Ozone in Passenger Cabins: Concentrations and Chemistry

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16. Abstract

Congressional Mandate

Monitor ozone in the cabin on a representative number of flights and aircraft and determine compliance with existing Federal Aviation Regulations; carry out the studies and analysis called for in the NRC report.

NRC report

Recommendation 1: Calls for the FAA to demonstrate the adequacy of FARs for cabin air quality; Recommendation 9: Calls for investigations of how ozone concentration in the cabin is affected by various factors (e.g., ambient concentrations, reactions with surfaces, the presence and effectiveness of catalytic converters), and the relationship between ozone levels and health effects.

Findings

1. Measurements in passenger cabins revealed that ozone levels can be moderate to high on domestic flights without ozone converters. On 8 of 46 domestic flights without converters, ozone levels exceeded at some during the flight the “0.1 parts per million by volume” (100 ppb) level specified in the FARs. On one flight ozone levels exceeded the “0.25 parts per million by volume” (250 ppb), a level not to be exceeded “at any time”. However, in the relevant FAR (Section 121.578), the 100 ppb level applies as a time-weighted average only for flight segments exceeding four hours. The highest time-weighted average over the full flight for the 46 domestic flights without converters was within ten percent of the 100 ppb limit. This was the only flight for which the time-weighted average exceeded 90 ppb. Furthermore, the flight planning approach specified by the FAR only requires a statistical

confidence of 84% that the limits on ozone levels will not be exceeded. Ozone converters reduce ozone levels substantially. Nonetheless, elevated ozone levels (up to about 60 ppb for the peak hourly average) were measured on transoceanic flights equipped with converters. There were no instances where the flight-average limit of 100 ppb was exceeded on aircraft with ozone converters. Within the constraints of the limitations on the number of flights that could be monitored, ozone levels in aircraft cabins were consistent with the requirements of the FARs.

2. Experiments conducted in a reconstructed section of a B-767 aircraft cabin indicated that more than half of the net ozone removal within the cabin was attributable to its reactions with passengers and crew. Ozone removal is dominated by reactions on surfaces; gas-phase reactions contribute little to the overall removal of ozone from cabin air.
3. Ozone reacts rapidly with skin lipids present on the exposed skin, hair and clothing of the cabin occupants. Ozone-initiated chemistry produces a series of carbonyls, dicarbonyls and hydroxycarbonyls. Inhalation of certain ozone-derived products may be meaningful for the health of passengers and crewmembers, especially on aircraft with elevated ozone levels.
4. Occupants judged the air quality worse and reported various symptoms in response to exposure to ozone and its oxidation products in cabin simulations. Self-assessed symptoms included complaints commonly reported by the flying public (e.g., irritated eyes and throat). In addition, ozone and certain byproducts of ozone-initiated chemistry are known to adversely affect human health at elevated levels.
5. The current FARs may not adequately protect the health of passengers and crew. This finding reflects the fact that the FARs were established about three decades ago, prior to i) the recognition that cabin occupants are exposed to products of ozone-initiated chemistry in addition to ozone itself; ii) the accrual of a large body of evidence regarding irritation, morbidity and mortality resulting from ozone exposures in polluted urban environments; and iii) a flying population that includes a larger number of vulnerable and sensitive individuals.

Recommendations

1. The FARs related to ozone in the cabin environment should be reevaluated since they do not appear to adequately protect the health of passengers and crew. Consideration should be given to the fact that the current national ambient air quality standard is 75 ppb measured over 8 hrs and a lower standard (down to 60 ppb as the peak hourly average) has been recommended (Federal Register, Vol. 75, No. 11, 2938, 19 Jan 2010).
2. The benefit-cost ratio of requiring ozone converters on all commercial flights should be evaluated with a view toward establishing a broader requirement for passenger aircraft be equipped with effective ozone converters. As an alternative, the FAA should consider establishing a requirement that airlines report for each flight, as a passenger books a ticket, whether or not the scheduled plane is equipped with an ozone converter.
3. A performance specification should be assessed as an alternative to an hours-of-service specification to ensure effective performance of ozone converters throughout a plane’s service life. An FAA-mandated industry-conducted program of random, periodic testing of in-service ozone converter performance should be evaluated; such a program could reduce exposures that result from degraded or poisoned catalysts.

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ABBREVIATIONS

As used in this report, the following abbreviations/acronyms have the meanings indicated

ABBREVIATION	MEANING
ACER	Airliner Cabin Environmental Research
B-767	Boeing model 767
DTU	Technical University of Denmark
EB	Eastbound (transoceanic flight)
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
h	hour
HEPA	high efficiency particle in air
L/s	liters per second
N	Number of flights monitored
NIOSH	National Institute of Occupational Safety and Health
NRC	National Research Council
O_3	ozone
ppb	parts per billion (by volume)
ppbv	parts per billion by volume
P-value	probability value
RITE	Research in the Intermodal Transport Environment
US	United States
VOC	volatile organic compound
WB	Westbound (transoceanic flight)
4-OPA	4-oxopentanal
6-MHO	6-methyl-5-hepten-2-one

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"When we try to pick out anything by itself,
we find it hitched to everything else in the universe."
—John Muir, 1911

SUMMARY

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INTRODUCTION

Passengers and crew in aircraft cabins may be exposed to elevated ozone that originates naturally in the stratosphere. The level of ozone in aircraft cabins depends on ambient concentrations, the presence (or absence) of control devices and their effectiveness, the rate of outdoor air supply, and the rate of ozone loss through within-cabin transformation processes, such as reactions with interior surfaces, including those associated with occupants. Ozone levels outside the aircraft vary with season and depend on flight altitude, tropopause height, and on meteorological processes that affect vertical mixing between the lower stratosphere and the upper troposphere. Exposure to ozone in cabin air has potential health significance for the flight crew and for the general flying population, which includes individuals who may be particularly sensitive to respiratory health effects, such as asthmatics, infants, and adults with cardiopulmonary conditions. Exposure to ground-level ozone and its reaction byproducts are strongly associated with adverse respiratory and cardiovascular effects (Levy et al., 2001; Bell et al., 2006; Weschler, 2006; Jerrett et al., 2009). Acute effects from short-term exposure range from breathing discomfort, respiratory irritation, and headache for healthy adults (Strøm-Tejsen et al., 2008) to asthma exacerbation and premature mortality for vulnerable populations (Gent et al., 2003; Bell et al., 2004). Chronic exposure effects may include enhanced oxidative stress (Chen et al., 2007), reduced lung function in young adults (Tager et al., 2005), and adult-onset asthma in males (McDonnell et al., 1999). Physical activity, as is undertaken by flight attendants, results in increased intake. There is no established “safe” level of ozone exposure (Bell et al., 2006).

Real-time measurements made during flights in the 1960s and 1970s revealed that in-cabin ozone was commonly above 100 parts per billion by volume (ppb), especially on flight routes through high latitudes (Brabets et al., 1967; Bischof, 1973; Nastrom et al., 1980). In 1980, in response to these data and to associated health concerns for flight attendants (Reed et al., 1980), the Federal Aviation Administration (FAA) established regulations (FAR 25.832 and FAR 121.578) that are designed to limit levels of ozone in airplane cabins (National Research Council, 2002). To comply with the regulations, many planes are equipped with “catalytic converters” that promote the decomposition of ozone in the ventilation supply air. Alternatively, airlines may comply by means of flight-route planning to reduce the probability of encountering elevated ozone. Not all planes are equipped with converters. Converters can fail to perform as designed owing, for example, to fouling by pollutants that poison the active surface sites. The probabilistic planning approach permits, by design, up to 16% of the flights to encounter elevated ambient ozone concentrations. Thus, the existence of the regulations, by themselves, do not assure that cabin occupants are protected from exposure to elevated ozone levels.

The ozone level in aircraft cabins is neither routinely monitored, nor has it been the subject of much additional research since the ozone standards were established. Spengler et al. (2004) presented a survey of flight-integrated ozone levels on 106 segments along with three-hour average ozone levels measured during the middle of the flight for segments over the Pacific ocean. The presence or absence of an ozone converter was determined by proxy and was not verified. To our knowledge, prior to efforts by ACER/RITE researchers summarized in this report, real-time in-cabin ozone data have been reported for just four flights since 1980 (Spicer et al., 2004). To address this data gap, the research team made real-time, continuous measurements of ozone levels in the passenger cabins of 76 commercial flight segments between February 2006 and August 2007.

When ozone is present in an aircraft cabin, ozone-derived reaction products are also present, both in the gas phase and on surfaces. The fact that ozone-initiated chemistry could meaningfully increase the levels of certain volatile and semivolatile organic compounds in aircraft cabin air was first demonstrated in a Boeing-funded study (Wisthaler et al., 2005) conducted in a simulated section of a B-767 (3 rows, 21 seats) at the Technical University of Denmark. Given the results of this preliminary study, as well as our understanding of ozone chemistry and effects observed in various indoor environments, the ACER/RITE research team undertook studies of the reaction of ozone with cabin materials, with a pesticide commonly used to disinsect aircraft, and with cabin occupants themselves.

Results from the various tasks that have constituted the ACER/RITE project investigating the concentrations and chemistry of ozone in passenger cabins are summarized in the following section of this report.

RESULTS AND DISCUSSION

Ozone levels in passenger cabins

Ozone levels in airplane cabins, and the factors that influence them, were studied on northern-hemisphere commercial passenger flights on domestic US routes as well as on transatlantic and transpacific international routes (Bhangar et al., 2008). Real-time data from 76 flights were collected during 2006 and 2007 with a battery-powered ozone monitor that works on the principle of ultraviolet spectrophotometry. Sampling occurred on flight segments of scheduled duration exceeding 3.5 hours. On each flight, ozone levels in the passenger cabin were monitored with one-minute time resolution throughout the period that the plane was above 10,000 feet (such that the use of portable electronic devices was allowed). Figure 1 shows representative ozone measurements from four consecutive domestic transcontinental US segments monitored within a 6-day interval in April 2006. For these four transcontinental flights sampled during spring following a major storm event, ozone levels were high on the three flight segments on planes without converters and low on the one segment on a plane equipped with an ozone converter.

Overall, the sample-average ozone level, peak-hour ozone level, and flight-integrated ozone exposures varied substantially across the 68 domestic flight segments sampled, with ranges of <1.5 to 146 ppb for the flight average, 3-275 ppb for the peak hour, and <1.5 to 488 ppb-hour for the flight-integrated exposures, respectively. On planes equipped with ozone catalysts (N = 22 flight segments), the mean peak-hour ozone level (4.7 ppb) was about a factor of 10 lower than on planes not equipped with catalysts (N = 46 flight segments; 47 ppb). Weighted cumulative distributions of peak-hour ozone levels for aircraft with and without converters are displayed in Figure 2.

The highest levels observed were on one transcontinental US flight on a plane not equipped with an ozone converter. The peak (one-minute average) ozone level on this flight was 308 ppb and the ozone level exceeded 250 ppb for 22 consecutive minutes. The average ozone level during the period sampled (2 hours and 49 minutes) was 132 ppb. We estimate that the average ozone level for the entire flight segment (3 hours and 51 minutes) was in the range 99-109 ppb. In all, the ozone level exceeded 250 ppb only on this one flight. The ozone level exceeded 100 ppb on eight flights, all domestic US routes on planes without ozone converters. The second-highest flight-averaged ozone level was 89 ppb.

Seasonal variation of in-cabin ozone levels on domestic routes without converters is reasonably modeled by a sinusoidal curve that predicts peak-hour levels to be approximately 70 ppb higher in February and March than in August and September. The temporal trend is broadly consistent with expectations, given the seasonal cycle in tropopause height. Episodically elevated (>100 ppb) ozone levels on domestic flights were associated with winter-spring storms that are linked to enhanced exchange between the lower stratosphere and the upper troposphere. All eight of the flights with ozone levels exceeding 100 ppb occurred during January-May.

Peak-hour ozone levels on eight transoceanic flight segments, all on planes equipped with ozone catalysts, were in the range <1.5 to 58 ppb (Figure 3). Instantaneous peak levels (one-minute averages) reached 75 ppb on one of these flights and 50 ppb on three others. The highest flight-average concentration on these eight flights was 25 ppb.

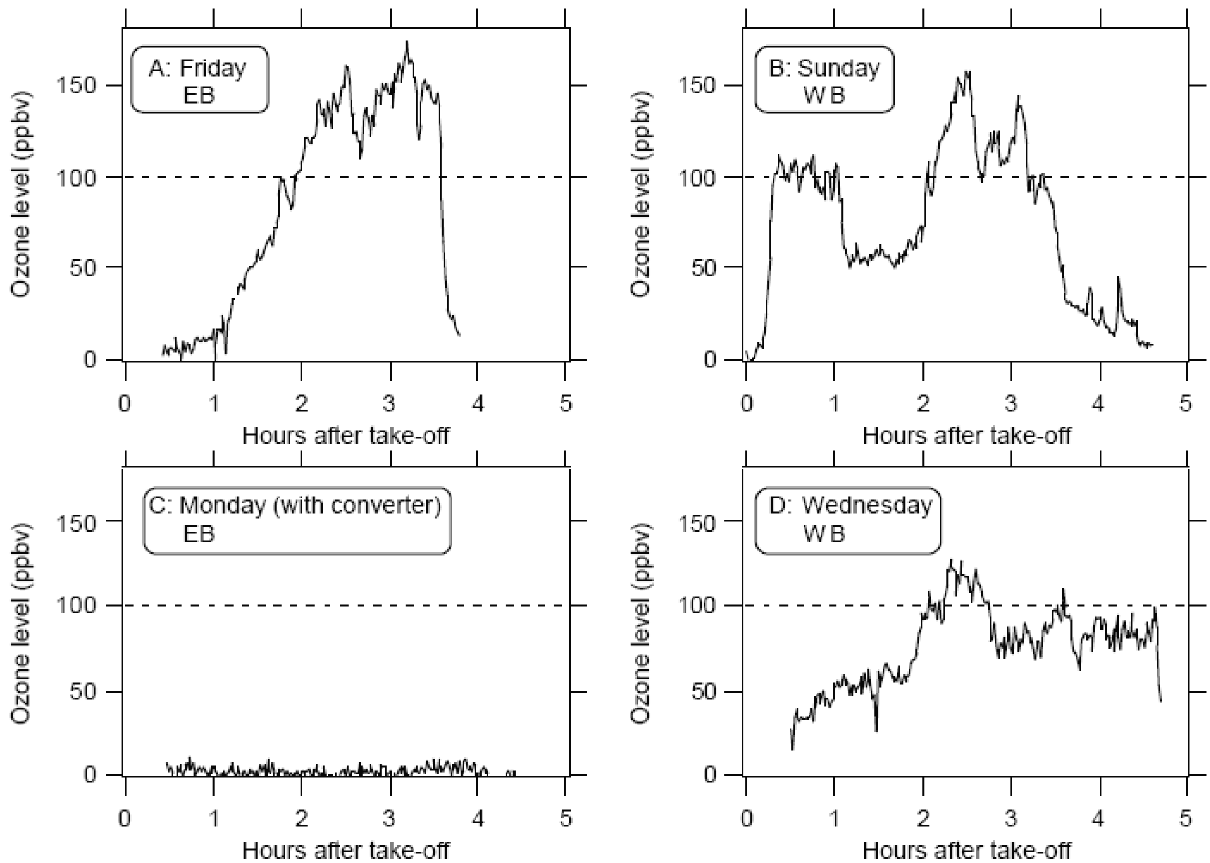

Figure 1. Real-time ozone data from four consecutive domestic transcontinental US flight segments monitored within a 6-day interval in April, arranged chronologically in panels A-D. The direction (EB: eastbound or WB: westbound) is indicated for each segment. Panel C represents data from an aircraft equipped with an ozone converter; the three other flights were aircraft without converters.

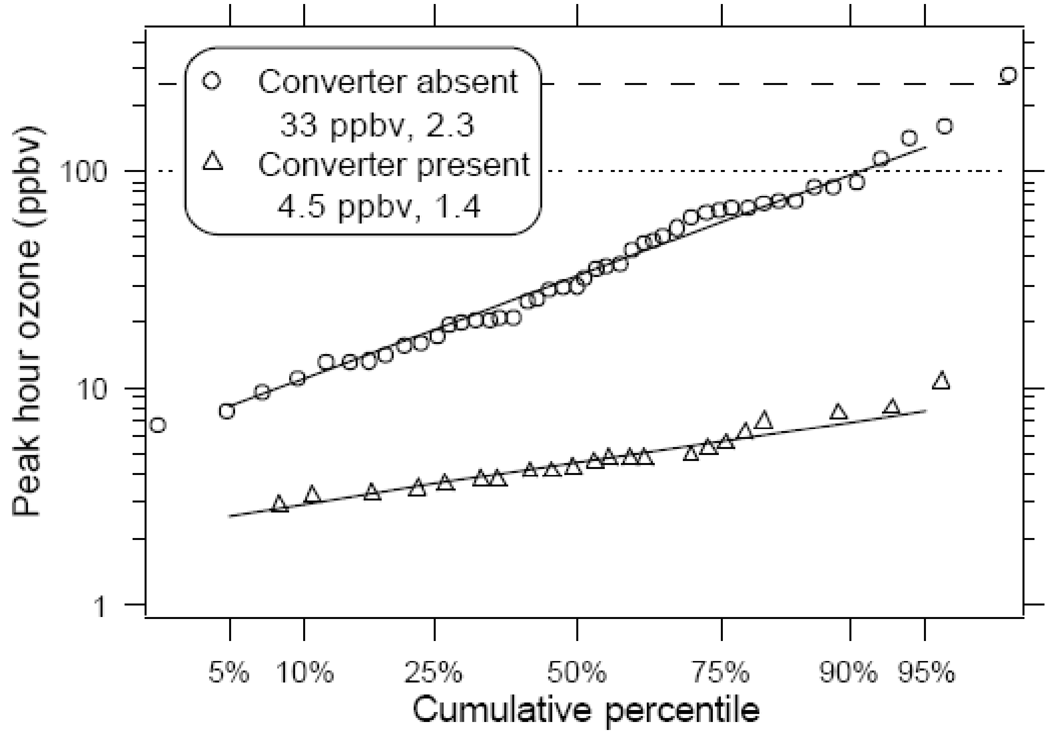

Figure 2. Weighted cumulative distributions of peak-hour ozone levels sampled in passenger cabins on 68 domestic US flight segments. Data are segregated by the presence or absence of an ozone converter. The weighted geometric mean and geometric standard deviation (reported in box), and the lognormal fits using these parameters (straight lines), are presented for each distribution.

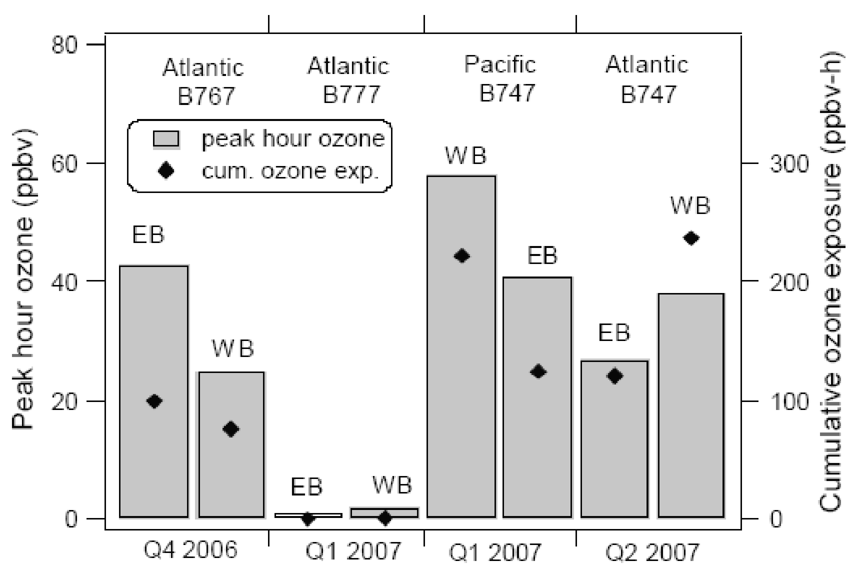

Figure 3. Ozone levels sampled on eight transoceanic flights. The shaded bars represent peak-hour ozone and the diamonds denote cumulative ozone exposure for each flight segment.

Ozone reactions with cabin materials

We measured ozone consumption and byproduct formation on materials commonly found in aircraft cabins under flight-relevant conditions (Coleman et al., 2008). Two series of small-chamber experiments were carried out, with most runs at low relative humidity (10%) and high air-exchange rate (20 air changes per hour). New and used cabin materials (seat fabric, carpet, and plastic) and laundered and worn clothing fabrics (cotton, polyester, and wool) were studied, one at a time. We measured ozone deposition to many material samples, and we measured primary and secondary emissions of volatile organic compounds (VOCs) from a subset of samples. Deposition velocities, reflecting the effective rate of ozone uptake on the fabrics, ranged from 0.06 to 0.54 centimeters per second. Emissions of VOCs were higher with ozone exposure than without ozone in every case. The most commonly detected secondary emissions were saturated aldehydes containing one to ten carbon atoms and also the squalene oxidation products 6-methyl-5-hepten-2-one and acetone. For the compounds measured, summed VOC emission rates in the presence of 55–128 ppb (residual level) ozone ranged from 1.0 to 8.9 millimoles per hour per square meter of material surface. Total byproduct yield ranged from 0.07 to 0.24 moles of volatile product emitted per mole of ozone consumed. Results were used to estimate the relative contribution of different materials to ozone deposition and byproduct emissions in a typical aircraft cabin. The dominant contributor to both was worn clothing fabric, followed by seat fabric. Results indicate that ozone reactions with surfaces substantially reduce the ozone levels in cabin air but also generate volatile byproducts of potential concern for the health and comfort of passengers and crew.

Ozone reaction with permethrin

Permethrin is commonly used in aircraft cabins for disinsection. Theoretical considerations suggested that the reaction of ozone with residual permethrin on cabin surfaces could potentially form phosgene. An assessment that was based on already published evidence about ozone levels and permethrin surface concentrations in aircraft cabins indicated that significant phosgene formation might occur in this setting. Consequently, chamber experiments were designed and executed to investigate whether this chemistry could occur with sufficient speed to cause the production of phosgene at levels that would raise health concerns. A chemical derivatization technique was developed to detect phosgene with a lower limit of detection of 2 ppb. Chamber experiments were conducted with permethrin-coated cabin-relevant materials (glass, carpet, seat fabric, and plastic) exposed to ozone under cabin-relevant conditions: 150 ppb of ozone, 4.5 air changes per hour, <1% relative humidity, and a surface loading of permethrin equivalent to 1.7 micrograms per square centimeter (Coleman et al., 2010). Phosgene emissions were not detected in any of these experiments. The reaction of ozone with permethrin appears to be hindered by the electron-withdrawing chlorine atoms adjacent to the double bond in permethrin. Our experimental results indicate that the upper limit on the reaction probability of ozone with surface-bound permethrin is low, approximately 10^{-7}. This result means that for every ten million collisions of an ozone molecule with a permethrin molecule attached to a surface, no more than one of those collisions, on average, would produce phosgene. Extrapolation by means of material-balance modeling indicates that the upper limit on the phosgene level in aircraft cabins resulting from this chemistry is approximately 1 microgram per cubic meter or 0.3 ppb. It was thus determined that phosgene formation, if it occurs in aircraft cabins, is not likely to exceed relevant, health-based exposure guidelines for this chemical.

Ozone removal in a simulated aircraft cabin

As reported in Tamás et al. (2006), a series of experiments was conducted at the Technical University of Denmark's (DTU) simulated cabin facility, a full-scale mock-up of three rows (21 seats) of a Boeing 767 aircraft (Figure 4).

Figure 4. Section of the simulated B-767 located at the Technical University of Denmark. The facility is equipped with three rows for passengers (21 used seats in all). It also contains used carpet, wall sections and HEPA filters recovered from commercial aircraft. The chamber volume is 28.5 cubic meters.

In the first set of experiments, ozone concentrations were measured concurrently inside the simulated aircraft cabin and in the airstream providing ventilation air to the cabin. Ozone decay rates were also measured after cessation of ozone injection into the supply airstream. By systematically varying the presence or absence of (a) people, (b) soiled T-shirts, (c) aircraft seats and (d) a used HEPA filter, we were able — over the course of 24 experiments — to isolate the contributions of these and other factors to the removal of ozone from the cabin air.

As is apparent from Figure 5, humans are large sinks for ozone. At the same ozone generation rates, ozone levels were much lower when passengers were present than when the cabin was empty. In the case of this simulated aircraft, people (including their exposed skin, hair and clothing) were responsible for almost 60% of the ozone removal occurring within the cabin and recirculation system; respiration can only have been responsible for about 4% of this removal; the aircraft seats removed about 25% of the ozone; the loaded HEPA filter, 7%; and the other surfaces, 10%. (See Figure 6.) Remarkably, a T-shirt that had been slept in overnight and then placed over the seat back removed roughly 70% as much ozone as an entire person, indicating that skin oils are indeed important factors influencing ozone removal in aircraft cabins. With people present, the measured ratio of ozone's concentration in the cabin to that outside the cabin was 0.15-0.21, smaller than levels reported in the literature. The results reinforce the conclusion that the optimal way to reduce people's exposure to both ozone and to the byproducts of ozone-initiated chemistry is to efficiently remove ozone from the aircraft's air supply system.

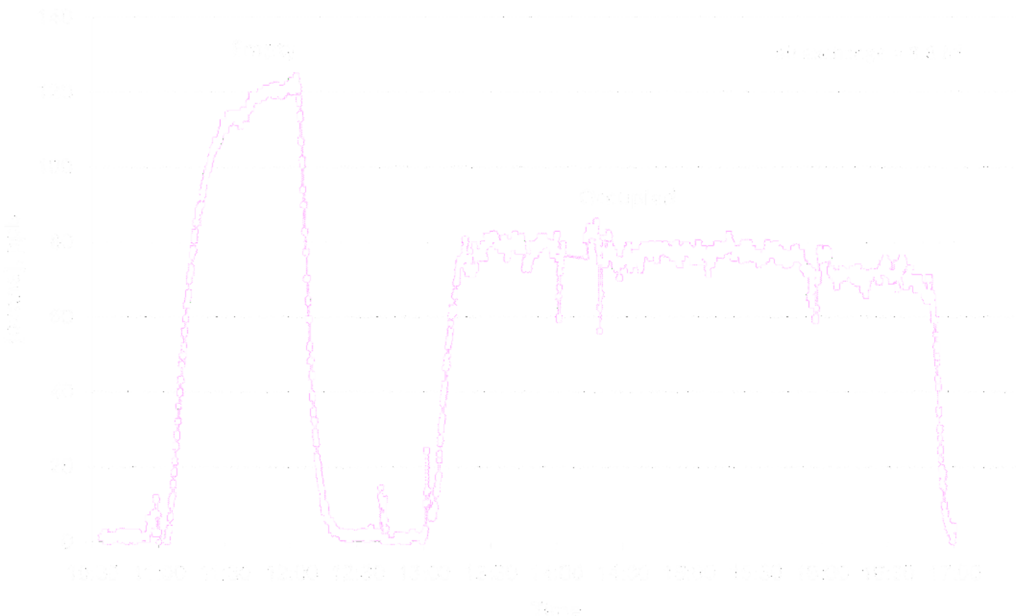

Figure 5. Ozone levels with the simulated B-767 when the cabin was empty and when 16 passengers were present; the ozone generation rate was the same for both conditions.

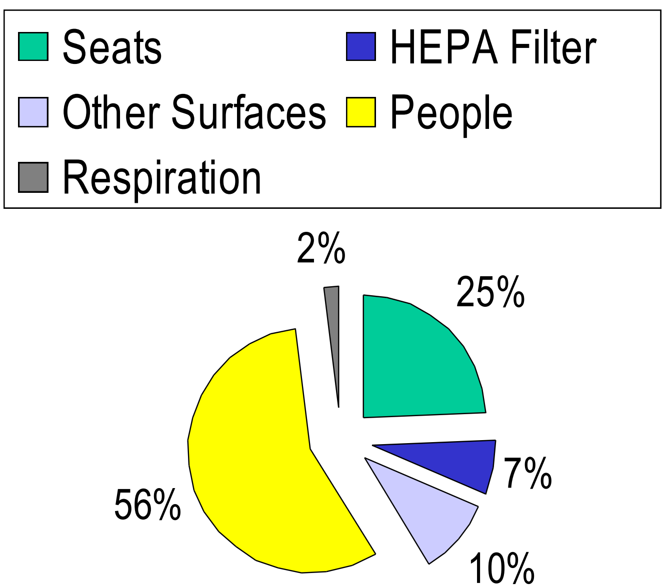

Figure 6. Fraction of ozone removed by the various sinks within the simulated section of the passenger cabin of a Boeing 767.

Ozone reaction with cabin materials and occupants in a simulated aircraft cabin

In a second set of experiments at DTU, we used multiple analytical methods to characterize the gas-phase products formed when ozone was added to cabin air during simulated four-hour flights that were conducted in the reconstructed section of a B-767 aircraft containing human occupants (Weschler et al., 2007). Two separate groups of 16 females were each exposed to four conditions: low air exchange (4.4 air changes per hour) and low (< 2 ppb) ozone; low air exchange and elevated (61-64 ppb) ozone; high air exchange (8.8 air changes per hour) and low (< 2 ppb) ozone; and high air exchange and elevated (73-77 ppb) ozone. The addition of ozone to the cabin air increased the levels of identified byproducts from ~70 to 130 ppb at the lower air-exchange rate and from ~30 to 70 ppb at the higher air-exchange rate (Figure 7).

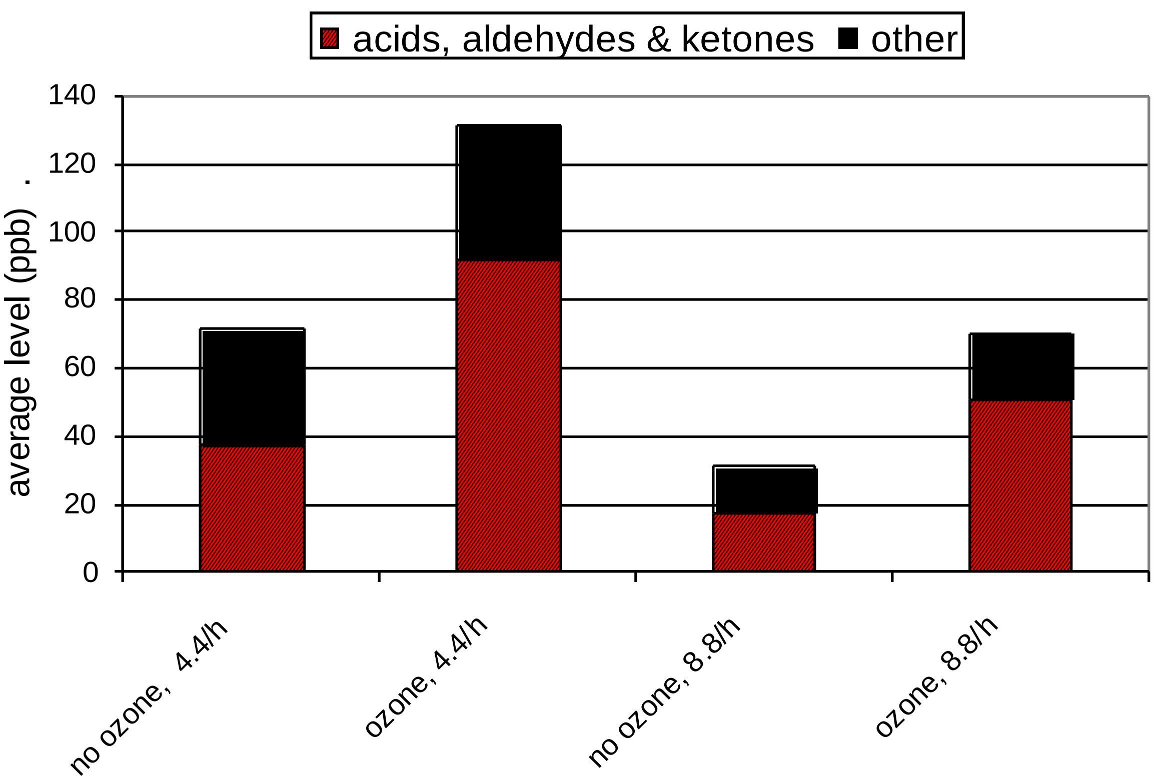

Figure 7. Sum of the organic compounds detected in the cabin air for the four different conditions indicated on the horizontal axis.

Most of the increase was attributable to acetone, nonanal, decanal, 4-oxopentanal (4-OPA), 6-methyl-5-hepten-2-one (6-MHO), formic acid, and acetic acid, with 0.25-0.30 moles of quantified volatile product generated per mole of ozone consumed. Figure 8 shows the yields of the major ozone-derived products at both the low and high air exchange rates. Several of these compounds reached levels above their reported odor thresholds. A recent study conducted by researchers at NIOSH indicates that in vitro exposure of pulmonary epithelial cells to 4-OPA results in expression of various inflammatory markers (Anderson et al., 2010). That finding is suggestive that exposure to 4-OPA might have associated health risks. Related research has further advanced the understanding of ozone's reactions with human skin lipids (Wisthaler and

Weschler, 2010). In our research, most of the byproducts of ozone-initiated chemistry were derived from surface reactions with occupants and their clothing, consistent with the inference that occupants were responsible for the removal of more than 55% of the ozone in the cabin.

The observations made in this study have implications for better understanding the health hazards of being exposed to ozone and its byproducts in aircraft cabins and also in other indoor settings. Whenever human beings and ozone are simultaneously present, one anticipates production of and increased human exposure to acetone, nonanal, decanal, 6-MHO, geranyl acetone, and 4-OPA. To the extent that these byproducts pose health risks, being exposed to a given level of ozone in a more densely occupied space will tend to pose higher health risks than in a less densely occupied space owing to the concomitant increase in exposure to the byproducts of ozone-initiated reactive chemistry.

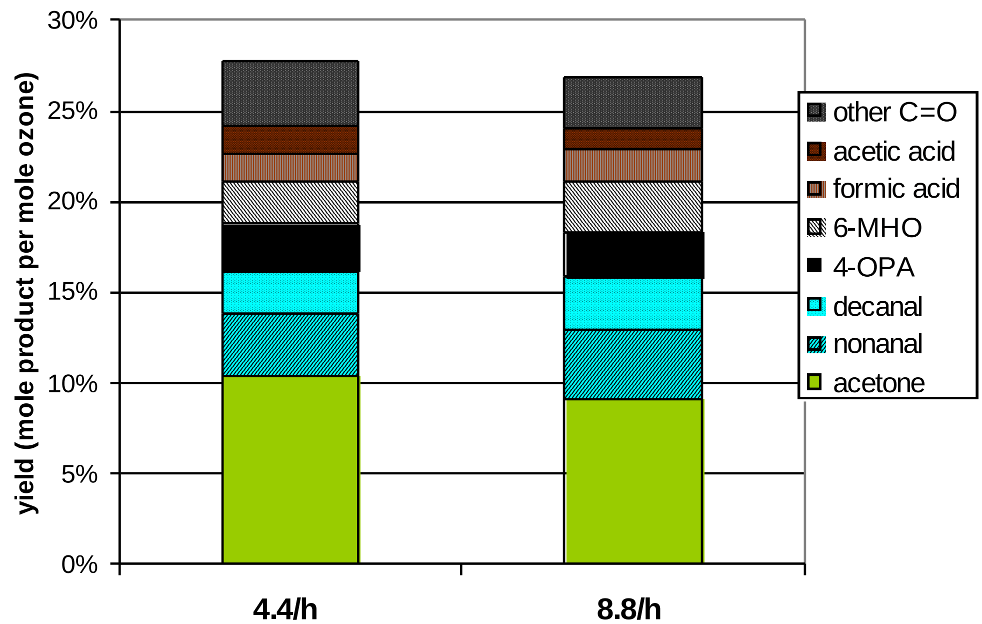

Figure 8. The yields of ozone-derived products were consistent for the experiments conducted at two different air exchange rates – 4.4 per hour (4.4/h) and 8.8 per hour (8.8/h).

Impact of ozone and ozone oxidation products on occupants' self-reported symptoms

In a third set of experiments conducted in DTU's reconstructed section of a B-767 aircraft cabin, Strøm-Tejsen et al. (2008) evaluated human subjects' symptoms related to air quality and comfort during simulated four-hour flights identical to those described in the previous subsection. Twenty-nine female subjects, age 19–27 years, were split into two groups. Each group was exposed to four conditions: two levels of ozone (less than 2 ppb and 60–80 ppb) were utilized at each of two outside air supply rates (4.4 and 8.8 air changes per hour, corresponding to 2.4 and 4.7 liters of ventilation air per second per person, respectively). The subjects completed questionnaires to provide subjective assessments of air quality and symptoms typical of complaints experienced during actual flight. Additionally, the subjects' visual acuity, nasal peak flow and skin dryness were measured. Based on self-recorded responses after 3.25 hours in the simulated cabin, the subjects judged the air quality (Figure 9) and eleven symptoms to be worse for the elevated ozone condition compared to the low ozone condition. Assessments for headache, eye achiness, nasal irritation and skin dryness are shown in Figure 10. Not shown, but also adversely impacted by exposure to ozone and ozone-derived byproducts, are assessments for odor, lip dryness, other eye complaints, dizziness, mental tension, and claustrophobia. Taken together, these results indicate that ozone and the products of ozone-initiated chemistry are contributing to such complaints. The findings imply that such complaints would be markedly reduced in situations where ozone is effectively removed from the ventilation air supplied to an aircraft cabin.

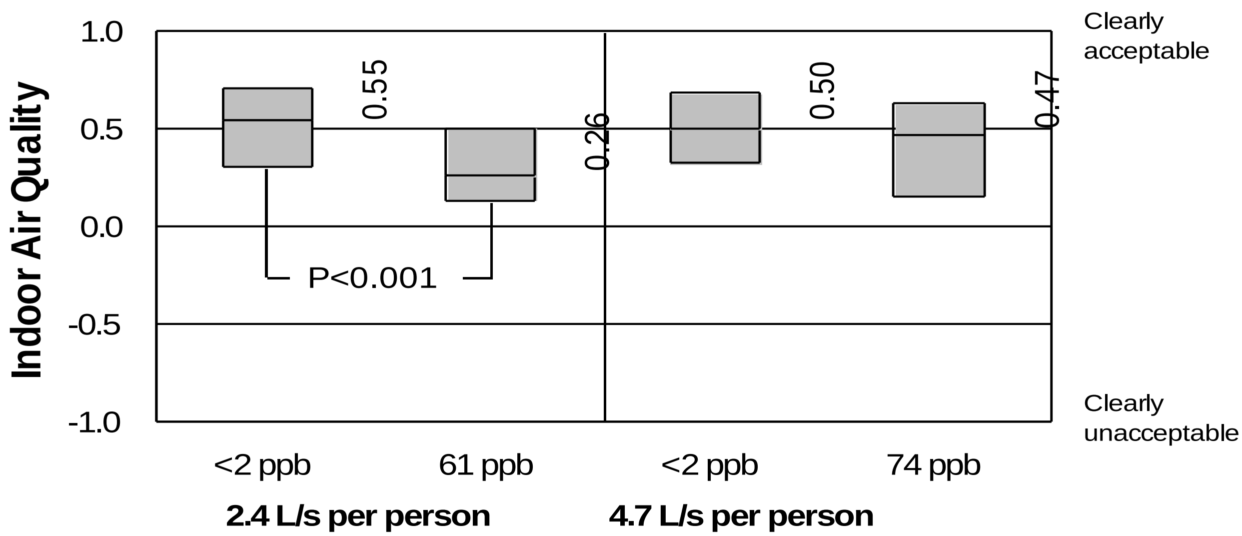

Figure 9. Subjective assessments by cabin occupants of indoor air quality for each of the four conditions (low air exchange, low O_3; low air exchange, 61 ppb O_3; high air exchange, low O_3; high air exchange; 74 ppb O_3) after passengers had been on the simulated flight for 3.25 hours. Each box represents the interquartile range, and the horizontal line dividing the box is the median, whose value appears to the right; all P-values are one-tail.

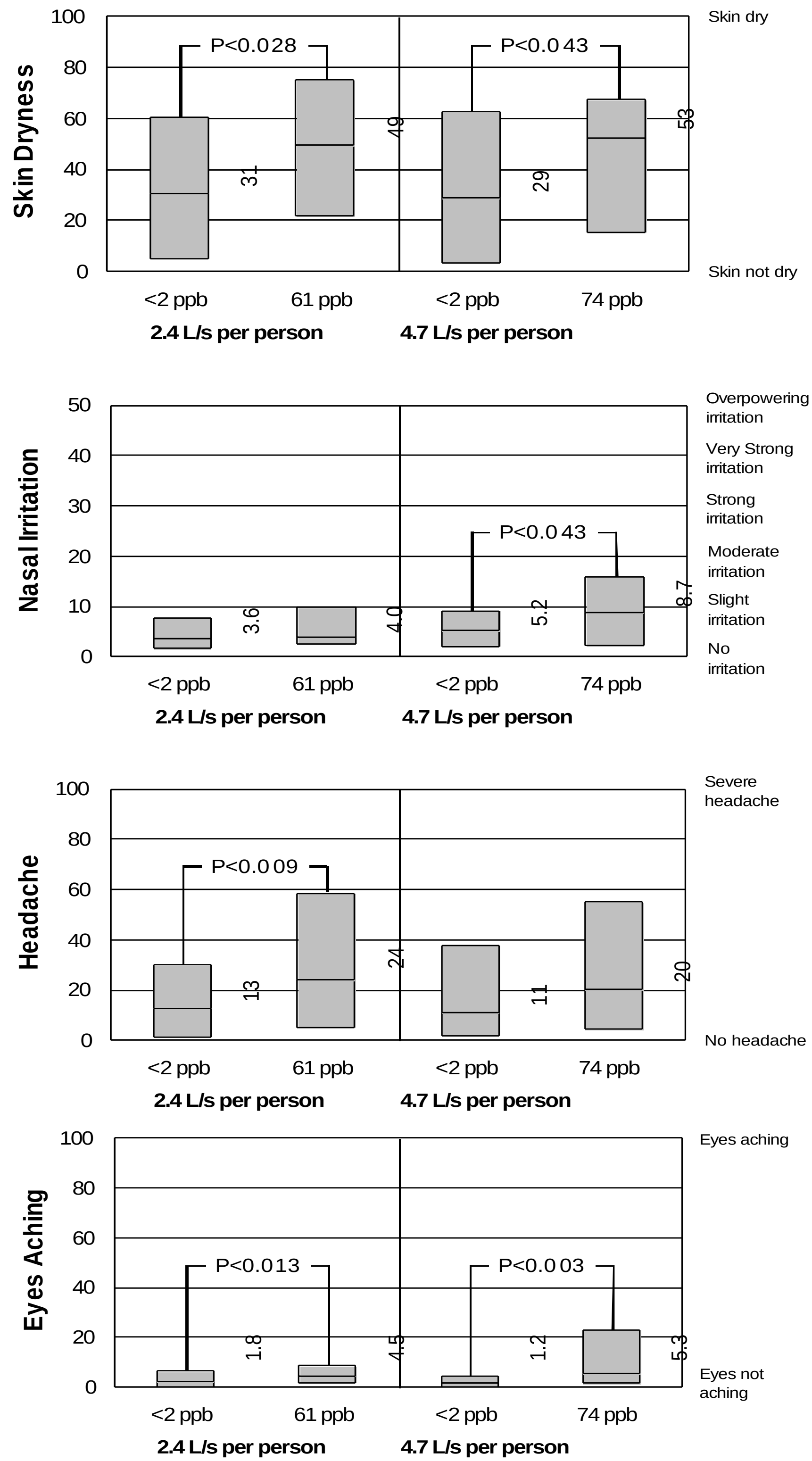

Figure 10. Subjective assessments by cabin occupants of headache, eye complaints, nasal complaints and perceived skin dryness for each of the four conditions, which are defined by ozone level and ventilation rate. See Figure 9 for further details.

CONCLUSIONS

The research undertaken by the ACER/RITE research team on ozone in aircraft cabins has produced an interconnected set of results that significantly advance our understanding about the levels of ozone and its reaction byproducts to which passengers and crew are exposed during flight along with some important information about the consequences of such exposures. Measurements on commercial flights found that ozone levels can be moderate to high on domestic flights without ozone converters. We also found that ozone can reach moderate levels in the cabin during transoceanic flights even though the planes are equipped with converters. These levels are compliant with the current requirements of the ozone FARS. However, elevated ozone levels in aircraft cabins take on amplified concern given that the US national ambient air quality standard for ozone has become more stringent over time. The standard is presently 75 ppb measured over 8 hrs and a lower standard (down to 60 ppb as the peak hourly average) has been recommended (Federal Register, Vol. 75, No. 11, 2938, 19 Jan 2010). Furthermore, in the event of high ambient air pollution events, people with respiratory health impairments are recommended to take shelter indoors where the ozone is typically only 20-70% of the outdoor level (Weschler, 2000). In an aircraft cabin with elevated ozone levels, passengers and crew are exposed without any knowledge and there is no place for someone with respiratory health impairment to take shelter.

When ozone is present within the cabin, various oxidation reactions occur, mainly on surfaces including those associated with the passengers themselves. Laboratory experiments conducted in small chambers confirmed that ozone reacts with numerous cabin materials, including clothing, yielding acetone, 6-MHO and a series of aldehydes. Simulated flight experiments conducted with human subjects in a reconstructed section of a B-767 aircraft cabin identified the same ozone derived byproducts as those measured in the laboratory experiments, as well as dicarbonyls, organic acids and other oxidation products. Strikingly, in these simulated flights, more than half of the net ozone removal within the cabin was attributable to its reactions with cabin occupants. The identities of the reaction products indicate that ozone reacts rapidly with skin lipids on exposed skin, hair and clothing. The reactions have substantial influence on the levels of these byproducts in cabin air. On a positive note, laboratory studies indicate that if phosgene is formed via the reaction of ozone with residuals of permethrin (a commonly applied disinsectant), the resulting levels of this compound are very likely to be lower than appropriate health-based standards.

Self-assessed symptoms during simulated four-hour flights with and without ozone indicate that ozone-oxidation products, in addition to ozone itself, may contribute to the complaints of mucous membrane irritation (e.g., irritated eyes and throat) commonly reported by the flying public. In addition, certain ozone oxidation products (e.g., formaldehyde, acrolein, and some dicarbonyls) are known or suspected of adversely affecting human health at elevated levels. Whether and to what extent exposures to the moderate-to-high ozone levels that occur on some flights contribute to acute or long-term health effects remains an open question.

A comparison of ozone levels on domestic flights with and without ozone converters makes clear that converters can substantially reduce exposures of passengers and crew to ozone, and, by inference, to the byproducts of ozone-initiated chemistry. However, we also found moderate ozone levels during some transoceanic flights on planes that were equipped with ozone converters. This evidence supports a conclusion that while ozone converters can be effective in controlling levels in cabin air, their presence alone does not ensure low levels.

IMPLICATIONS

The results derived from the ACER/RITE ozone project have these implications:

- Health and safety evaluations for the aircraft cabin environment should consider the products of ozone-initiated chemistry in addition to ozone itself. Exposure to certain ozone-derived products may have meaningful consequences for the health and well-being of passengers and crewmembers, especially on flights with moderate to high ozone concentrations.
- It would be appropriate for FAA to re-evaluate the FARs for ozone to determine whether they are adequately protective of the health of passengers and crew. Concerns arise for the following reasons:
  - The current FARs do not reflect additional knowledge, accrued since 1980, regarding direct adverse health effects of ozone exposure.
  - The current FARs do not reflect ozone chemistry and resultant exposures of passengers and crew to the byproducts of ozone-intiated chemistry.
  - The flying population may include more individuals who are vulnerable to the adverse effects of air pollutant exposure than was the case before 1980.
- Adopting as a standard practice the use of ozone converters on all commercial flights may be warranted. This practice appears to be common in northern Europe, based on conversations with carriers based in this region.
- A program of random periodic testing of in-service ozone converters could reduce exposures that result from degraded or poisoned catalysts.
- Future studies could fruitfully investigate improved technologies for ozone control in aircraft cabins. Examples include activated carbon filters to remove ozone and ozone-derived products from recirculating air in aircraft cabins and methods to prevent poisoning of in-service converters, which would extend their useful life.

PUBLICATIONS DERIVED FROM THIS PROJECT

The following journal articles report on the detailed research investigations conducted as part of the ACER/RITE ozone project for the period 2004-2010, as summarized in this technical report. Copies of these articles are available on request from WW Nazaroff (nazaroff@ce.berkeley.edu) or CJ Weschler (weschlch@umdnj.edu).

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