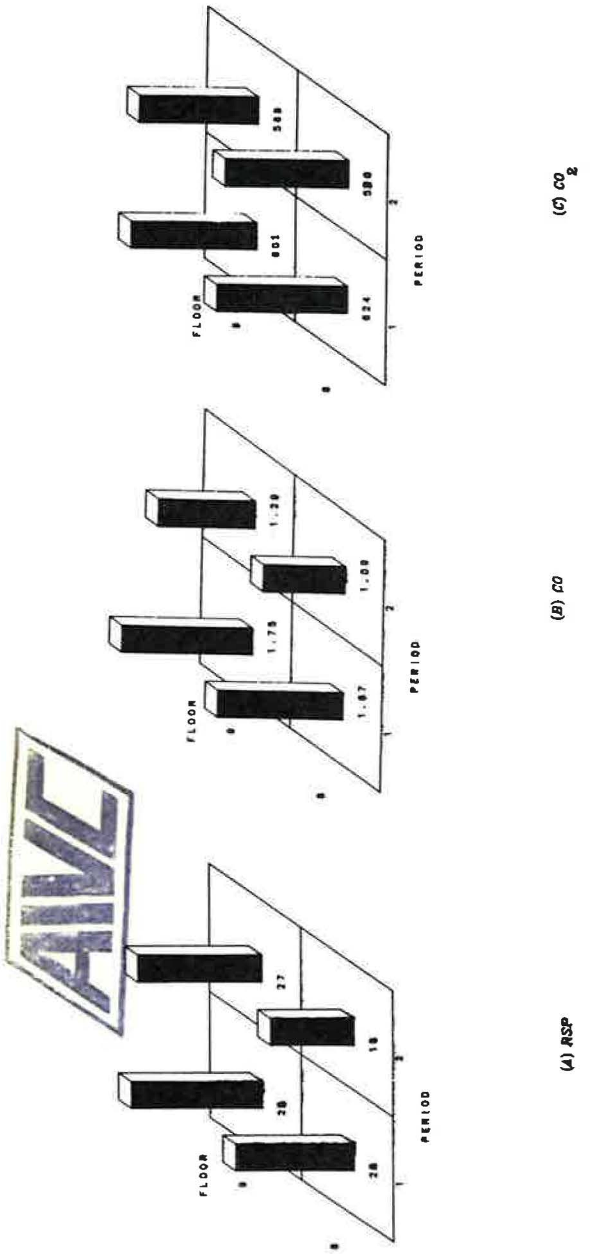

Figure 6. Mean RSP, CO and CO_2 levels on the test floor (Floor 8) and the control floor (Floor 9), before and after the new smoking policy.

OFFICE ENERGY CONSERVATION: THE EFFECT ON AIRBORNE PARTICLES AND THEIR CHEMICAL CONSTITUENTS

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Energy conservation is a prime consideraton in the operation of telephone office buildings. Following the soaring cost of energy in the mid-1970s, an energy saving program based on a larger permissible range for indoor temperatures was initiated. Whereas the previous practice was for air handling fans to run continuously, under the new program fans operated only when necessary to bring the temperature within allowable limits. The effects of fan operation on indoor airborne particles and the chemicals associated with those particles were monitored at several representative telephone offices. During the tests the building fans were cycled between 2-week intervals of continuous fan operation and 2-week intervals of intermittent fan operation.

Results indicate that filtration of recirculated air is a major factor determining the average indoor concentration of airborne particles. When the fans are off the concentration of airborne particles increases, primarily because of the lack of recirculation/filtration. The concentrations of most of the chemical constituents of the indoor particles increase by the same relative amount that the concentration of the particles increases. The major exceptions are organic compounds that are associated with airborne particles through an adsorption process. Their concentrations do not scale in a simple way with particle mass, sometimes increasing by a much larger factor. This is due to both an increase in the fraction of such compounds attached to particles (as the surface area/unit volume of air increases) and to a greater overall concentration of such compounds (as the dilution with outside air decreases).

An expression has been derived for the relative increase in airborne particles when the building fans are turned off. Among other factors, the relative increase is directly proportional to the efficiency of the building filters and to the rate at which air is recirculated through them.

INTRODUCTION

Airborne particles and the chemicals associated with these particles can seriously affect the operation of electronic equipment. In telephone offices the effects include improper closure between electromechanical contacts, current leakage across dust bridges, excessive arcing leading to the erosion of contact surfaces, the formation of resistive films on connector surfaces, the corrosion of metal components, and the degradation of certain plastics and other materials. When energy saving procedures were introduced in telephone buildings in the mid-1970s there was concern that the concentration of contaminants within these offices would increase. To evaluate this concern, detailed studies were conducted over a period of six months at two representative offices in the midwest[1]. During the study each office operated for 2 weeks in standard mode, followed by 2 weeks in an energy saving mode. The 4-week test cycle was then repeated.

Fine and coarse airborne particles were collected inside each office throughout the study period. Outdoor samples were collected at the same time as the indoor samples. The major chemicals associated with these particles, including water soluble anions and cations, trace metals, and organic compounds, were determined by a variety of techniques. The results of these studies provide information concerning the effect of specific energy saving measures on the indoor concentrations of fine and coarse airborne particles, as well as the major chemical species associated with these particles.

EXPERIMENTAL

The first test series was conducted in Wichita, Kansas during the fall and early winter of 1981; the second series of tests was conducted in Lubbock, Texas during the late winter and spring of 1982. The Wichita office has an 8000 cfm air handling system and a total internal volume of 68,000 cubic feet resulting in approximately 0.12 air changes/min. This office does not pre-filter the make-up air; the air handling plenum contains one inch thick polyester mat filters that have an ASHRAE Dust Spot rating of 12 percent. The Lubbock office has a 13,000 cfm air handling system and a total internal volume of 55,000 cubic feet resulting in about 0.24 air changes/min. The Lubbock office pre-filters the make-up air using two inch Farr 30-30 filters; the air handling plenum contains one inch Farr 30-30 filters followed by bag filters that have an ASHRAE Dust Spot rating of 85 percent.

Under the energy saving program, a building is not heated if above 65°F or cooled if below 80°F. Between these limits the temperature is allowed to drift. The building fans operate only when necessary to bring the temperature within allowable limits, rather than continuously. The normal test procedures called for the office to operate for 2 weeks with heating, ventilating, and air conditioning (HVAC) fans on continuously (standard mode), and then 2 weeks with thermostatic fan cycling while maintaining building temperatures between 65° and 80°F. The 4-week test cycle was then repeated.

The concentration of airborne particles, both indoors and outdoors, was determined using Sierra Automatic Dichotomous Samplers, Model No. 245. The entrained particles are size fractionated into fine particles smaller than 2.5 micron diameter and coarse particles between 2.5 and 15 micron diameter by means of virtual impaction. The nominal flow rate was 0.59 cfm. The particles were collected on 2.0 micron pore size Teflon membrane filters (37mm diameter) with nonwoven polypropylene backing. The filters were precleaned with water followed by methanol using ultrasonic agitation. After three such cleaning cycles, the filters were air dried and equilibrated at least one day at 55 percent R.H. before weighing. Typical tare weights ranged from 0.088-0.103 g. The recorded weight for each filter was the average of 3 weighings to the nearest microgram on a microanalytical balance.

At each location the indoor sampler was located adjacent to the switching equipment frames and the outdoor sampler was located on the roof (approximately 6 m above ground). Samplers were run continuously, with two outdoor samples collected for every indoor sample. Typically, the outdoor sampling interval was 84 h, and the indoor sampling interval was 168 h. Further details are given elsewhere[1].

Analysis for the major anions and cations associated with the particles has been previously described[2]. Briefly, the Teflon membrane filters were extracted with 10 ml of water using ultrasonic agitation for at least 1 hour. The 10 ml volumes were then split into equal portions for separate anion and cation analysis using a Dionex Model 12 ion chromatograph with an autosampler. Appropriate blank corrections were made for unloaded Teflon filters.

Characterization of the organic compounds associated with the airborne particles has been outlined in other reports[3,4]. To summarize, organic compounds were separated and identified with a Hewlett-Packard 5992A gas chromatograph-mass spectrometer (GC/MS). Nonpolar organic constituents of aerosol particles were detected by a thermal desorption procedure[3]. In a typical analysis a loaded Teflon membrane filter was heated to 250°C for twenty seconds in a stream of helium. The helium purged the volatilized organics from the filter into the GC/MS for subsequent separation and identificaton. Fatty acids associated with the aerosol particles were characterized with the aid of a methylation procedure[4]. In a typical analysis a loaded Teflon membrane filter was extracted with petroleum ether. A boron trifluoride - methanol solution was added to the petroleum ether extract; the mixture was heated at 100°C for 10 minutes; the reaction was quenched; and the petroleum ether layer containing the methyl esters was removed. The methyl esters were separated and identified using standard GC/MS techniques.

RESULTS AND DISCUSSION

Throughout the studies at both offices, sensors monitored the on/off status of the HVAC fans. The sensors indicated that for the major portion of the tests at both Wichita and Lubbock, the HVAC fans were off 100% of the time during thermostatic cycling. An earlier report[1] lists the percent "on" time during each test phase. The same report includes week by week listings of the indoor and outdoor concentrations of fine, coarse, and total suspended particles at the Wichita and Lubbock sites. Table 1 is a summary of the particle concentrations measured within the Wichita office with the air handling system in both the standard mode and the energy saving mode. Table 2 is a similiar summary for the Lubbock office. Indoor/outdoor (I/O) ratios are also included in each table.

At Wichita, the average concentration of indoor fine particles rises almost a factor of three when the energy saving measures are employed. Taking the outdoor concentrations into account, the I/O ratio for fine particles rises about a factor of 2.5. The energy saving measures have no discernible effect on the concentration of indoor coarse particles.

At Lubbock, when the energy saving measures are in effect, the average concentration of indoor fine particles increases a factor of 8 and the respective I/O ratio increases a factor of ten. The average concentration of indoor coarse particles increases about a factor of 6. Note, however, that because of the small concentrations of indoor coarse particles, the standard deviations associated with the coarse values are large and comparisons between coarse I/O ratios are not meaningful.

The energy saving measures have a greater effect on the particle concentrations at the Lubbock site (fine mode I/O increases ~10x; coarse particle concentration also increases) than on the particle concentrations at Wichita (fine mode I/O increases ~2.5x; coarse particle concentration does not change). A simple model suggests that this is due primarily to differences in the efficiency of the building filters through which the air is recirculated. The model assumes that there is uniform mixing within the building and that the system is in a steady state[1,5]. The assumption of uniform mixing is supported by measurements of relatively invariant surface accumulations at various locations throughout the office[2]. When the HVAC fans are on, there are 3 major sources of indoor particles: generation within the office, leakage of outdoor particles into the office, and the introduction of outdoor particles with the makeup air. There are 4 major sinks for the indoor particles: settling onto indoor surfaces, removal by the building filters of particles suspended in the recirculated air, leakage out of the office, and the expulsion of particles suspended in the air that is exhausted and replaced with makeup air. Assuming that the source terms equal the sink terms, the average indoor particle concentration is given by the expression:

$$C_i = \frac{R_i + v_1(1 - F_1)C_e + v^*(1 - F_p)(1 - F_s)fC_e}{k_d A_d + v^* F_s + v^*(1 - F_s)f + v_1} \qquad (1)$$

where:

C_i = average indoor dust concentration ($\mu g/m^3$)
R_i = internal rate of dust generation ($\mu g/min$)
v_1 = volume of air leaking into and out of the building (m^3/min)
F_1 = fractional equivalent filter efficiency of leakage paths (0-1)
C_e = average outdoor dust concentration ($\mu g/m^3$)
v^* = volume of air flow in air handling system (m^3/min)
F_p = fractional primary filter efficiency; the fraction of particles in a given size range removed by the primary filter (0-1)
F_s = fractional secondary filter efficiency; the fraction of particles in a given size range removed by the secondary filter (0-1)
f = fraction of recirculation made up with outside air (0-1)
k_d = internal dust deposition rate constant (m/min)
A_d = internal dust deposition area (m^2)

Equation 1 can be used to estimate the relative increase in indoor particle concentrations when the energy saving measures are employed (i.e., when the HVAC fans are off). To simplify the discussion, assume no outside air is being introduced, a reasonable assumption during the winter months. Then f=0, and equation 1 simplifies to:

$$C_i(on) = \frac{R_i + v_1(1 - F_1)C_e}{k_d A_d + v^* F_s + v_1} \qquad (2)$$

When the fans are off, $v^*=0$ and

$$C_i(off) = \frac{R_i + v_1(1 - F_1)C_e}{k_d A_d + v_1} \qquad (3)$$

The relative increase in indoor particle concentrations when HVAC fans are turned off is then given by:

$$\frac{C_i(off)}{C_i(on)} = 1 + \frac{v^* F_s}{k_d A_d + v_1} \qquad (4)$$

This expression indicates that the relative increase in indoor particle concentration when the HVAC fans are turned off depends directly on both the efficiency of the filters through which the air is recirculated and the rate at which the air is recirculated. It depends inversely on the rate at which particles settle out of the air and the rate at which air leaks out of the office. Note that this ratio does not depend on the outdoor particle concentration. Approximate values for v^* and A_d for the Wichita and Lubbock offices are known[1]. Deposition velocities within the offices for both fine and coarse particles have been estimated[1] and measured[2]. Average values for the volume of air leaking into and out of the building can be calculated from data[2] on the simultaneous indoor and outdoor concentrations of chemical species that have only outdoor sources. (Such calculations yield $\nu_1 = 5m^3/min$ (Wichita) and $\nu_1 = 21m^3/min$ (Lubbock). These values are averages derived from 7 day sampling intervals. One would expect shorter sampling intervals to reveal fluctuations in air leakage rates with varying indoor/outdoor temperatures and wind conditions). Using these values, together with the representative filter efficiencies, F_s, the effect of turning off the HVAC fans at Wichita and Lubbock can be calculated. Table III compares calculated and observed increases at both sites. It should be noted that the calculated values in Table III assume no introduction of outside air. These values are, in effect, upper limits on the relative increase, since the introduction of outside air results in a lower relative increase (no change in C_i(off); larger C_i(on)). The observed values include some periods when outside air was introduced. Wichita has standard polyester filters, and the calculated increase in fine particles when the fans are turned off is a factor of 3, in good agreement with the observed value. Despite a calculated increase, the coarse level remains virtually unchanged due to compensating factors. The Lubbock office has high efficiency filters, and the calculated increase in fine particles when the fans are turned off is a factor of 14, while that of coarse particles is a factor of 9. Considering the introduction of outside air, both values are in reasonable agreement with the observed values.

Analyses of the major anions[2], cations[2], and trace metals[6] associated with the airborne particles indicate that their concentrations simply track the concentration of the airborne particles. Table IV lists indoor concentrations and indoor/outdoor ratios for ionic species associated with fine particles at the Lubbock site during two representative weeks - one with the fans running continuously and a second with the fans off. The last entries in Table IV are the indoor concentrations and the I/O ratios for fine particles during each of these weeks. Comparisons indicate that for most of the ionic species the increases in their I/O ratios that occur with the implementation of energy conservation measures match the increase in the I/O ratio that occurs for fine particles. (It is more appropriate to compare I/O ratios of the various ionic species and the fine particle mass than it is to compare the absolute concentrations of the ionic species and the fine particle mass, since the fractional contribution of ionic species to the fine particle mass can vary with wind direction, source strengths, etc.) This result is expected since the major anions, cations, and metals are integrally associated with the particles. Consequently, when the building fans are turned off, the indoor concentrations of species such as calcium, sodium, potassium, sulfate, nitrate, chloride, iron, and lead will increase by the same relative amount that the indoor particle concentration increases.

Observations for certain organic compounds associated with airborne particles are very different from those just described for the inorganic species. The concentrations of the majority of the fatty acids and certain straight chain alkanes (n-C_{23}- n-C_{29}) roughly track the concentrations of the indoor particles. However, for n-C_{30}, n-C_{31}, the

branched alkanes, and the phthalate, phosphate, and azelate esters, when energy saving measures are introduced, their indoor concentrations do not scale in a simple way with the particle mass and frequently increase by a much larger factor. As discussed in other reports[3,4], these latter compounds have predominantly indoor sources. Furthermore, variations in concentrations with particle size suggest that these compounds are associated with the airborne particles through an adsorption process (i.e., they are attached to the surface of the particles). The vapor phase/particle surface partitioning of the organic compounds with strong indoor sources helps to explain the fact that their concentrations do not scale with the concentrations of the indoor particles. C. E. Junge[7] derived an expression to describe the partitioning of an organic compound between the vapor phase and the surface of airborne particles:

$$\phi = \frac{c\theta}{p_o + c\theta} \qquad (5)$$

where ϕ = (amount of substance adsorbed on particles)/(total concentration, gas phase and condensed phase), θ = surface area of particles (cm^2/cm^3 air), p_0 = saturation vapor pressure, and c is a constant that depends on the molecular weight and the heat of condensation. If the concentration of fine mode particles increases a factor of eight, as is observed at Lubbock when the HVAC fans are turned off, the surface density, θ, also increases a factor of eight. This affects ϕ, the fraction of the total concentration of the organic compound attached to airborne particles. The point is perhaps best illustrated with some typical values. Assume that the surface area of fine indoor particles is initially 7×10^{-8} cm^2/cm^3. For an organic compound with a saturation vapor pressure of 1×10^{-8} mm Hg and a value for c of 0.143 mm Hg cm^3/cm^2, the value of ϕ calculated from equation 5 is 0.5 (i.e., half of the organic compound will be attached to particles, the remainder will be in the gas phase). Now if the surface area of fine indoor particles increases a factor of eight to $5.6 \times 10^{-7} cm^2/cm^3$, then, for this same organic compound, ϕ = 0.89 (i.e., nine tenths of this organic compound will be attached to airborne particles). The partitioning fraction has increased from 0.5 to 0.89. So while the concentration of fine particles increases a factor of eight, the concentration of this hypothetical organic compound associated with the fine particles increases a factor of 1.8.

When the energy saving measures are employed at these offices there is a second factor that contributes to the disproportionate increase in the concentration of the organic compounds adsorbed on airborne particles. The reduced use of building fans is often accompanied by reduced air exchange (depending on outdoor temperatures). This results in less dilution of organic compounds that have predominantly indoor sources. Consequently, the overall concentration of these compounds increases, and, even if the fraction attached to particles were to remain constant, the amount attached to particles would increase. Reduced dilution is typically more important than shifting vapor phase/particle surface partitioning in determining the overall relative increase in the concentration of compounds adsorbed on airborne particles. Hence, particulate concentrations of such organic compounds are frequently much larger than would be estimated from just the increase in the fraction of such organic compounds attached to these particles.

CONCLUSIONS

At the two offices examined in this study, the energy conservation measures resulted in non-operation of the HVAC fans for most of the time. Equation 4 predicts the relative increase in indoor particle concentrations when the HVAC fans are turned off. In telephone equipment buildings, there is likely to be less variation in v*, A_d, and (normalized for the internal office volume) than there is in F_s. Using typical values for v*, k_d, A_d, and ν_1 one can estimate the effect of turning off HVAC fans in telephone offices with different types of filters (different values of F_s). Such estimates indicate that for an office with glass fiber or polyester filters (small value of F_s), the indoor concentrations of both fine and coarse particles will increase by a factor of 2-3. For an office with high efficiency filters (large value of F_s), the indoor fine particles will most likely increase by a factor of 10-15, while the indoor coarse particles will likely increase by a factor of 7-10.

For water soluble ionic species, trace metals, and organic compounds integrally associated with airborne particles, equation 4 can again be used to predict the relative increase in concentrations that occurs when fans are turned off. $C_i(off)/C_i(on)$ will simply match that for airborne particles. However, for organic species associated with airborne particles through an adsorption mechanism, the relative increase can be much larger than that predicted by equation 4. This point is of special significance in offices that have large indoor sources of plasticizers, surfactants, and similar compounds (i.e., compounds that have saturation vapor pressures between 10^{-6} and 10^{-9} torr) that tend to be adsorbed on particles.

In the United States there are over ten thousand telephone office buildings similar to the offices at Wichita and Lubbock. The present findings are of general applicability to such buildings. These results can also be extended to other office buildings whose sources and sinks are adequately described by equation 1.

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TABLE I. AVERAGE CONCENTRATIONS AND INDOOR/OUTDOOR RATIOS FOR FINE AND COARSE AEROSOL PARTICLES AT THE WICHITA SITE

Status of Air Handling System	Concentration of Indoor Fine, μg/m^3	I/O, Fine	Concentration of Indoor Coarse, μg/m^3	I/O, Coarse
Standard Mode (fans on)	4.3 ± 0.5	0.4 ± 0.1	0.4 ± 0.3	0.05 ± 0.05
Energy Saving Mode (fans off)	12.6 ± 1.7	1.0 ± 0.3	0.4 ± 0.2	0.02 ± 0.02

TABLE II. AVERAGE CONCENTRATIONS AND INDOOR/OUTDOOR RATIOS FOR FINE AND COARSE AEROSOL PARTICLES AT THE LUBBOCK SITE

Status of Air Handling System	Concentration of Indoor Fine, μg/m^3	I/O, Fine	Concentration of Indoor Coarse, μg/m^3	I/O, Coarse
Standard Mode (fans on)	0.8 ± 0.1	0.09 ± 0.01	0.4 ± 0.4	0.02 ± 0.02
Energy Saving Mode (fans off)	6.4 ± 0.9	0.9 ± 0.2	2.4 ± 0.4	0.06 ± 0.03

TABLE III. RELATIVE INCREASES IN INDOOR PARTICLE CONCENTRATIONS WHEN HVAC FANS ARE TURNED OFF

	$\frac{C_i(\text{off})}{C_i(\text{on})}$, fine particles		$\frac{C_i(\text{off})}{C_i(\text{on})}$, coarse particles	
	observed[a]	calculated[b]	observed[a]	calculated[b]
Wichita	2.9	3.0	1.0	3.9
Lubbock	8.0	13.8	6.0	8.8

[a] Includes both periods when outside air was and was not being introduced.

[b] Calculated assuming no outside air was being introduced. This value is, in effect, an upper limit on the relative increase, since the introduction of outside air results in a lower relative increase (no change in $C_i(\text{off})$; larger $C_i(\text{on})$).

TABLE IV. INDOOR CONCENTRATIONS AND INDOOR/OUTDOOR RATIOS FOR IONIC SPECIES ASSOCIATED WITH FINE PARTICLES AT LUBBOCK DURING FEBRUARY 4-11 1982 (STANDARD) AND MARCH 4-11 1982 (ENERGY SAVING)

Status of Air Handling System	Ion	Concentration of Indoor Fine, ng/m^3	I/O, Fine
Standard[a]	$SO_4^=$	443	.08
Energy Saving[b]	$SO_4^=$	1600	.73
Standard	$C\ell^-$	4	.4
Energy Saving	$C\ell^-$	67	4.5
Standard	NO_3^-	37	-
Energy Saving	NO_3^-	292	2.5
Standard	Na^+	9	.13
Energy Saving	Na^+	60	1.9
Standard	NH_4^+	150	.05
Energy Saving	NH_4^+	430	.58
Standard	K^+	12	.75
Energy Saving	K^+	210	1.9
Standard	Ca^{++}	9	.12
Energy Saving	Ca^{++}	36	.08
Standard	Fine Particles	970	.09
Energy Saving	Fine Particles	6760	1.1

a) Fans on

b) Fans off

VENTILATION INTAKE AIR CONTAMINATION BY NEARBY EXHAUSTS

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Buildings with mechanical ventilation systems often place air intakes and exhausts close to each other to make the most efficient use of space. This is particularly true for direct air-to-air exchangers for exhaust heat recovery. The greatest hazards occur for exhausts on laboratories, hospitals and industrial buildings where concentrated emissions of solvents, toxic gases and pathogens are carried by the wind or their own momentum from exhaust to intakes. Tracer gas studies in wind tunnel simulations are reviewed, and correlated to show the contributions of exhaust jet plume rise, building induced turbulence, and large scale atmospheric turbulence on dilution between an exhaust and an intake. Measurements show that the two major factors that influence dilution are distance between exhaust and intake, and the ratio of exhaust jet velocity to windspeed. The location of the exhaust intake pair on the building is also important, with good design placing the intake on the lower third of the building and the exhaust on the upper two thirds. Flow visualization tests show the reason for this. A simple theory for exhaust to intake dilution is presented. The theory, which accounts for dilution close to the exhaust, is in good agreement with wind tunnel data, and with full scale tracer gas tests on large buildings. The implications for good design of closely spaced exhausts and intakes are discussed. It is shown that the fraction of recirculated exhaust in intake air can change by a factor of five with only minor changes in design, such as the removal of a rain cap.