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T-Method Duct Design, Part V: Duct Leakage Calculation Technique and Economics

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ABSTRACT

The procedure of incorporating duct leakage into the T-method simulates leakage as an additional parallel section with zero length for each duct section. The assumption that additional air leakage creates additional system resistance is wrong. Leakage always reduces, not increases, system resistance. How fan power consumption changes due to leakage depends on the fan performance curve.

Methodology was developed to add duct leakage to the T-method previously developed for both the design and simulation of duct systems. It is shown that in most cases the sealing of ductwork is economical. Duct sealing is not recommended when electricity cost is less than 2¢/kWh and sealing cost is greater than \$1.5/m². A simple rule is: the higher the system cost, the greater the need for ductwork sealing.

INTRODUCTION

For the series of T-method duct design research projects, the following papers have been published: "Part I, Optimization Theory" (Tsal et al. 1988a); "Part II, Calculation Procedure and Economic Analysis" (Tsal et al. 1988b); "Part III, Simulation" (Tsal et al. 1990); "Part IV, Duct Leakage Theory" (Tsal et al. 1998).

This paper covers calculation technique and leakage studies to determine the economics of sealing ductwork.

There are two applications of T-method duct design: optimization and simulation. T-method duct optimization is based on calculation of duct sizes that minimize the life-cycle cost, including energy, duct, and fan costs. T-method duct simulation calculates actual airflows and the fan operating point for given systems with known duct sizes and fan performance. Due to leakage, the actual flow rate is usually less than designed. To compensate for lost air, fan flow is increased by changing the operating point on the fan curve. It is impossible to manually analyze actual flow due to the distribution of air leakage through a duct system.

A supply system may have places where static pressure will be negative due to the change of air velocity and static regain or static loss and/or turbulence such as that caused by an elbow. Practically, this sucks air in from the outside instead of leaking it out. For practical reasons, calculation of this phenomenon is avoided by assuming zero supply ductwork infiltration.

The technique developed was tested using the sample problem in the "Duct Design" chapter of the *1985 ASHRAE Handbook—Fundamentals* (ASHRAE 1985).

LEAKAGE IN A BRANCHED DUCT SYSTEM

Theory and Calculation Technique

Duct Simulation. The purpose of T-method simulation is to determine the flow within each section of a duct system of known duct sizes and fan characteristics. Incorporating duct leakage means that downstream airflow at each section is different from upstream due to air leakage through the duct walls. T-method with duct leakage incorporates the following major procedures:

1. *System condensing.* Condense the branched tree system into a single imaginary duct section with identical hydraulic characteristics. Duct leakage is simulated as an additional duct section connected in parallel to each duct section in a duct system.
2. *Selection of an operating point.* Determine the system flow and pressure by locating the intersection of the system characteristic and the fan performance curve.

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3. *System expansion.* Expand the condensed imaginary duct section into the original system with flow distribution.

Leakage at the i-section is simulated as an additional x-section that is connected in parallel to section i at the node. Pressure loss for the leakage x-section is the same as for section I, and flow is ΔQ. This is the main idea of incorporating duct leakage into the T-method. Therefore, the same formulas that are used by the T-method without duct leakage are used for the T-method with leakage incorporated. The difference is four parallel sections at each node instead of two. Condensing duct sections connected in series yields Equation 1 (Tsal et al. 1990, Equation 12).

$$K_{1-2} = (K_1^{-2} + K_2^{-2})^{-0.5} \tag{1}$$

Condensing duct sections connected in parallel (Figure 1) yields

$$K_{1-2} = K_1 + K_2 + Kx_1 + Kx_2 \tag{2}$$

Condensing a tee (Figure 2) yields Equation 3.

$$K_{1-3} = [(K_1 + K_2 + Kx_1 + Kx_2)^{-2} + K_3^{-2}]^{-0.5} \tag{3}$$

The selection and expansion procedures for T-method duct simulation with leakage incorporated are the same as without leakage (Tsal et al. 1990).

Duct Optimization. The T-method incorporates the following major procedures:

1. *System condensing.* Condensing a branched tree system into a single imaginary duct section with identical hydraulic characteristics and the same owning cost as the entire system.
2. *Air-handling unit selection.* Selecting an optimal fan and establishing the optimal system pressure loss.
3. *System expansion.* Expanding the condensed imaginary duct section into the original system with optimal distribution of pressure losses.

Two sections connected in series are compressed using the following equation (Tsal et al. 1988b, Equation 1.32).

$$K_{1-2} = (K_1^{0.833} + K_2^{0.833})^{1.2} \tag{4}$$

Two sections connected in parallel are condensed using the following equation (Figure 1).

$$K_{1-2} = K_1 + K_2 + Kx_1 + Kx_2 \tag{5}$$

Condensing a tee (Figure 2) yields

$$K_{1-3} = \left\lfloor (K_1 + K_2 + Kx_1 + Kx_2)^{0.833} + K_3^{0.833} \right\rfloor^{1.2} \tag{6}$$

The selection and expansion procedures for T-method duct optimization with leakage incorporated are the same as without leakage (Tsal et al. 1988).

Leakage Percentage Study

Five-Section System. Leakage was studied using a five-section duct system (Figure 3) with the following parameters: absolute roughness 0.0003 m (0.001 ft), air temperature 22°C (71.6°F), kinematic viscosity 1.54×10^{-5} m²/s (1.66×10^{-4} ft²/s), and air density 1.20 kg/m³ (0.075 lbm/ft³). The system studied had significant leakage ($C_L = 48$), and the airflow/surface area ratio was 21.1 (L/s)/m² (4.2 cfm/ft²). For these conditions and a system static pressure of 200 Pa (0.8 in. wg), the *ASHRAE Handbook* indicates that leakage as a percentage of system airflow is 9.6% (ASHRAE 1993, Chapter 32, Table 7). Leakage calculation is based on approximate formulas (Tsal et al. 1998). The three following calculations are performed to analyze leakage phenomena.

- The first calculation is for a system with no leakage. Results of simulation are presented in Table 1. The results are also represented by point A in Figure 4. Total flow rate at the system terminals (outlets) is 1.423 m³/s (3016 cfm), and the fan motor power is 0.71 kW.
- The second calculation is for a system with $C_L = 48$ (Table 2). The total system leakage is 0.088 m³/s (186 cfm), and the system operates at point B (fan speed constant). Leakage is 6.19% and is represented by points b through d. However, since the fan operating point was shifted to the right, the actual leakage is only the value between points a and d. This leakage is 0.039 m³/s (84 cfm), which is only

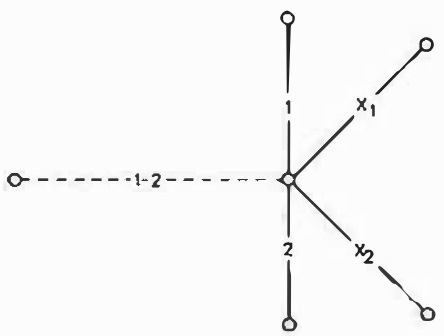

Figure 1 *Two duct sections in parallel with air leakage.*

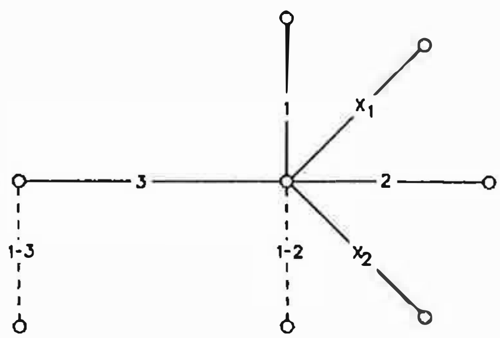

Figure 2 *Junction with air leakage.*

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TABLE 1
Five-Section Duct System with No Air Leakage

INPUT DATA

Fan flow, m3/s =	0.62	1.02	1.42	1.82	2.22
Fan pressure, in.WG =	330	326	318	275	202
Fan efficiency =	0.75	0.83	0.85	0.83	0.82

Qfan = 1.423 m3/s = 3015 cfm
Pfan = 318.1 Pa = 1.27 in.WG

Motor Efficiency = 0.75
Absolute Roughness = 0.0003 m = 0.0001 ft
Air Temperature = 22.00 C = 71.6 F
Leakage Class = 0
Air Density = 1.20 m3/s = 0.075 ft3/s
Kinematic Viscosity = 1.54E-5 m2/s = 1.66E-4 ft2/s
Efan = 0.850
Mfan = 0.710 kW

1 Sec (S)	2 Ch1 (S1)	3 Ch2 (S2)	4 Duct Lengt m (L)	5 Rough. Factor m (R)	6 Duct Size Height m (H)	7 Duct Size Width m (W)	8 Duct Size Diam. m (D)	9 C-Coeff. (C)	10 Ratios Flow (Q/Qc)	11 Ratios Area (A/A)	12 Ratios Vel. (V/Vc)	13 Diameter by Friction m (Df)	14 Diameter by Velocity m (Dv)	15 Surface m2 (As)	16 Average Air Velocity m/s (Vav)	17 Friction Factor (f')	18 Friction Factor (f)	19 Sect. Character m (mu)
1	0	0	14.0		0.254	0.257		0.80	0.78	0.81	0.94	0.255	0.288	14.3	10.68	0.0219	0.0219	0.576
2	0	0	12.0				0.170	0.65	0.24	0.28	0.86	0.170	0.170	6.4	9.81	0.0243	0.0243	0.402
3	1	2	8.0				0.320	0.18	0.64	0.54	1.20	0.320	0.320	8.0	11.41	0.0206	0.0206	0.222
4	0	0	16.0				0.231	0.65	0.36	0.28	1.27	0.231	0.231	11.6	12.06	0.0223	0.0223	0.506
5	3	4	19.8				0.437	1.50				0.437	0.437	27.2	9.50	0.0193	0.0193	1.037

1 Sec (S)	20 Condensing Actual Press. Loss Pa (dP)	21 Sectional Coefficients Leakage (Kx)	22 Sectional Coefficients Total (K)	23 Tee Coefficients (Kt)	24 Tee Coefficients (T)	25 Expansing Pressure at nodes Upper Pa (Pu)	26 Pressure at nodes Lower Pa (Pd)	27 Average Static Pressure Pa (Psav)	28 Leakage Flow m3/s (dQ)	29 Flow at nodes Upper m3/s (Qu)	30 Flow at nodes Lower m3/s (Qd)	31 Excess Path Pr.Loss Pa (dPp)	32 Comparison Flow at Terminals Notes m3/s (Qd')	33 % (Qd%)
1	136.2	0.0000	0.0596	0.0596	0.757	136.1	-0.2	33.9	0.000	0.695	0.895	0.2	0.895	-0.03
2	136.2	0.0000	0.0191	0.0191	0.243	136.1	-0.2	39.2	0.000	0.223	0.223	0.2	0.223	0.02
3	54.0	0.0000	0.1248	0.0665	0.645	190.1	136.1	85.2	0.000	0.918	0.918			
4	190.3	0.0000	0.0367	0.0367	0.355	190.1	-0.2	51.6	0.000	0.506	0.506	0.2	0.506	0.01
5	128.0	0.0000	0.1258	0.0798	1.000	318.1	190.1	200.1	0.000	1.423	1.423			

Airflow/Surface Ratio, L/s/m2 = 21.1 , Leakage = 0.00 %,Qsum 1.423 , Qsum = 1.423 -0.01 %

TABLE 2
Five-Section Duct System with Leakage Class 48, Fan Rotation Speed 1

INPUT DATA

Fan flow, m3/s =	0.62	1.02	1.42	1.82	2.22
Fan pressure, in.WG =	330	326	318	275	202
Fan efficiency =	0.75	0.83	0.85	0.83	0.82

Qfan = 1.471 m3/s = 3117 cfm
Pfan = 312.8 Pa = 1.25 in.WG

Motor Efficiency = 0.75
Absolute Roughness = 0.0003 m = 0.0001 ft
Air Temperature = 22.00 C = 71.6 F
Leakage Class = 48
Air Density = 1.20 m3/s = 0.075 ft3/s
Kinematic Viscosity = 1.54E-5 m2/s = 1.66E-4 ft2/s
Efan = 0.710
Mfan = 0.724 kW

1 Sec (S)	2 Ch1 (S1)	3 Ch2 (S2)	4 Duct Lengt m (L)	5 Rough. Factor m (R)	6 Duct Size Height m (H)	7 Duct Size Width m (W)	8 Duct Size Diam. m (D)	9 C-Coeff. (C)	10 Ratios Flow (Q/Qc)	11 Ratios Area (A/A)	12 Ratios Vel. (V/Vc)	13 Diameter by Friction m (Df)	14 Diameter by Velocity m (Dv)	15 Surface m2 (As)	16 Average Air Velocity m/s (Vav)	17 Friction Factor (f')	18 Friction Factor (f)	19 Sect. Character m (mu)
1	0	0	14.0		0.254	0.257		0.80	0.75	0.81	0.92	0.255	0.288	14.3	10.43	0.02189	0.0219	0.576
2	0	0	12.0				0.170	0.65	0.24	0.28	0.85	0.170	0.170	6.4	9.61	0.02436	0.0244	0.403
3	1	2	8.0				0.320	0.18	0.62	0.54	1.17	0.320	0.320	8.0	11.29	0.02059	0.0206	0.222
4	0	0	16.0				0.231	0.65	0.34	0.28	1.23	0.231	0.231	11.6	11.88	0.02227	0.0223	0.507
5	3	4	19.8				0.437	1.50				0.437	0.437	27.2	9.64	0.01924	0.0192	1.036

1 Sec (S)	20 Condensing Actual Press. Loss Pa (dP)	21 Sectional Coefficients Leakage (Kx)	22 Sectional Coefficients Total (K)	23 Tee Coefficients (Kt)	24 Tee Coefficients (T)	25 Expansing Pressure at nodes Upper Pa (Pu)	26 Pressure at nodes Lower Pa (Pd)	27 Average Static Pressure Pa (Psav)	28 Leakage Flow m3/s (dQ)	29 Flow at nodes Upper m3/s (Qu)	30 Flow at nodes Lower m3/s (Qd)	31 Excess Path Pr.Loss Pa (dPp)	32 Comparison Flow at Terminals Notes m3/s (Qd')	33 % (Qd%)
1	129.9	0.0008	0.0595	0.0603	0.758	128.3	-1.6	31.7	0.009	0.683	0.874	1.6	0.695	-3.04
2	130.9	0.0004	0.0193	0.0195	0.244	128.3	-2.8	36.5	0.004	0.220	0.216	2.6	0.223	-3.04
3	52.8	0.0005	0.1249	0.0678	0.645	181.2	128.3	78.5	0.009	0.913	0.903			
4	185.0	0.0007	0.0367	0.0374	0.355	181.2	-3.8	48.4	0.010	0.503	0.494	3.8	0.506	-2.37
5	131.8	0.0025	0.1259	0.0832	1.000	312.8	181.2	191.5	0.056	1.471	1.416			

Airflow/Surface Ratio, L/s/m2 = 21.8 , Leakage = 6.19 %,Qsum 1.383 , Qsum = 1.423 -2.80 %

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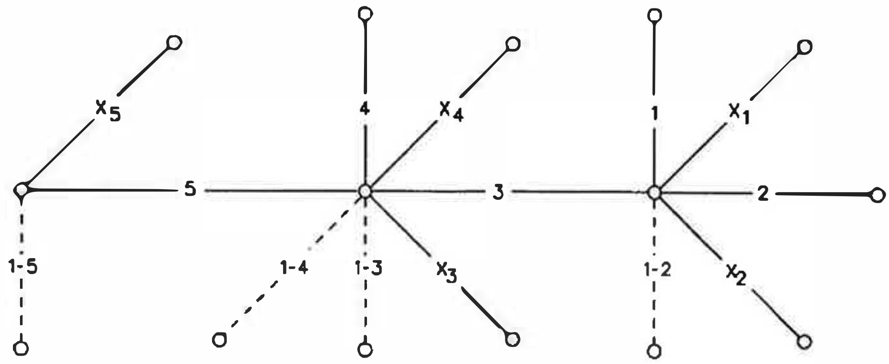

Figure 3   *Five-section duct system schematic.*

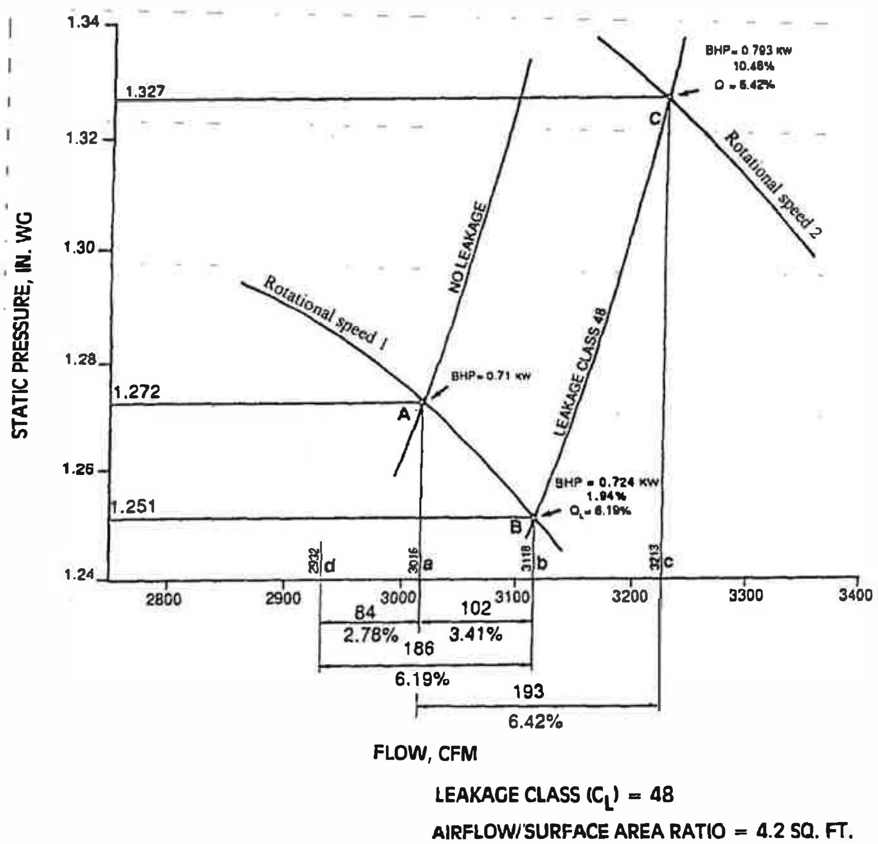

Figure 4   *Five-section duct system performance analysis.*

2.78% of the total flow rate. Fan motor power for this calculation is 0.724 kW, which is 1.94% higher than for a no-leakage system.

- The third calculation (Table 3) compensates for air leakage by increasing the fan speed to operating point C (1.516 m^3/s [3213 cfm], 331.7 Pa [1.327 in. wg], 0.793 kW). The percentage of additional power necessary to compensate for leakage is 10.5%.

The following is a discussion of why leakage and fan power are much lower than traditionally expected.

- Leakage rate is 6.2%, not 9.6%, as stated by ASHRAE. The leakage percentage in *ASHRAE Fundamentals* (ASHRAE 1993, Table 7, p. 32.16) is calculated for one section at constant pressure. However, the majority of duct systems are not one section but branched trees where the number of terminal sections is higher than the number

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TABLE 3
Five-Section Duct System with Leakage Class 48, Fan Rotation Speed 2

INPUT DATA

Fan flow, m3/s	=	0.62	1.02	1.42	1.82	2.22
Fan pressure, in.WG	=	330	326	318	275	202
Fan efficiency	=	0.75	0.83	0.85	0.83	0.82

Qfan = 1.516 m3/s = 3212 cfm
Pfan = 331.7 Pa = 1.327 in.WG

Motor Efficiency = 0.75
Absolute Roughness = 0.0003 m = 0.0001 ft
Air Temperature = 22.00 C = 71.6 F
Leakage Class = 48
Air Density = 1.20 m3/s = 0.075 ft3/s
Kinematic Viscosity = 1.54E-5 m2/s = 1.66E-4 ft2/s
Efan = 0.845
Mfan = 0.783 kW

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
INPUT DATA									RATIOS			Diameter-Surface			Velocity-Pressure-Resistance			
Sections			Duct Lengt	Rough. Factor	Duct Size			C-Coeff.	Flow	Area	Vel.	by			Average Air Velocity	Friction Factor		Sect. Character
Sec	Ch1	Ch2	m	m	Height m	Width m	Diam. m					Friction m	Velocity m	Surface m2	m/s			m
S	S1	S2	L	R	H	W	D	C	Ql/Qc	Al/A	Vl/Vc	Df	Dv	As	Vav	f'	f	mu
1	0	0	14.0		0.254	0.257		0.80	0.75	0.81	0.92	0.255	0.288	14.3	10.74	0.02185	0.0219	0.575
2	0	0	12.0				0.170	0.85	0.24	0.28	0.85	0.170	0.170	6.4	9.90	0.02432	0.0243	0.403
3	1	2	8.0				0.320	0.18	0.62	0.54	1.17	0.320	0.320	8.0	11.83	0.02055	0.0206	0.222
4	0	0	16.0				0.231	0.65	0.34	0.28	1.23	0.231	0.231	11.6	12.24	0.02223	0.0222	0.506
5	3	4	19.8				0.437	1.50				0.437	0.437	27.2	9.93	0.0192	0.0192	1.036

1	20	21	22	23	24	25	26	27	28	29	30	31	32	33
	CONDENSING					EXPANSING							COMPARISON	
	Actual Press. Loss	Sectional Coefficients		Tee Coefficients		Pressure at nodes		Average Static Pressure	Leakage Flow	Flow at nodes		Excess Path Pr.Loss	Flow at Terminals Noles	
Sec	Pa	Leakage	Total			Upper Pa	Lower Pa	Pa	m3/s	Upper m3/s	Lower m3/s	Pa	m3/s	%
S	dP	Kx	K	Kt	T	Pu	Pd	Psav	dQ	Qu	Qd	dPp	Qd'	Qd%
1	137.6	0.0008	0.0596	0.0604	0.756	136.1	-1.5	33.0	0.009	0.703	0.694	1.5	0.695	-0.16
2	138.6	0.0004	0.0191	0.0195	0.244	136.1	-2.5	38.8	0.005	0.227	0.222	2.5	0.223	-0.15
3	56.0	0.0005	0.1250	0.0678	0.645	192.1	138.1	83.2	0.010	0.940	0.930			
4	196.0	0.0007	0.0367	0.0374	0.355	192.1	-3.9	51.3	0.010	0.518	0.508	3.9	0.506	0.53
5	139.6	0.0025	0.1258	0.0833	1.000	331.7	192.1	203.0	0.058	1.516	1.458			

Airflow/Surface Ratio, L/s/m2 = 22.5 , Leakage = 6.42 %,Qsum 1.425 , Qsum = 1.423 = 0.12 %

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of parent sections. Terminal sections always have low pressure. The average static pressure at terminal sections is the lowest in the system and at terminals is zero. Therefore, a branched tree system will always have less leakage than one duct of the same surface area and pressure loss.

- Air leakage can be simulated by a number of small holes in ductwork. Part of the air will be leaked in or out through these leakage sites. This will move the system curve to the right, creating a new operating point on the fan curve. Therefore, the fan will be actively involved in this process by increasing fan airflow and reducing fan pressure. This can be seen in Figure 4 where operating point A moves to point B. How fan pressure is reduced depends on the fan performance curve. Therefore, the assumption that additional air leakage into a system creates additional system resistance is wrong. Leakage always reduces, not increases, system resistance. How the fan power consumption increases depends on the fan performance curve.
- There is a traditional, but incorrect, belief that in systems where no allowance has been made for leakage, fan motor power increases as the cube of the ratio of the air quantity (AABC 1983). Therefore, it is commonly stated that leakage can be compensated for by additional fan horsepower based on the following fan law equation, where M is the fan motor power and Q is fan airflow.

$$\frac{M_1}{M_2} = \left(\frac{Q_1}{Q_2}\right)^3 \qquad (7)$$

Using flow rates from Tables 1 and 2 or Figure 4, the new fan motor power requirement M is

$$M_2 = M_1\left(\frac{Q_2}{Q_1}\right)^3 = 0.71\left(\frac{3118}{3016}\right)^3 = 1.1\text{kW}$$

or

$$\Delta M = (1.1 - 0.71)100/0.71 = 55.6\%.$$

However, Equation 7 is not appropriate for comparison since the system with no leakage and the system with leakage have different system curves. The results of the calculation summarized in Figure 4 shows that the actual increase in power is only 10.5%, not 55.6%.

- Point B on the fan curve (Figure 4) presents the actual leakage rate of 6.2% in the five-section system for unsealed ducts (C_L = 48). This does not mean that the design airflow at the terminals will supply 6.2% less air because the fan curve moves right, increasing the system airflow rate. As shown by Table 2 and Figure 4, the total leakage is 6.2% of which 3.4% is above the design flow rate because, for a constant fan speed, flow increases as the system resistance decreases. Thus, the system leakage relative to the design flow rate is only 2.8%.

ASHRAE Example. The simulation procedure with leakage is tested on the duct system presented in the 1985 *ASHRAE Fundamentals* (Example 5) and is called herein the "ASHRAE example." The return ductwork includes Sections 1 through 6; the supply, Sections 7 through 19. General input data are:

Air temperature (t)	22°C (71.6°F)
Absolute roughness (R)	0.0003 m (0.001 ft)
Kinematic viscosity (ν)	1.54×10^{-5} m²/s (1.66×10^{-4} ft²/s)
Air density (ρ)	1.2 kg/m³ (0.075 lbm/ft³)

There is a SISW (single inlet, single width) centrifugal fan with air-foil blades and a 380 mm (15 in.) wheel operating at 2635 rpm. The fan operating point for the no duct leakage condition (C_L = 0) is Q_{fan} = 2.018 m³/s (4277 cfm) and P_{fan} = 711.1 Pa (2.84 in. wg). The fan curve is represented by the following five fan rating points:

Q_{fan} = 1.59 m³/s (3369 cfm), P_{fan} = 1121 Pa (4.48 in. wg)

Q_{fan} = 1.76 m³/s (3729 cfm), P_{fan} = 996 Pa (3.98 in. wg)

Q_{fan} = 1.92 m³/s (4068 cfm), P_{fan} = 832 Pa (3.33 in. wg)

Q_{fan} = 2.09 m³/s (4428 cfm), P_{fan} = 623 Pa (2.49 in. wg)

Q_{fan} = 2.26 m³/s (4789 cfm), P_{fan} = 373 Pa (1.49 in. wg)

Calculations (Table 4) were performed for the same fan and a system leakage class of C_L = 48. Leakage creates a new system curve and a new operating point: Q_{fan} = 2.042 m³/s (4327 cfm), P_{fan} = 681.4 Pa (2.73 in. wg). This operating point requires 2.22 kW, which is 2.7% less than the kW for the same system with no duct leakage. Leakage is 0.164 m³/s (346 cfm) for the return subsystem and 0.122 m³/s (257 cfm) for the supply subsystem. Considering that this is just one combined system divided into two parts, return and supply, air leakage is calculated as average: (0.164 + 0.122)/2 = 0.143 m³/s (302 cfm), or 7.0%.

In the second calculation, the fan speed was increased to compensate for leakage in both subsystems. The solution (Table 5) is: Q_{fan} = 2.160 m³/s (4577 cfm), P_{fan} = 760.3 Pa (3.04 in. wg). Total leakage is 0.279 m³/s (592 cfm), which is 12.9% of the total airflow. Fan motor power is 2.65 kW, a 16.2% increase over the no-leakage system. Compared to the flow rates for a no-leakage system, the return subsystem is 1.6% less air and the supply subsystem is 1.7% additional air. For this system, according to ASHRAE (1993, chapter 32, Table 7: C_L = 48, airflow/surface area ratio = 2 cfm/ft²), the predicted leakage rate is 46.1%. Using the cube fan law (Equation 7), the fan motor power requirement increases 22.6%. Our study shows that the actual leakage rate is only 13.1% and that the fan motor power increases 16.2%.

The same system was calculated for a leakage class (C_L) of 12. The return subsystem leakage is 2.1% and the supply subsystem leakage is 1.3%. The increase in fan motor power is only 4.0%.

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TABLE 4
ASHRAE Example with Unsealed Ductwork, Fan Rotation Speed 1

INPUT DATA

Fan flow, m3/s =	1.59	1.76	1.92	2.09	2.26
Fan pressure, in.WG =	1121	996	832	623	373
Fan efficiency =	0.75	0.83	0.86	0.83	0.82

Motor Efficiency = 0.75
Absolute Roughness = 0.0003 m = 0.0001 ft
Air Temperature = 22.00 C = 71.6 F
Leakage Class = 48
Air Density = 1.20 m3/s = 0.075 ft3/s
Kinematic Viscosity = 1.54E-5 m2/s = 1.66E-4 ft2/s
Efan = 0.836
Nfan = 2.221 kW

Qfan = 2.042 m3/s = 4327 cfm
Pfan = 681.5 Pa = 2.73 in.WG

Columns 1–16 (INPUT DATA; RATIOS; Diameter-Surface):

1 Sec (S)	2 Ch1 (S1)	3 Ch2 (S2)	4 Duct Length m (L)	5 Rough. Factor m (R)	6 Duct Size Height m (H)	7 Duct Size Width m (W)	8 Diam. m (D)	9 C-Coeff. (C)	10 Leaks Class (Class)	11 Ratios Flow (Qi/Qc)	12 Ratios Area (Ai/A)	13 Ratios Vel. (Vi/Vc)	14 Diameter by Friction m (Df)	15 Diameter by Velocity m (Dv)	16 Surface m2 (As)
1	0	0	24.38				0.305	0.38	48	0.74	1.00	0.73	0.305	0.305	23.3
2	0	0	23.77				0.203	0.94	48	0.24	0.44	0.53	0.203	0.203	15.2
3	1	2	7.32				0.305	0.50	48	0.47	0.50	0.94	0.305	0.305	7.0
4	0	0	1.52		0.610	0.610		6.93	48	0.96	3.74	0.26	0.610	0.688	3.7
5	4	0	28.42				0.356	1.76	48	0.51	0.68	0.74	0.356	0.356	22.8
6	3	5	11.89				0.432	0.24	48	1.00			0.432	0.432	18.1
7	0	0	4.27				0.305	3.44	48	0.54	0.51	1.05	0.305	0.305	4.1
8	0	0	1.22				0.305	5.66	48	0.44	0.51	0.86	0.305	0.305	1.2
9	7	8	7.62		0.254	0.559		3.43	48	0.96	1.83	0.53	0.349	0.425	12.4
10	9	0	13.72		0.254	0.305		3.48	48	0.20	0.43	0.45	0.277	0.314	15.3
11	0	0	9.14		0.254	0.356		1.56	48	0.44	0.50	0.88	0.296	0.339	11.1
12	0	0	6.71		0.254	0.356		0.97	48	0.55	0.50	1.10	0.298	0.339	8.2
13	11	12	10.67		0.254	0.711		-0.01	48	0.80	1.00	0.80	0.374	0.478	20.6
14	10	13	4.57		0.254	0.711		0.06	48	0.86	1.00	0.87	0.374	0.479	8.8
15	0	0	9.57		0.203	0.152		1.36	48	0.48	0.67	0.70	0.174	0.199	6.8
16	0	0	6.10		0.203	0.152		1.46	48	0.50	0.67	0.76	0.174	0.199	4.3
17	15	16	9.14		0.305	0.152		3.31	48	0.12	0.26	0.48	0.203	0.243	8.4
18	14	17	7.01		0.254	0.711		2.71	48	0.99	0.59	1.69	0.374	0.478	13.5
19	18	0	3.66		0.432	0.711		2.30	48	1.00			0.537	0.625	8.4
Fan	6	19	0.1		0.45	0.72							0.554	0.642	0.2

Columns 17–34 (Velocity-Pressure-Resistance; CONDENSING; EXPANSING; COMPARISON):

1 Sec (S)	17 Average Air Velocity m/s (Vav)	18 Friction Factor (f')	19 Friction Factor (f)	20 Sect. Character m (mu)	21 Actual Press. Loss Pa (dP)	22 Sectional Coefficients Leakage (Kx)	23 Sectional Coefficients Total (K)	24 Tee Coefficients (Kt)	25 Tee Coefficients (T)	26 Pressure at nodes Upper Pa (Pu)	27 Pressure at nodes Lower Pa (Pd)	28 Average Static Pressure Pa (Paav)	29 Leakage Flow m3/s (dQ)	30 Flow at nodes Upper m3/s (Qu)	31 Flow at nodes Lower m3/s (Qd)	32 Excess Path Pr.Loss Pa (dPp)	33 Comparison Flow at Terminals Notes m3/s (Qd')	34 % (Qd%)
1	9.45	0.02108	0.0211	0.628	110.0	0.0032	0.0657	0.0690	0.751	105.0	-5.0	108.5	0.033	0.706	0.673	5.0	0.728	7.6
2	6.93	0.02388	0.0239	0.755	106.7	0.0017	0.0217	0.0235	0.249	105.0	-1.6	82.1	0.018	0.234	0.216	1.6	0.241	10.5
3	13.00	0.02068	0.0207	0.303	100.6	0.0010	0.0946	0.0671	0.480	205.6	105.0	256.4	0.017	0.957	0.938			
4	2.67	0.0202	0.0202	4.800	29.7	0.0003	0.1818	0.1821	1.000	24.0	-5.7	19.1	0.002	0.991	0.989	5.7	1.049	5.7
5	10.21	0.02018	0.0202	1.037	181.6	0.0029	0.0752	0.0724	0.520	205.0	24.0	176.6	0.044	1.035	0.991			
6	13.78	0.0189	0.0189	0.328	86.3	0.0022	0.2172	0.1196	1.000	291.9	205.6	382.3	0.050	2.042	1.992			
7	2.41	0.02438	0.0244	1.151	13.1	0.0003	0.0486	0.0488	0.563	33.3	19.6	22.8	0.002	0.177	0.175	18.6	0.193	9.5
8	1.96	0.02517	0.0252	1.755	13.2	0.0001	0.0393	0.0394	0.447	33.3	19.5	24.0	0.001	0.143	0.142	19.5	0.156	8.8
9	2.29	0.02374	0.0237	1.675	12.3	0.0010	0.0924	0.0648	1.000	46.0	33.3	36.4	0.009	0.326	0.320			
10	4.34	0.02313	0.0231	1.450	52.1	0.0012	0.0465	0.0390	0.198	98.7	46.0	60.9	0.015	0.343	0.328			
11	6.77	0.02177	0.0218	0.756	61.1	0.0005	0.0782	0.0787	0.447	78.6	18.5	19.7	0.005	0.814	0.808	16.5	0.633	3.8
12	8.42	0.0214	0.0214	0.493	61.5	0.0002	0.0988	0.0970	0.553	78.6	18.4	4.6	0.001	0.760	0.758	16.4	0.784	3.2
13	7.67	0.02033	0.0203	0.272	20.0	0.0014	0.3097	0.1542	0.802	98.7	78.8	53.3	0.018	1.392	1.374			
14	9.64	0.02	0.02	0.146	18.9	0.0005	0.4235	0.1763	0.875	115.6	98.7	51.4	0.008	1.743	1.735			
15	3.68	0.02648	0.0265	0.557	22.7	0.0004	0.0239	0.0243	0.479	41.3	17.8	21.2	0.003	0.116	0.112	17.8	0.121	7.3
16	4.03	0.02619	0.0262	0.471	23.0	0.0003	0.0260	0.0263	0.521	41.3	17.7	19.5	0.002	0.126	0.124	17.7	0.132	6.0
17	5.29	0.02448	0.0245	1.072	73.7	0.0007	0.0288	0.0255	0.125	115.6	41.3	61.8	0.008	0.250	0.241			
18	11.11	0.01982	0.0198	1.477	227.3	0.0011	0.1330	0.1122	1.000	343.4	115.6	155.6	0.024	2.017	1.993			
19	6.58	0.01881	0.0188	1.518	[illegible]	0.0000	0.2547	0.1013	1.000	389.5	343.4	349.0	0.025	2.042	2.017			
Fan								0.0773	1.000	681.4				2.042				

Fan static pressure = 685.2 Pa
Ratio L/s/m2 = 0.56
Leakage by ASHRAE = 46.1 %

Return: Leakage =	0.164 m3/s	1.878	8.03 %	2.018	-7.0
Supply: Leakage =	0.122 m3/s	1.920	5.97 %	2.018	-4.9
Total or average: Leakage =	0.286 m3/s	1.889	14.00 %	2.018	-5.9

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TABLE 5
ASHRAE Example with Unsealed Ductwork, Fan Rotation Speed 2

I N P U T   D A T A

Fan flow, m3/s =	1.59	1.76	1.92	2.09	2.26
Fan pressure, in.WG =	1121	988	832	623	373
Fan efficiency =	0.75	0.83	0.85	0.83	0.82

Qfan........ = 2.160 m3/s = 4577 cfm
Pfan........ = 780.3 Pa = 3.04 in.WG

Motor Efficiency .... = 0.75
Absolute Roughness... = 0.0003 m = 0.0001 ft
Air Temperature......... = 22.00 C = 71.6 F
Leakage Class .... = 48
Air Density............ = 1.20 m3/s = 0.075 ft3/s
Kinematic Viscosity.... = 1.54E-5 m2/s = 1.66E-4 ft2/s
Efan.............. = 0.825
Mfan.............. = 2.851 kW

INPUT DATA / RATIOS / Diameter-Surface / Velocity-Pressure-Resistance

1 Sec S	2 Ch1 S1	3 Ch2 S2	4 Duct Length m L	5 Rough. Factor m R	6 Duct Size Height m H	7 Duct Size Width m W	8 Diam. m D	9 C-Coeff. C	10 Leaks Class Class	11 Flow Q/Qc	12 Area A/A	13 Vel. V/Vc	14 by Friction m Df	15 by Velocity m Dv	16 Surface m2 As	17 Average Air Velocity m/s Vav	18 Friction Factor f'	19 Friction Factor f	20 Sect. Character m mu
1	0	0	24.38				0.305	0.38	48	0.74	1.00	0.73	0.305	0.305	23.3	10.00	0.021	0.021	0.628
2	0	0	23.77				0.203	0.84	48	0.24	0.44	0.53	0.203	0.203	15.2	7.33	0.02377	0.0238	0.755
3	1	2	7.32				0.305	0.50	48	0.47	0.50	0.94	0.305	0.305	7.0	13.75	0.02062	0.0206	0.303
4	0	9	1.52		0.610	0.610		6.93	48	0.96	3.74	0.26	0.610	0.688	3.7	2.82	0.02004	0.02	4.800
5	4	0	20.42				0.356	1.76	48	0.51	0.68	0.74	0.356	0.356	22.8	10.79	0.02011	0.0201	1.037
6	3	5	11.89				0.432	0.24	48	1.00			0.432	0.432	16.1	14.58	0.01884	0.0188	0.328
7	0	0	4.27				0.305	3.44	48	0.54	0.51	1.06	0.305	0.305	4.1	2.61	0.02409	0.0241	1.151
8	0	0	1.22				0.305	5.86	48	0.44	0.51	0.86	0.305	0.305	1.2	2.12	0.02486	0.0249	1.755
9	7	8	7.62		0.254	0.559		3.43	48	0.96	1.83	0.53	0.349	0.425	12.4	2.46	0.02349	0.0235	1.875
10	9	0	13.72		0.254	0.305		3.48	48	0.20	0.43	0.45	0.277	0.314	15.3	4.63	0.02297	0.023	1.450
11	0	0	9.14		0.254	0.356		1.56	48	0.44	0.50	0.89	0.296	0.339	11.1	7.21	0.02166	0.0217	0.756
12	0	0	6.71		0.254	0.356		0.97	48	0.55	0.50	1.10	0.296	0.339	8.2	8.95	0.02131	0.0213	0.493
13	11	12	10.67		0.254	0.711		-0.01	48	0.80	1.00	0.80	0.374	0.479	20.6	8.14	0.02024	0.0202	0.272
14	10	13	4.57		0.254	0.711		0.06	48	0.87	1.00	0.87	0.374	0.479	8.8	10.22	0.01892	0.0199	0.146
15	0	0	9.57		0.203	0.152		1.36	48	0.47	0.67	0.70	0.174	0.199	6.8	3.96	0.02625	0.0263	0.557
16	0	0	6.10		0.203	0.152		1.46	48	0.51	0.67	0.77	0.174	0.199	4.3	4.32	0.02599	0.026	0.471
17	15	16	9.14		0.305	0.152		3.31	48	0.12	0.26	0.48	0.203	0.243	8.4	5.62	0.02433	0.0243	1.072
18	14	17	7.01		0.254	0.711		2.71	48	0.99	0.59	1.78	0.374	0.479	13.5	11.77	0.01975	0.0198	1.477
19	16	0	3.66		0.432	0.711		2.30	48	1.00			0.537	0.625	8.4	6.58	0.01881	0.0188	1.518
Fan	6	19	0.1		0.45	0.72							0.554	0.642	0.2	3.12	0.02025	0.0202	0.002

CONDENSING / EXPANSING / COMPARISON

1 Sec S	21 Actual Press. Loss Pa dP	22 Sectional Coefficients Leakage Kx	23 Sectional Coefficients Total K	24 Tee Coefficients Kt	25 Tee Coefficients T	26 Pressure at nodes Upper Pa Pu	27 Pressure at nodes Lower Pa Pd	28 Average Static Pressure Pa Pasv	29 Leakage Flow m3/s dQ	30 Flow at nodes Upper m3/s Qu	31 Flow at nodes Lower m3/s Qd	32 Excess Path Pr.Loss Pa dPp	33 Flow at Terminals Nolaz m3/s Qd'	34 % Qd%
1	123.0	0.0032	0.0657	0.0688	0.751	116.7	-6.3	115.0	0.034	0.748	0.712	6.3	0.728	2.3
2	119.2	0.0017	0.0217	0.0235	0.249	116.7	-2.5	88.2	0.019	0.247	0.228	2.5	0.241	5.4
3	112.4	0.0010	0.0946	0.0671	0.480	229.1	116.7	285.9	0.019	1.012	0.993			
4	33.2	0.0003	0.1818	0.1821	1.000	26.4	-6.8	15.6	0.001	1.047	1.046	6.8	1.049	0.3
5	202.9	0.0030	0.0752	0.0725	0.520	229.1	26.3	197.3	0.048	1.095	1.047			
6	96.3	0.0023	0.2174	0.1197	1.000	325.5	229.1	404.3	0.054	2.160	2.106			
7	15.4	0.0002	0.0486	0.0488	0.353	17.2	1.8	6.6	0.001	0.191	0.190	1.8	0.193	1.6
8	15.4	0.0001	0.0393	0.0394	0.447	17.2	1.8	7.3	0.000	0.155	0.154	1.8	0.156	1.3
9	14.2	0.0009	0.0924	0.0646	1.000	33.5	18.3	22.8	0.006	0.351	0.345			
10	59.1	0.0012	0.0465	0.0389	0.198	88.7	27.6	44.4	0.012	0.364	0.352			
11	69.2	0.0006	0.0702	0.0788	0.447	86.2	-3.1	17.6	0.005	0.853	0.848	3.1	0.633	-2.4
12	69.5	0.0003	0.0968	0.0971	0.598	66.2	-3.4	9.1	0.002	0.809	0.806	3.4	0.784	-2.9
13	22.5	0.0012	0.3097	0.1542	0.802	88.7	64.2	35.8	0.014	1.477	1.463			
14	19.0	0.0005	0.4235	0.1762	0.875	106.3	67.3	34.3	0.006	1.848	1.842			
15	26.2	0.0004	0.0239	0.0242	0.479	29.3	3.1	10.0	0.002	0.123	0.121	3.1	0.121	-0.1
16	26.4	0.0002	0.0260	0.0262	0.521	29.3	2.9	0.1	0.001	0.134	0.133	2.9	0.132	-0.8
17	83.3	0.0006	0.0286	0.0255	0.125	106.3	23.0	45.7	0.007	0.264	0.258			
18	255.1	0.0011	0.1330	0.1121	1.000	334.1	78.8	125.6	0.021	2.135	2.114			
19	62.8	0.0000	0.2547	0.1013	1.000	434.9	372.1	377.6	0.027	2.160	2.133			
Fan				0.0773	1.000	760.3				2.160				

Fan static pressure = 685.2 Pa
Ratio L/s/m2 = 0.56
Leakage by ASHRAE = 46.1 %

Return: Leakage = 0.174 m3/s 1.986 8.08 % 2.018 -1.6
Supply: Leakage = 0.104 m3/s 2.093 4.84 % 2.018 1.7
Total or average: Leakage = 0.278 m3/s 2.018 12.81 % 2.018 0.0

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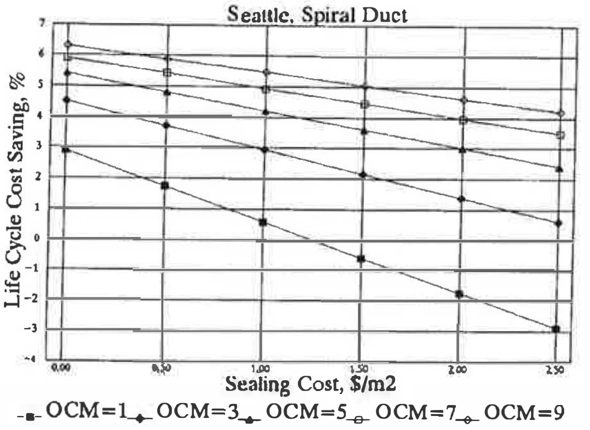

Figure 5a *Parametric economic study for Seattle and galvanized ductwork.*

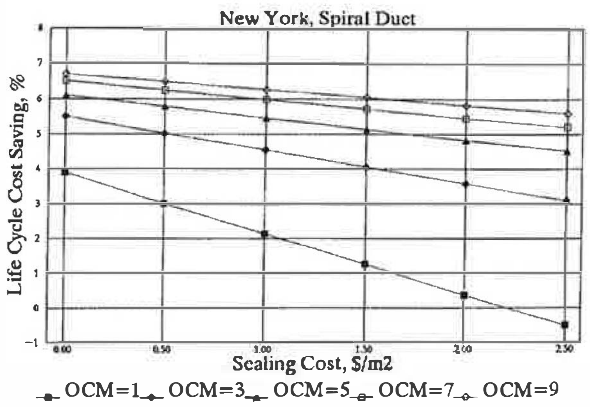

Figure 5c *Parametric economic study for New York City and galvanized ductwork.*

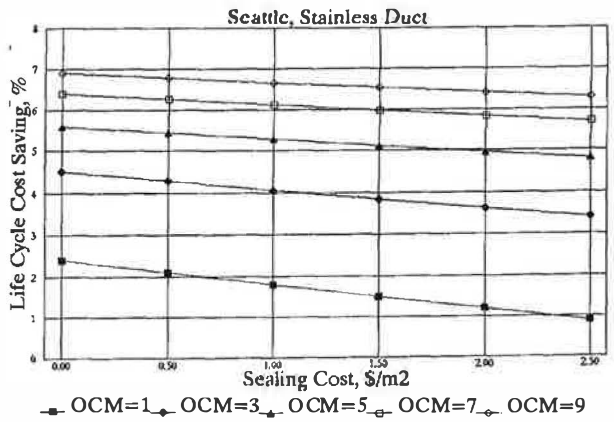

Figure 5b *Parametric economic study for Seattle and stainless ductwork.*

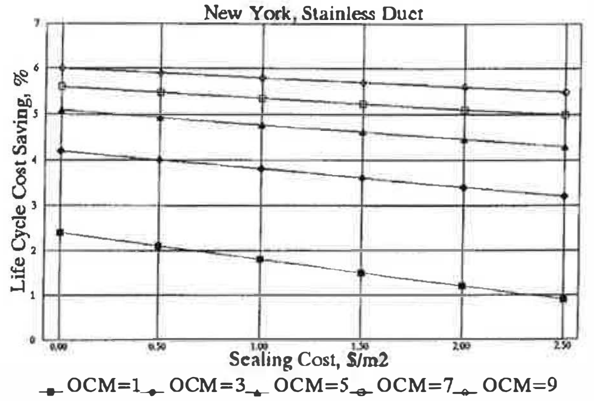

Figure 5d *Parametric economic study for New York City and stainless ductwork.*

Duct Leakage Economics Study

The system studied for leakage effects is the ASHRAE example in the *1985 ASHRAE Handbook* (Tsal et al. 1988a). The difference in calculation is air velocity, average sectional static pressure, and leakage. Table 6 summarizes the results for an unsealed system, where $C_L = 48$ for the rectangular ductwork (supply subsystem) and $C_L = 30$ for the round ductwork (return subsystem). The calculations are shown by Figures 5a through 5d for various ductwork, energy, and sealing costs.

The sealing cost for the sample problem is $2.5 per m^2 ($0.25 per ft^2) of duct surface. Comparison of the results to a zero-leakage system is presented in Table 7. For sealed ductwork, the return ($C_L = 3$) and supply ($C_L = 6$) subsystem leakage is 0.012 m^3/s (25 cfm) and 0.025 m^3/s (53 cfm). The total leakage, supply and return, is 0.037 m^3/s (78 cfm), or 2.0% of fan flow. In this case, the system flow rate for sealed ductwork is only 1.6% higher (1.91 m^3/s vs. 1.88 m^3/s).

For unsealed ductwork, as summarized in Table 7, the return and supply subsystem leakage is 0.125 m^3/s (265.4 cfm) and 0.211 m^3/s (447.9 cfm). The higher leakage for the supply system is due to the longer duct. The total leakage, supply and return, is 0.336 m/s (713.3 cfm), or 16.1% of fan flow. However, the preferred procedure is to compare the leakage percentage for the return-supply system based on the maximum leakage in one of these systems. In this case, the system flow rate for unsealed ductwork is only 10% higher (2.09 m^3/s vs. 1.88 m^3/s, or 0.211 m^3/s). For unsealed ductwork, the percentage of increased operating cost ($2239 vs. $2013) is proportional to the increase of fan flow (2.09 vs. 1.88), or 10%. Life-cycle cost increased 3.8%.

A parametric study was performed using the ASHRAE example for various cities, duct costs, and leakage classes. The analysis was an optimized duct system with leakage. Life-cycle cost was determined by Equation 8, which includes operating cost (*Ep*), owning cost (*Es*), and sealing cost (*As.Ss*).

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TABLE 6
ASHRAE Example Optimized with Air Leakage

Fan Total Pressure	=	835 Pa												
Initial Fan Flow (no leak.)	=	1.88 m3/s	Escalation Rate	=	0.03	PWEF	=	8.81	Air Density	=	1.20 kg/m3			
Energy Cost	=	0.0293 $/kwh	Interest Rate	=	0.06	Actual flow	=	2.09 m3/s	Life Cycle Cos	=	8417 $	Operation C	=	2241 $
Duct Cost	=	33.38 $/m2	Amort. Period	=	10	Kinematic Viscosity	=	1.54E-5 m2/s	Return Leakag	=	6.90 %	Owning Cos	=	6177 $
Fan Efficiency	=	0.75	Min. velocity	=	2 m/s	Pfan	=	835 Pa						
Motor Efficiency	=	0.8	Max. velocity	=	18 m/s	Supply Leakage	=	9.92 %						
Number of Hours per Year	=	4400 hrs/year												
Absolute Roughness	=	0.0003 m												
Air Temperature	=	22.80 C												

INPUT DATA / VELOCITY-SIZE-FRICTION

A Sec	B Ch1	C Ch2	D Air Flow m3/s	E Duct Length m	F Additional Pressure Loss Pa	G Rough. Factor m	H Required Duct Size Height m	I Required Duct Size Width m	J Required Duct Size Dia. m	K C-Coef.	L Leak. Class	S Air Vel. m/s	T Rectng. Size Height m	U Rectng. Size Width m	V Eqv. Diameter by Fric. m	W Eqv. Diameter Vel. m	X Friction Factor Altshul	Y Friction Factor Tsal	Z Actual Press. Loss Pa
S	S1	S2	Q	L	dPa	R	Hz	Wz	Dz	C	Cl	V	H	W	Df	Dv	f	f	dP
1	0	0	0.71	24.4						0.23	30	12.47				0.271	0.0213	0.0213	199.5
2	0	0	0.24	23.8						1.23	30	8.58				0.190	0.0239	0.0239	201.2
3	1	2	0.54	7.3						0.24	30	10.85				0.341	0.0203	0.0203	47.9
4	0	0	0.84	1.6	24.9		0.610	0.610		0.52	40	2.53	0.61	0.610	0.610	0.688	0.0200	0.0200	37.1
5	4	0	0.94	20.4						1.06	30	12.22				0.316	0.0206	0.0206	213.8
6	3	5	1.88	11.9	54.8					0.24	30	11.76				0.464	0.0187	0.0187	114.2
7	0	0	0.28	4.3	24.9				0.306	1.84	30	3.88			0.305	0.304	0.0229	0.0229	37.2
8	0	0	0.28	1.2	37.4				0.306	6.30	30	3.87			0.306	0.304	0.0229	0.0229	83.5
9	7	0	0.56	7.6			0.254			1.28	40	8.37	0.254	0.249	0.347	0.279	0.0221	0.0221	101.9
10	9	0	0.56	13.7			0.264			2.19	40	8.63	0.254	0.274	0.264	0.298	0.0218	0.0218	144.6
11	0	0	0.47	9.1			0.254			1.78	40	10.40	0.254	0.180	0.210	0.241	0.0228	0.0228	179.2
12	0	0	0.47	6.7			0.254			1.19	40	12.33	0.254	0.181	0.180	0.221	0.0232	0.0232	182.9
13	11	12	0.84	10.7			0.254			0.12	40	14.59	0.254	0.253	0.253	0.286	0.0214	0.0214	137.3
14	10	13	1.50	4.8			0.264			0.94	40	12.86	0.254	0.487	0.334	0.397	0.0200	0.0200	31.8
15	0	0	0.19	0.8			0.152			1.27	40	10.40	0.152	0.121	0.133	0.153	0.0255	0.0255	201.8
16	0	0	0.19	6.1			0.152			1.89	40	11.59	0.152	0.104	0.124	0.142	0.0258	0.0258	203.1
17	16	16	0.38	9.1			0.203			0.34	40	12.39	0.203	0.180	0.177	0.201	0.0234	0.0234	143.4
18	14	17	1.88	7.8	10.0		0.610			4.28	40	4.97	0.61	0.441	0.530	0.721	0.0183	0.0183	76.1
19	18	0	1.88	3.7	12.5		0.610			3.06	40	4.83	0.61	0.734	0.687	0.784	0.0182	0.0182	84.0

CONDENSING / EXPANSION / LEAKAGE / PRES. LOSS

Sec	AB Sectional Coefficients (mu) m	AC Sectional Coefficients K	AD Tee Coefficients Kt	AE Tee Coefficients T	AF Max. Addit. Press. Loss Pa	AH Pres. at Upper Node Pa	AI Required Pressure Loss Duct Pa	AJ Required Pressure Loss Total Pa	AK Pres. at Lower Node Pa	AL Estimated Dia. m	AN Aver. Static Pres. Pa	AO Surface m2	AP Flow Leakage m3/s	AQ Flow at nodes Upper m3/s	AR Flow at nodes Lower m3/s	AU Total in Path Pa	AV Exces. in Path Pa
S	(mu)	K	Kt	T	dPmax	Pu	dPr	dPt	Pd	D	Psav	S	dQ	Qu	Qd	DPp	dPax
1	0.883	10.03	21.12	0.32	0.0	209.9	193.0	193.0	16.9	0.271	206.3	20.76	0.0270	0.733	0.705	361	-1
2	0.868	12.95	14.72	0.90	3.3	239.8	188.8	188.8	21.0	0.190	189.4	14.19	0.0161	0.201	0.235	363	-2
3	0.230	5.32	45.26	0.17	0.0	262.8	43.0	43.0	209.8	0.341	301.7	7.84	0.0135	0.987	0.964		
4	0.392	0.00	0.13	0.00	37.1	47.4	3.2	37.1	20.3	0.888	37.7	3.73	0.0026	0.843	0.840	356	0
5	0.786	10.84	21.13	0.91	27.1	252.8	205.4	205.4	47.4	0.316	239.4	20.27	0.03	0.973	0.943		
6	0.334	12.29	67.56	0.19	81.9	360.6	53.0	107.8	252.8	0.464	389.4	17.33	0.0381	2.005	1.970		
7	0.414	0.00	0.14	0.00	37.2	107.2	12.3	37.2	70.0	0.304	78.6	4.09	0.0029	0.285	0.282	446	31
8	1.939	0.00	0.93	0.00	85.6	107.2	43.3	85.7	21.8	0.304	86.4	1.16	0.0007	0.283	0.282	403	-16
9	0.542	6.05	7.86	0.82	85.6	205.5	98.3	98.3	107.2	0.279	103.9	7.84	0.0104	0.578	0.568		
10	0.990	12.29	26.79	0.52	85.8	335.4	129.9	129.9	205.5	0.298	226.9	14.50	0.0331	0.611	0.578		
11	0.568	7.14	0.57	0.06	0.0	204.8	176.0	176.0	28.5	0.241	70.0	7.93	0.0084	0.478	0.470	478	-2
12	0.446	4.92	6.72	0.88	0.0	204.6	180.0	180.0	24.4	0.221	56.8	6.43	0.003	0.476	0.470	481	-8
13	0.292	0.16	28.78	0.39	0.0	326.4	130.8	130.8	204.6	0.296	136.6	10.82	0.0177	0.971	0.953		
14	0.125	4.22	64.26	0.10	86.6	363.1	27.7	27.7	335.4	0.397	280.4	6.78	0.0185	1.899	1.882		
15	0.477	4.90	8.16	0.83	0.0	232.4	192.9	192.9	39.8	0.163	83.9	1.33	0.0044	0.194	0.189	476	0
16	0.336	2.80	3.47	0.86	0.0	232.4	199.9	199.5	32.5	0.142	73.2	3.13	0.0034	0.191	0.188	477	-1
17	0.314	0.58	14.90	0.36	0.0	363.1	130.7	130.7	232.4	0.201	206.0	6.67	0.0141	0.400	0.386		
18	2.331	12.88	104.11	0.17	88.8	429.9	66.8	66.8	363.1	0.721	381.7	17.84	0.0576	2.047	1.999		
19	2.389	6.38	122.00	0.09	100.0	476.5	33.1	46.6	429.9	0.784	439.8	9.55	0.0346	2.093	2.060		

Return	=	87.86	0.43	81.9	300.8
Supply	=	122.00	0.57	100.0	476.5
Total	=	239.7		183.9	835.0 <-- Pfan

Return	=	84.1	0.1282	6.80 %,	dPminr	17
Supply	=	101.1	0.2106	9.82 %,	dPmins	22
Total	=	185.2	0.3388	16.82 %		

TABLE 7
Life-Cycle Cost Comparison for Sealed and Unsealed Ductwork

LEAKAGE	FAN FLOW (m³/s)	LEAKAGE (m³/s) SUPPLY	LEAKAGE (m³/s) RETURN	LEAKAGE (m³/s) TOTAL	TOTAL LEAKAGE (%)	MAXIMUM LEAKAGE m³/s	MAXIMUM LEAKAGE %	SYSTEM COST OWNING $	SYSTEM COST OPERATING $	SYSTEM COST LIFE CYCLE $	SYSTEM COST LIFE CYCLE %	DUCT SURFACE (m²)	SEALING COST ($)	TOTAL DUCT COST $	TOTAL DUCT COST %
None	1.88	0	0	0	0	0	0	6084	2013	8097	0	182.4	0	8097	0
Sealed Ductwork	1.91	0.025	0.012	0.037	2.0	0.025	1.3	6121	2040	8161	0.8	183.5	459	8619	6.4
Unsealed Ductwork	2.09	0.211	0.125	0.336	16.1	0.211	10.0	6177	2239	8416	3.8	185.2	0	8416	3.9

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$$E = Ep + Es + As \cdot Ss \quad (8)$$

The operating cost can be presented as basic operating cost (Eb) and its operating cost multiplier (OCM).

$$Ep = Eb(\text{OCM}) \quad (9)$$

The parameters that were used as variables for graphical interpretation (Figures 5a through 5d) in the life-cycle cost analysis are:

- *Duct cost* (Sd). Galvanized (\$33.36/m^2), stainless ducts (\$127.98/m^2).
- *Operating cost multiplier* (OCM). 1, 3, 5, 7, 9. This coefficient identifies the operating cost in a practical range for duct systems with different electrical energy costs multiplied by system operation time per year. It is used for graphical interpretation (Figures 5a to 5d). When Ep presents actual operating cost and the lowest operation time of a basic system, OCM is equal to 1.
- *Sealing cost* (Ss). 0, 0.50, 1.00, 1.50, 2.50 \$/m^2, where the highest cost (\$2.50/m^2) is from SMACNA.* On the other hand, according to a Midwest sheet metal contractor,† the duct sealing cost is insignificant. Sheet metal contractors usually seal longitudinal duct seams on roll forming machines. The contractor stated that the increase in cost is insignificant unless special sealers are used. Therefore, the lowest sealing cost considered is zero.
- *Basic electrical energy cost* (Ec) is a part of the basic operating cost (Eb) selected for two cities—the cheapest, which is 1.89¢/kWh for Seattle, and the most expensive, which is 16.34¢/kWh for residential buildings in New York and 11.88¢/kWh for industrial buildings in San Diego (based on Electric Sales and Revenue, EIA, Washington, DC).

The results of the study are summarized in Table 8 where theoretical conditions at no leakage are included for comparison. It was found that higher system leakage increased both operating and owning costs. Tables 9 through 12 present the results of the parametric study. Figure 5 is a graphical representation of the results. There is a small range where duct sealing is not recommended: operating cost multiplier (OCM) is less than 2 (which is mostly exhaust systems), electricity cost is less than 2.00¢/kWh, and sealing cost is higher than \$1.50/m^2.

CONCLUSIONS

Methodology was developed to add duct leakage to the T-method previously developed for the design and simulation of systems. It is shown that in most cases the sealing of ductwork is economical. Duct sealing is not recommended when the operating cost multiplier (OCM) is less than 2 (generally exhaust systems), electricity cost is less than 2.00¢/kWh, and sealing cost is greater than \$1.50/m^2. A simple rule is: the higher the system cost, the greater the need for ductwork sealing.

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NOMENCLATURE

A	= duct cross-sectional area, m^2 (ft^2)
As	= duct surface, m^2 (ft^2)
C	= local loss coefficient, dimensionless
C_L	= leakage class, dimensionless
D	= duct diameter, m (in.)
D_f	= equivalent-by-friction diameter of rectangular duct, m (in.)
D_v	= equivalent-by-velocity diameter of a rectangular duct, m (in.)
E	= present worth owning and operating cost, \$
Eb	= basic operating cost, \$
Ec	= electrical energy cost, \$/kWh
Ep	= operating cost, \$
Es	= owning cost, \$
f	= friction factor, dimensionless
H	= duct height, m (in.)
L	= duct length, m (in.)
LCC	= life-cycle cost, \$
M	= fan motor power, kW (hp)
OCM	= operating cost multiplier, dimensionless
P_d	= downstream pressure, Pa (in. wg)
P_{fan}	= fan total pressure, Pa (in. wg)
Ps_{av}	= average static pressure, Pa (in. wg)
P_t	= system total pressure, Pa (in. wg)
P_u	= upstream pressure, Pa (in. wg)
PWEF	= present worth escalation factor, dimensionless
Q	= airflow, m^3/s (cfm)
Q_d	= downstream flow rate, m^3/s (cfm)
Q_{fan}	= fan flow rate, m^3/s (cfm)
Q_u	= upstream flow rate, m^3/s (cfm)
Q_d	= terminal airflow with zero leakage, m^3/s (cfm)
R	= absolute roughness factor, m (ft)
Sd	= duct cost, \$/m^2 (\$/ft^2)
Ss	= sealing cost, \$/m^2 (\$/ft^2)
t	= air temperature, °C (°F)
V	= mean air velocity, m/s (fpm)

* Telephone conversation with J. H. Stratton, director of technical services, SMACNA, Chantilly, Va., March 21, 1990.

† Telephone conversation with Mr. C. R. James, vice president, the Robert Irsay Company, Skokie, Ill., November 28, 1990.

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V_{av} = average air velocity, m/s (fpm)
W = duct width, m (in.)
dP, ΔP = total pressure loss, Pa (in. wg)
dPp, ΔPp = path pressure loss, Pa (in. wg)
dP_{ex} = excess path pressure loss, Pa (in. wg)
dQ,ΔQ = flow leakage rate, m^3/s (cfm)
ρ = air density, kg/m^3 (lbm/ft^3)
ν = kinematic viscosity, m^2/s (ft^2/s)

TERMINOLOGY

The following terminology is adapted from Horowitz and Sahni (1976). References are to the system illustrated by Figure 3.

Children and parent. Duct sections connected at the same node. The parent section is the one that collects or distributes the total flow. The rest are children sections. In Figure 3, Section 3 is the parent with two children, Sections 1 and 2. Parent Section 5 has two children, Sections 3 and 4.

Path. A set of descendants connected in series. Paths from node 3-4-5 are 4, 1-3, and 2-3. Paths from the root node 5 are 1-3-5, 2-3-5, and 4-5.

Tee. Sections linked at the same node. The tee 1-2-3 consists of Sections 1, 2, and 3.

Terminal sections (nodes). Sections connected to the terminals: Sections 1, 2, and 4.

Tree. A system of duct sections connected at nodes with no circuits.

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TABLE 8
Ductwork Sealing Life-Cycle Cost Comparisons for Various Cities

CITY CONSUMER DUCT MATERIAL	LEAKAGE	Electric Cost (c/kW-h)	Duct Cost ($/m²)	FAN Flow (m³/s)	FAN Pressure (Pa)	LEAKAGE SUPPLY (m³/s)	LEAKAGE RETURN (m³/s)	LEAKAGE TOTAL (m³/s)	LEAKAGE TOTAL (%)	LEAKAGE MAX. (m³/s)	LEAKAGE MAX. (%)
1. New York, Residential, Galvanized	None	16.34	33.36	1.88	285.3	0.000	0.000	0.000	0.00	0.000	0.00
New York, Residential, Galvanized	Sealed Ductwork	16.34	33.36	1.90	289.0	0.022	0.007	0.030	1.56	0.022	1.17
New York, Residential, Galvanized	Unsealed Ductwork	16.34	33.36	2.06	288.5	0.179	0.075	0.255	12.36	0.179	8.70
2. San Diego, Industrial, Stainless	None	11.88	127.98	1.88	552.5	0.000	0.000	0.000	0.00	0.000	0.00
San Diego, Industrial, Stainless	Seal Ductwork	11.88	127.98	1.90	567.1	0.023	0.010	0.033	1.73	0.023	1.19
San Diego, Industrial, Stainless	Unsealed Ductwork	11.88	127.98	2.07	565.0	0.187	0.105	0.292	14.11	0.187	9.05
3. Seattle, Residential, Galvanized	None	1.89	33.36	1.88	732.1	0.000	0.000	0.000	0.00	0.000	0.00
Seattle, Residential, Galvanized	Sealed Ductwork	1.89	33.36	1.90	754.6	0.024	0.012	0.036	1.89	0.024	1.28
Seattle, Residential, Galvanized	Unsealed Ductwork	1.89	33.36	2.09	749.9	0.202	0.118	0.321	15.37	0.202	9.70
4. Seattle, Industrial, Stainless	None	2.03	127.98	1.88	1751.2	0.000	0.000	0.000	0.00	0.000	0.00
Seattle, Industrial, Stainless	Sealed Ductwork	2.03	127.98	1.92	1821.6	0.037	0.019	0.056	2.92	0.037	1.95
Seattle, Industrial, Stainless	Unsealed Ductwork	2.03	127.98	2.20	1760.4	0.303	0.171	0.474	21.58	0.303	13.81

CITY CONSUMER DUCT MATERIAL	LEAKAGE	Electric Cost (c/kW-h)	Duct Cost ($/m²)	SYSTEM COST Owning $	SYSTEM COST Operating $	SYSTEM COST Operating %	SYSTEM COST Life Cycle $	SYSTEM COST Life Cycle %	Duct Surface (m²)	Sealing Cost ($)	TOTAL COST $	TOTAL COST %
1. New York, Residential, Galvanized	None	16.34	33.36	8928	5535	0	14464	0	267.6	0	14464	0
New York, Residential, Galvanized	Sealed Ductwork	16.34	33.36	8839	5672	2.47	14511	0.33	265.0	662	15173	4.90
New York, Residential, Galvanized	Unsealed Ductwork	16.34	33.36	8958	6135	10.84	15093	4.35	268.5	0	15093	4.35
2. San Diego, Industrial, Stainless	None	11.88	127.98	26284	7797	0	34080	0	205.4	0	34080	0
San Diego, Industrial, Stainless	Seal Ductwork	11.88	127.98	26043	8095	3.83	34138	0.17	203.5	509	34647	2.59
San Diego, Industrial, Stainless	Unsealed Ductwork	11.88	127.98	26192	8774	12.53	34965	2.60	204.7	0	34965	2.60
3. Seattle, Residential, Galvanized	None	1.89	33.36	6329	1643	0	7972	0	189.7	0	7972	0
Seattle, Residential, Galvanized	Sealed Ductwork	1.89	33.36	6273	1715	4.39	7989	0.21	188.0	470	8459	6.10
Seattle, Residential, Galvanized	Unsealed Ductwork	1.89	33.36	6356	1867	13.62	8223	3.14	190.5	0	8223	3.14
4. Seattle, Industrial, Stainless	None	2.03	127.98	20556	4221	0	24777	0	160.6	0	24777	0
Seattle, Industrial, Stainless	Sealed Ductwork	2.03	127.98	20465	4962	17.55	25427	2.62	159.9	400	25827	4.20
Seattle, Industrial, Stainless	Unsealed Ductwork	2.03	127.98	20435	4961	17.53	25396	2.50	160.0	0	25396	2.50

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TABLE 9
Operating Cost Parametric Study for Seattle and Galvanized Ductwork

Sealing Cost ($/m²)	Operating Cost Multiplier (OCM)									
	1		3		5		7		9	
	LCC		LCC		LCC		LCC		LCC	
	$	%	$	%	%	%	$	%	$	%
Not Sealed	8223	0	11957	0	15691	0	19425	0	23159	0
0.00	7988	2.9	11418	4.5	14848	5.4	18278	5.9	21708	6.3
0.50	8082	1.7	11512	3.7	14942	4.8	18372	5.4	21802	5.9
1.00	8176	0.6	11606	2.9	15036	4.2	18466	4.9	21896	5.5
1.50	8270	-0.6	11700	2.1	15130	3.6	18560	4.5	21990	5.0
2.00	8364	-1.7	11794	1.4	15224	3.0	18654	4.0	22084	4.6
2.50	8458	-2.9	11888	0.6	15318	2.4	18748	3.5	22178	4.2

Seattle: 1.89 $/kWh
Galvanized Ductwork: 33.36 $/m²

TABLE 10
Operating Cost Parametric Study for Seattle and Stainless Ductwork

Sealing Cost ($/m²)	Operating Cost Multiplier (OCM)									
	1		3		5		7		9	
	LCC		LCC		LCC		LCC		LCC	
	$	%	$	%	(%)	%	$	%	$	%
Not Sealed	25396	0	35318	0	45240	0	55162	0	65084	0
0.00	24777	2.4	33733	4.5	42689	5.6	51645	6.4	60601	6.9
0.50	24856	2.1	33812	4.3	42768	5.5	51724	6.2	60680	6.8
1.00	24936	1.8	33892	4.0	42848	5.3	51804	6.1	60760	6.6
1.50	25015	1.5	33971	3.8	42927	5.1	51883	5.9	60839	6.5
2.00	25094	1.2	34050	3.6	43006	4.9	51962	5.8	60918	6.4
2.50	25174	0.9	34130	3.4	43086	4.8	52042	5.7	60998	6.3

Seattle: 1.89 $/kWh
Stainless Ductwork: 127.98 $/m²

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TABLE 11
Operating Cost Parametric Study for New York City and Galvanized Ductwork

Sealing Cost	Operating Cost Multiplier (OCM)									
	1		3		5		7		9	
	LCC		LCC ($)		LCC		LCC		LCC	
($/m²)	$	%	$	%	%	%	$	%	$	%
Not Sealed	15094	0	27364	0	39634	0	51904	0	64174	0
0.00	14511	3.9	25855	5.5	37199	6.1	48543	6.5	59887	6.7
0.50	14644	3.0	25988	5.0	37332	5.8	48676	6.2	60020	6.5
1.00	14776	2.1	26120	4.5	37464	5.5	48808	6.0	60152	6.3
1.50	14909	1.2	26253	4.1	37597	5.1	48941	5.7	60285	6.1
2.00	15041	0.4	26385	3.6	37729	4.8	49073	5.5	60417	5.9
2.50	15174	-0.5	26518	3.1	37862	4.5	49206	5.2	60550	5.6

New York City: 16.34 $/kWh
Galvanized Ductwork: 33.36 $/m²

TABLE 12
Operating Cost Parametric Study for New York City and Stainless Ductwork

Sealing Cost	Operating Cost Multiplier (OCM)									
	1		3		5		7		9	
	LCC		LCC ($)		LCC		LCC		LCC	
($/m²)	$	%	$	%	$	%	$	%	$	%
Not Sealed	34966	0	52514	0	70062	0	87610	0	105158	0
0.00	34138	2.4	50328	4.2	66518	5.1	82708	5.6	98898	6.0
0.50	34240	2.1	50430	4.0	66620	4.9	82810	5.5	99000	5.9
1.00	34342	1.8	50532	3.8	66722	4.8	82912	5.4	99102	5.8
1.50	34443	1.5	50633	3.6	66823	4.6	83013	5.2	99203	5.7
2.00	34545	1.2	50735	3.4	66925	4.5	83115	5.1	99305	5.6
2.50	34647	0.9	50837	3.2	67027	4.3	83217	5.0	99407	5.5

New York City: 16.34 $/kWh
Stainless Ductwork: 127.98 $/m²