECTRIC ENERGY COST					
Annual Cost	95,691	96,516	98,125	97,618	102,839
LCC Factor	13.78	13.78	13.78	13.78	13.78
Present Value—$	1,318,622	1,329,990	1,352,163	1,345,176	1,417,121
COST OF GAS					
Annual Cost	4208	4207	4480	4195	5823
LCC Factor	16.42	16.42	16.42	16.42	16.42
Present Value—$	69,095	69,079	73,562	68,882	95,614
MAINTENANCE COST (labor and parts)					
Annual Cost	0	2640	600	6120	–1000
LCC Factor	17.22	17.22	17.22	17.22	17.22
Present Value—$	0	45,461	10,332	105,386	–17,220
TOTAL PRESENT VALUE	**1,387,717**	**1,447,960**	**1,437,056**	**1,527,424**	**1,492,515**

* Based on NISTIR 85-3273-14r (Rev. 4/99) *Energy Price Indices and Discount Factors for Life Cycle Cost Analysis* (1999).

TABLE 7
Life Cycle Cost Analysis for 25 Years—Atlanta Location*

ITEM	ALT 1 Waiting rooms air recirculation	ALT 2 Waiting rooms HEPA on return air	ALT 3 Waiting rooms 100% exhaust	ALT 4 Building HEPA on return air	ALT 5 Building 100% exhaust
INVESTMENT COST—$		3430	1000	7980	–3000
ELECTRIC ENERGY COST					
Annual Cost	104,673	105,541	107,105	106,918	113,239
LCC Factor	16.04	16.04	16.04	16.04	16.04
Present Value—$	1,678,955	1,692,878	1,717,964	1,714,965	1,816,354
COST OF GAS					
Annual Cost	2382	2382	2437	2379	3096
LCC Factor	16.75	16.75	16.75	16.75	16.75
Present Value—$	39,899	39,899	40,820	39,848	51,858
MAINTENANCE COST (labor and parts)					
Annual Cost	0	2640	600	6120	–1000
LCC Factor	17.22	17.22	17.22	17.22	17.22
Present Value—$	0	45,461	10,332	105,386	–17,220
TOTAL PRESENT VALUE	**1,718,853**	**1,781,667**	**1,770,116**	**1,868,179**	**1,847,992**

* Based on NISTIR 85-3273-14r (Rev. 4/99) *Energy Price Indices and Discount Factors for Life Cycle Cost Analysis* (1999).

CONCLUSIONS

The 100% exhaust systems should not be replaced by HEPA filtration unless a detailed cost analysis is performed.

The difference in annual energy cost between alternatives varies to no more than $9280 per year.

The difference in life-cycle cost between the 100% building exhaust system (Alternative 5) and the recirculation system (Alternative 1) varies between $129,138 for Atlanta and $76,536 for Los Angeles.

All of these cost differences, annual or even life-cycle, are insignificant if compared to the cost of the medical treatment of one TB patient, which is approximately $100,000.

The 100% exhaust systems are simple and easy to maintain, and the supplementary energy cost becomes irrelevant when compared to its enormous advantage of reducing the risk of airborne disease contamination. The utilization of 100% exhaust (100% outside air) systems in health care facilities makes sense in any climate.

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