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Indoor Air Quality Implications of Germicidal 222 nm Light

Victoria Barber^{1,2§*}, Matthew B. Goss^{1§}, Lesly J. Franco Deloya⁴, Lexy N. LeMar⁵, Yaowei Li⁶, Erik Helstrom¹, Manjula Canagaratna⁷, Frank N. Keutsch^{6,8,9}, Jesse H. Kroll^{1,5*}

¹Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States

²now at Department of Chemistry and Biochemistry, University of California Los Angeles, Los Angeles, California, 90095

⁴Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States

⁵Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States

⁶John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, United States

⁷Center for Aerosol and Cloud Chemistry, Aerodyne Research Incorporated, Billerica, Massachusetts 01821, United States

⁸Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts 02138, United States

⁹Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts 02138, United States

[§]V.P.B. and M.B.G. contributed equally to this work *Corresponding Authors

Email: vbarber@chem.ucla.edu

Phone: 424-259-5198

University of California, Los Angeles

Department of Chemistry and Biochemistry

607 Charles E. Young Drive, East, YH3077B

Los Angeles, CA 90095

Email: jhkroll@mit.edu

Phone: 617-253-2409

Massachusetts Institute of Technology

Department of Civil and Environmental Engineering

77 Massachusetts Avenue, 48-331

Cambridge, MA 02139

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34

35

Abstract

36 One strategy for mitigating the indoor transmission of airborne pathogens, including the SARS-
37 CoV-2 virus, is irradiation by germicidal UV light (GUV). A particularly promising approach is
38 222 nm light from KrCl excimer lamps (GUV₂₂₂); this inactivates airborne pathogens and is
39 thought to be relatively safe for human skin and eye exposure. However, the impact of GUV₂₂₂
40 on the composition of indoor air has received little experimental study. Here, we conduct
41 laboratory experiments in a 150 L Teflon chamber to examine the formation of secondary
42 species by GUV₂₂₂. We show that GUV₂₂₂ generates ozone (O₃) and hydroxyl radicals (OH),
43 both of which can react with volatile organic compounds to form oxidized volatile organic
44 compounds and secondary organic aerosol particles. Results are consistent with a box model
45 based on known photochemistry. We use this model to simulate GUV₂₂₂ irradiation under more
46 realistic indoor air scenarios, and demonstrate that under some conditions, GUV₂₂₂ irradiation
47 can lead to levels of O₃, OH, and secondary organic products that are substantially elevated
48 relative to normal indoor conditions. The results suggest that GUV₂₂₂ should be used at low
49 intensities and in concert with ventilation, decreasing levels of airborne pathogens while
50 mitigating the formation of air pollutants.

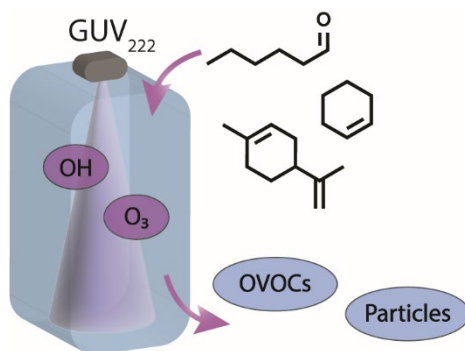
51

Synopsis

52 Germicidal ultraviolet light at 222 nm (GUV₂₂₂) can inactivate airborne pathogens, but has an
53 unknown effect on indoor air quality. This study shows that GUV₂₂₂ forms ozone and hydroxyl
54 radicals, forming oxidized byproducts and fine particulate matter.

55

TOC Graphic



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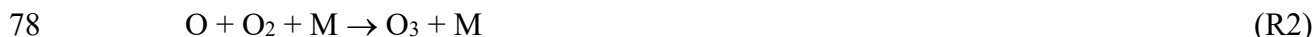
57

58 Introduction

59 The COVID-19 pandemic has highlighted the critical need to develop and implement strategies
60 to decrease the transmission of airborne pathogens. Approaches include both source control
61 (isolation, masking), and remediation (ventilation, air cleaning). One approach that has received
62 substantial attention is the use of germicidal ultraviolet (GUV) light, which inactivates airborne
63 pathogens. This approach goes back decades,¹ traditionally using 254 nm light from mercury
64 lamps. Since light of this wavelength can cause damage to skin and eyes, care must be taken to
65 minimize occupants' direct exposure to the GUV light.^{2,3}

66 A promising new approach to GUV-based air cleaning is the use of KrCl excimer lamps, which
67 emit at 222 nm (GUV₂₂₂).⁴ In contrast to 254 nm GUV, GUV₂₂₂ does not penetrate deeply into
68 biological materials. Therefore, while GUV₂₂₂ is effective at inactivating airborne viruses and
69 bacteria, it is unable to penetrate the outer layer of dead skin cells or the ocular tear layer.⁵ 222
70 nm light is hence less likely to reach and damage living human tissues, offering the potential for
71 air disinfection throughout an entire, occupied indoor space.

72 A risk with GUV₂₂₂-based air cleaning, as with all types of air cleaning that rely on chemical
73 and/or photolytic processes, is the potential formation of unwanted secondary byproducts.^{6,7} A
74 particular concern with GUV₂₂₂ is the formation of ozone (O₃), a harmful air pollutant that acts
75 as a strong oxidant and can lead to respiratory distress when inhaled.⁸ O₃ is formed by the UV
76 photodissociation of oxygen (R1-2)



79 Since absorption of UV by O₂, and hence O₃ production, is strongest at short wavelengths,⁹
80 manufacturers of KrCl lamps have added filters to block wavelengths shorter than 222 nm. But
81 since O₂ absorbs weakly even at 222 nm ($\sigma = 4.09 \times 10^{-24} \text{ cm}^2$),⁹ all KrCl lamps have the potential
82 to generate ozone, possibly in concentrations higher than is typically found indoors.¹⁰

83 Ozone generated indoors, in addition to posing a direct health hazard, can set off a cascade of
84 chemical reactions that can also affect indoor air quality. Ozone reacts directly with alkenes,
85 present both in the air and on indoor surfaces, forming a range of oxidized volatile organic
86 compounds (OVOCs)^{11,12} and secondary organic aerosol (SOA),¹³ which may negatively impact
87 human health.¹⁴⁻¹⁷ O₃ chemistry can also lead to the formation of the hydroxyl radical (OH), an
88 even stronger oxidant. This occurs both through reactions with alkenes, which are known to form
89 OH (R3),^{11,18} and through O₃ photolysis (R4-5)¹⁹:



93 Any increased levels of indoor O₃ from GUV₂₂₂ would likely enhance the importance of these
94 reactions, leading to higher levels of indoor OH. This includes O₃ photolysis (R4-5), which is the

95 main source of OH in the troposphere, but under normal conditions is negligible in indoor
96 environments, due to the lack of low-wavelength UV. Any OH radicals formed from R3-5 may
97 then oxidize a wide range of organic species and contribute further to the formation of OVOCs
98 and SOA.

99 GUV₂₂₂ therefore has the potential to dramatically affect the chemical composition of indoor air,
100 and may lead to the formation of chemical species that are hazardous to human health. However,
101 the extent and nature of this impact remains quite uncertain, even as GUV₂₂₂ is being deployed in
102 indoor spaces.²⁰ Two very recent experimental studies^{21,22} demonstrate O₃ production from
103 GUV₂₂₂, but these do not examine the overall effects on indoor air quality (including the
104 production of OH, OVOCs, and SOA) by GUV₂₂₂. To our knowledge the only published work
105 that has is a box-modeling study by Peng et al.²³ That work predicted that 222 nm irradiation
106 could lead to elevated levels of O₃ and other secondary species relative to non-illuminated
107 conditions, especially under low-ventilation conditions.

108 Here we describe a series of laboratory experiments aimed at better understanding the effects of
109 222 nm irradiation on indoor air quality. The goal of this work is to gain process-based insight
110 into how such irradiation affects the chemical composition of the air; we do not examine the
111 effects of GUV₂₂₂ light on pathogens, indoor surfaces, or human health. These experiments,
112 which use a flow-through Teflon chamber coupled to a range of real-time analytical instruments,
113 explore the effects of several parameters relevant to indoor air processes (VOC level, ventilation,
114 222 nm light intensity, and humidity) on the generation of oxidants and secondary products.
115 Results are then used to validate a simple chemical model of GUV₂₂₂ irradiation of indoor air,
116 which in turn is used to examine the interplay between GUV₂₂₂ and ventilation in controlling the
117 levels of ozone and other chemical species in the indoor environment.

118 **Materials and Methods**

119 *Experimental Methods*

120 Experiments are carried out in a 150 L Teflon chamber, outfitted with inlet ports (for
121 introduction of clean air and trace species) and outlet ports (for sampling by analytical
122 instrumentation). Clean dry air from a zero-air generator (Aadco Model 737) is introduced into
123 the chamber either directly, or after passing through a bubbler filled with Milli-Q water. Mass
124 flow controllers are used to adjust these two flows to control chamber relative humidity. Dilution
125 rates are measured using acetonitrile, an inert dilution tracer ($8.0 \times 10^{-4} - 9.7 \times 10^{-4} \text{ s}^{-1}$, 2.9 – 3.5
126 ACH). Most experiments are conducted at 22°C and ~25% RH, while “higher RH” experiments
127 are carried out at ~45% RH.

128 GUV₂₂₂ light is provided by a single filtered KrCl excimer lamp (Ushio, Care222 B1 Illuminator,
129 peak emission at 222 nm), centered directly above the Teflon chamber. Average fluence rate
130 within the chamber is ~45 $\mu\text{W}/\text{cm}^2$, estimated geometrically from the lamp intensity profile
131 provided by the manufacturer²⁴ (see Section S1.1). The indirect estimation of the lamp intensity
132 is a limitation of this work, but the agreement between modeled and measured ozone production
133 (see Results and Discussion, below) indicates that it is reasonably accurate. More quantitative
134 estimates of UV fluence rate and its relationship to O₃ generation are available in recent work by

135 Peng et al.²² and Link et al.²¹ Most experiments are carried out at the full light intensity. For “low
136 light” experiments, the lamp emission is attenuated by several layers of plastic, achieving a
137 factor of ~5 reduction in intensity (determined by the reduction in the steady-state O₃
138 concentration which is assumed to scale linearly with average UV fluence).^{21,22} For the “O₃-
139 only” experiments, the light is left off, and O₃ is introduced via a Pen-Ray ozone generator, with
140 a steady-state O₃ concentration matching that of the GUV₂₂₂ experiments (~100 ppb). Reaction
141 conditions for each experiment are described in detail in Table S1.

142 For all VOC oxidation experiments, the chamber is first allowed to reach a steady-state
143 concentration of O₃, either via 222 nm irradiation or direct addition. This is followed by the
144 addition of 5.3 ppb of acetonitrile (the dilution tracer) (C₂H₃N, 99.8%, Sigma Aldrich), 1.2 ppb
145 of 1-butan-d₉-ol (intended as an OH tracer, but not used here due to the relatively low OH
146 levels) (C₄D₉OH, 98%, Cambridge Isotope Laboratories, Inc.), and 120 ± 11 μg m⁻³ of
147 ammonium sulfate particles (to act as seed particles for any SOA production) ((NH₄)₂SO₄,
148 ≥99%, Sigma Aldrich). Finally, the relevant VOC (10 or 100 ppb) is added to chamber. VOCs
149 used in this study include hexanal (C₆H₁₂O, 98%, Sigma Aldrich), cyclohexene (C₆H₁₀, 99%,
150 Sigma Aldrich), and (R)-(+)-limonene (C₁₀H₁₆, 97%, Sigma Aldrich). Reactant addition
151 procedures are described in greater detail in Section S1.2. Because the oxidants are already
152 present in the chamber, oxidation begins immediately, so VOC injection is taken as t = 0.

153 Real-time measurements of gas- and particle-phase composition in the chamber are conducted using a
154 suite of analytical instruments. Ozone is measured by a UV absorption monitor (2BTech). NO_x is
155 monitored using a chemiluminescence NO-NO₂-NO_x analyzer (Thermo Fisher Scientific) and was below
156 the instrument detection limit in all experiments. Reactant VOC and OVOC products are monitored
157 using a Vocus proton transfer-reaction mass spectrometer (PTR-MS, ToFwerk, Aerodyne Research,
158 Inc.²⁵), and an ammonium chemical ionization mass spectrometer (NH₄⁺ CIMS, modified PTR3, see
159 Zaytsev et al.²⁶). Particle concentration and composition are measured using a scanning mobility particle
160 sizer (SMPS, TSI) and an aerosol mass spectrometer (AMS, Aerodyne Research, Inc.²⁷). Analytical
161 instruments are summarized in Table S2. Gas-phase mass spectrometric data is background-subtracted
162 and corrected for dilution. The analysis does not account for variations in detection efficiencies, which
163 may be substantial,²⁶ and we therefore report relative signals, which are unaffected by such calibration
164 uncertainties, rather than absolute concentrations. Particle-phase data is corrected for dilution and wall
165 losses by normalizing to the ammonium sulfate seed particle concentration. Data analysis and
166 quantification approaches are described in more detail in Section S1.3.

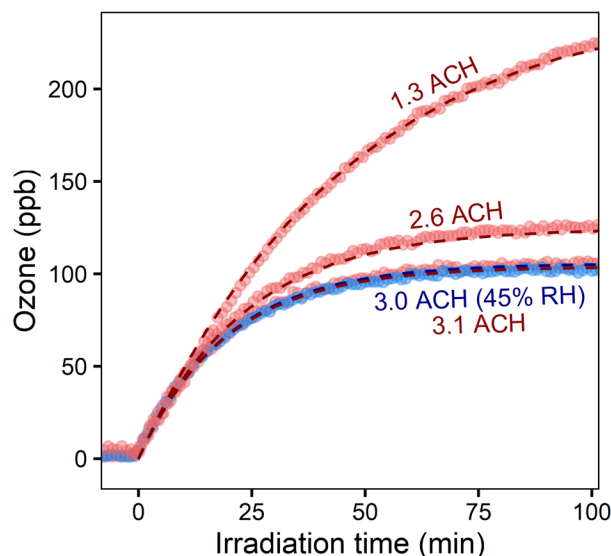
167 **Results and Discussion**

168 *Ozone production*

169 The production of ozone by 222 nm light is examined via the irradiation of clean chamber air.
170 Figure 1 shows results from four representative irradiation experiments, run at different
171 ventilation rates (1.3 to 3.1 air changes per hour (ACH)) and relative humidities (25%-45%). O₃
172 production is observed to occur immediately when the lights are turned on. O₃ levels increase
173 quickly at first, eventually leveling off to a steady-state value, in which photolytic production is
174 balanced by removal by outflow. The O₃ production rate is measured at 324 ± 18 ppb hr⁻¹, in
175 reasonably good agreement with previous measurements²² when differences in average GUV₂₂₂

176 fluence rate are considered (see Section S3.1). The steady-state O₃ concentration is independent
177 of relative humidity, and inversely proportional to ventilation rate (Figure S3).

178 Dashed lines in Figure 1 denote O₃ concentrations predicted from a simple box model. This
179 model includes O₂ photolysis (R1-2), O_x-HO_x chemistry, and dilution (See Table S3 for rate
180 constants and photochemical parameters^{9-11,28-32}). Model parameters (e.g., light intensity, air-
181 exchange rate, and RH) are matched to each experiment. O₃ deposition, which is likely small on
182 Teflon surfaces, is not included. The model accurately predicts measured O₃ levels, indicating
183 that the processes describing ozone levels (formation from O₃ photolysis at 222 nm, loss by
184 outflow) are well-captured by the simple model.

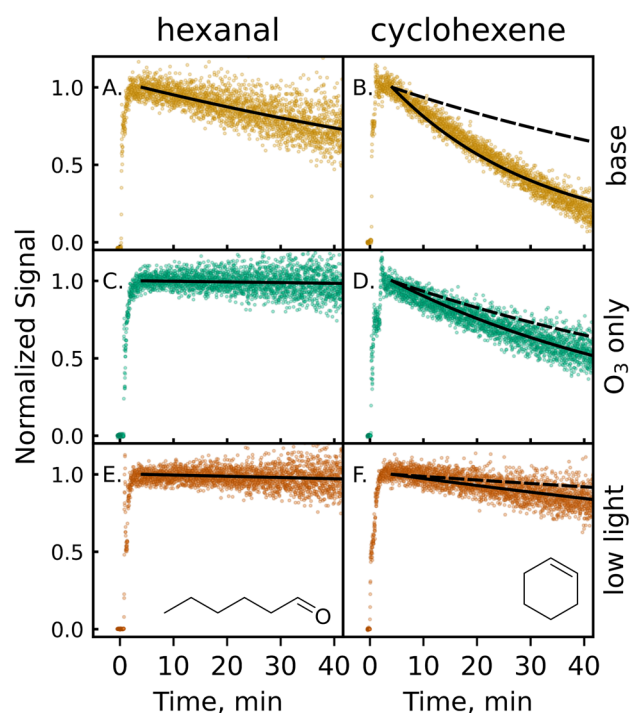


185
186 *Figure 1:* Observed ozone production for clean-chamber irradiation experiments. Measurements
187 agree well with the predictions from the simple box model (dashed lines) across a range of
188 ventilation rates and relative humidities. Measurements shown in red are taken at 25% RH.

189
190 *Decay of VOCs upon 222 nm irradiation.*

191 In a second set of experiments (Table S1), VOCs are added to the irradiated chamber after O₃
192 levels reach steady state. Experiments center on two VOCs: hexanal, a C₆ compound that reacts
193 only with OH, and cyclohexene, a C₆ compound that reacts with both OH and O₃. VOC decays
194 are shown in Figure 2. Negligible change in O₃ concentration is observed upon introduction of
195 10 ppb of VOC; when 100 ppb of cyclohexene is introduced, a small O₃ depletion (~4.3 ppb) is
196 observed.

197



198

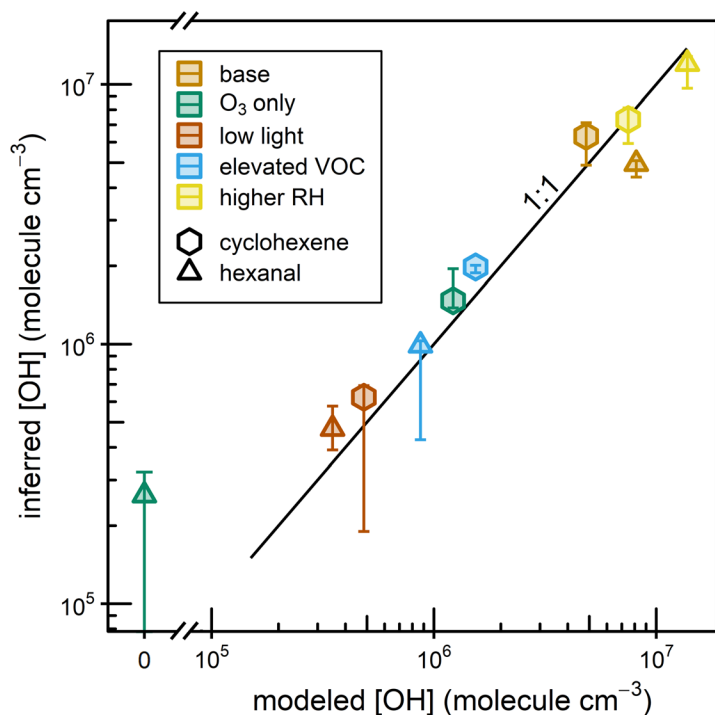
199 *Figure 2:* Normalized decays of two VOCs (hexanal and cyclohexene) after introduction to the
 200 *GUV*₂₂₂-irradiated chamber (see also Figure S4). Time = 0 refers to when the VOC was injected
 201 into the chamber. Traces are background- and dilution-corrected, so observed decays are from
 202 oxidative loss only. Details of each experimental condition (base, O₃ only, low light) are given in
 203 the text and Table S1. Solid black lines denote single-exponential fits to the observed decays;
 204 dashed black lines show the expected decay of cyclohexene from reaction with O₃ only.²⁸

205

206 Under “base conditions” (10 ppb VOC precursor, 222 nm light, ~25% RH) (Figure 2AB), the
 207 concentrations of both hexanal and cyclohexene decrease after being introduced to the irradiated
 208 chamber. Concentrations are corrected for dilution; losses by direct photolysis and uptake to
 209 surfaces are expected to be minimal (see Section S3.2). Therefore, decays indicate oxidative loss
 210 only. This oxidation cannot be explained by O₃ alone. Hexanal does not react with O₃ – a very
 211 small decay of hexanal is attributed to minor, non-oxidative loss pathways (see SI). While
 212 cyclohexene does react with O₃, its decay is far faster than what can be attributed to the O₃
 213 reaction (dashed line). Indeed, for experiments in which the *GUV*₂₂₂ light is off and VOCs are
 214 exposed to the same levels of O₃ as in the irradiated case (Figure 2CD), the hexanal does not
 215 decrease at all, and cyclohexene decays far less than in the irradiation case, at a rate consistent
 216 with reaction with O₃ (plus a small contribution from OH generated by the ozonolysis reaction,
 217 reaction R3). This observed “excess reactivity” (the difference in observed decays and decays
 218 expected from O₃ reaction alone) indicates that *GUV*₂₂₂ irradiation generates not only O₃ but
 219 other oxidants as well.

220 Additional experiments carried out under a range of reaction conditions provide evidence that
 221 these additional oxidants are OH radicals, formed from reactions 3-5. For example, experiments
 222 with the 222 nm fluence rate attenuated substantially ($\sim 9 \mu\text{W cm}^{-2}$, Figure 2EF) exhibit VOC
 223 decay rates that are much slower compared to those under base conditions. This attenuation is
 224 assumed to decrease steady-state O_3 concentrations proportionally. However, the observed
 225 excess reactivity disproportionately decreases, by approximately an order of magnitude. This is
 226 consistent with OH formation, which depends on the photolysis of both O_2 and O_3 , as well as (in
 227 the case of cyclohexene) the ozonolysis reactions. The dependence of decays on other
 228 experimental parameters, such as VOC concentration and relative humidity, are also consistent
 229 with OH production from GUV_{222} lights; this is discussed in detail in Section S3.3.

230 We estimate average OH levels in all experiments using an exponential fit to the VOC timeseries
 231 and known OH rate constants.^{29,30} For cyclohexene experiments, average measured $[\text{O}_3]$ and the
 232 $\text{O}_3 + \text{cyclohexene}$ rate constant are included in the fit to account for excess reactivity. The range
 233 of $[\text{OH}]$ measured in each experiment is calculated by applying the same exponential fits to a
 234 rolling 15-minute window (see Section S3.4 for more details). We also calculate OH levels using
 235 our simple box model by including a highly simplified oxidation scheme (Table S3) for each
 236 injected VOC. Reaction rates of the VOC with OH and O_3 are taken from the literature, and
 237 oxidation products are assumed to have the same OH reactivities as their precursors. Measured
 238 and modeled average $[\text{OH}]$ agree well (Figure 3), providing strong evidence that GUV_{222}
 239 produces not only O_3 (R1-2) but also OH (R3-5), and that oxidation by both O_3 and OH can take
 240 place upon irradiation with 222 nm light.

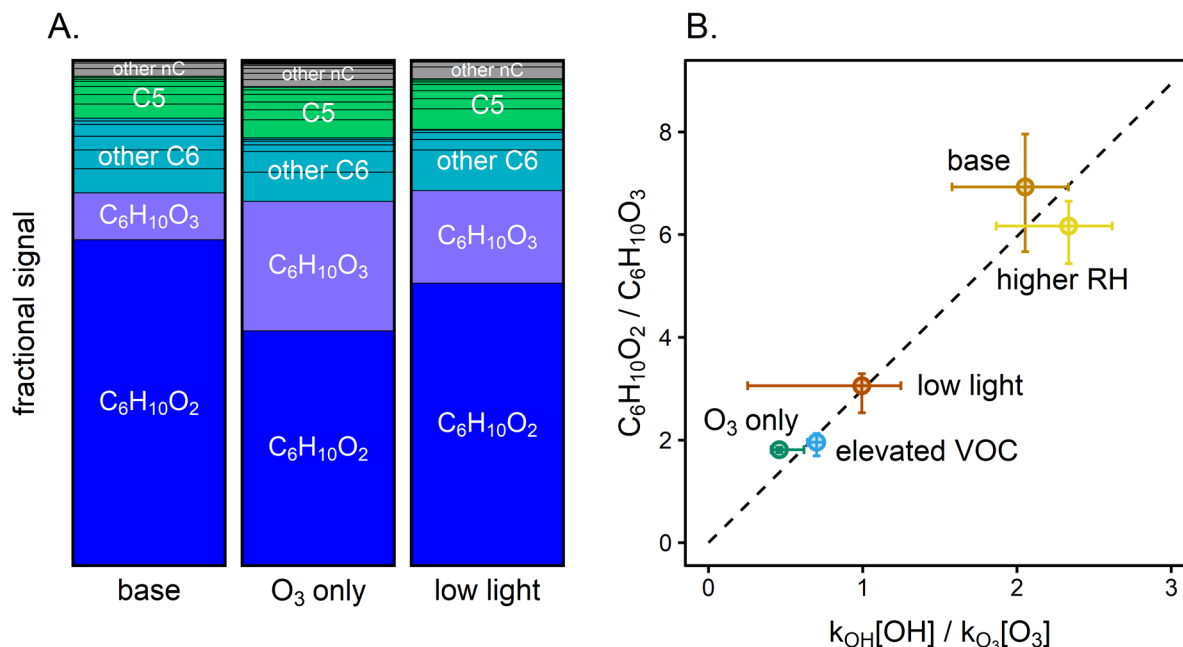


241
 242 *Figure 3:* Experimentally-derived average OH concentration vs. average OH concentration
 243 predicted by the box model, for all cyclohexene and hexanal experiments (see Section S3.4).

244 Note the break in the x-axis. Error bars represent the range of values observed throughout the
245 experiment.

246 *Formation of gas-phase oxidation products*

247 The formation of oxidized gas-phase products is observed in all experiments in which VOC
248 oxidation occurs. Product distributions for three cyclohexene experiments (base conditions, O₃
249 only, and low light) are shown in Figure 4. Additional product distributions and time-series
250 results (including for the hexanal experiments) are provided in Figures S5 and S6.



251
252 *Figure 4: Gas-phase products from cyclohexene experiments. Panel A: Normalized mass*
253 *spectrometric signal of products formed for the GUV222 irradiation (base conditions), O₃-only,*
254 *and low-light experiments (see Section S3.5 for calculations and Figure S5 for other*
255 *experimental conditions). Signals are integrated from $t = 250$ s to 2500 s, normalized to total*
256 *integrated ion signal and grouped by carbon number (nC). In all cases products are dominated by*
257 *C₆H₁₀O₂ (the major cyclohexene + OH reaction product) and C₆H₁₀O₃, (the major cyclohexene +*
258 *O₃ product). Panel B: The ratio of the C₆H₁₀O₂-to-C₆H₁₀O₃ signals vs. the ratio of the rates of*
259 *OH and O₃ oxidation, for all cyclohexene experiments. Concentrations of OH are determined*
260 *from the fits in Figure 2, while concentrations of O₃ are measured directly. The dashed line is a*
261 *linear fit to the data; since the two products have differing sensitivities in the instrument, this*
262 *differs from the 1:1 line. Error bars represent the range of values observed throughout the*
263 *experiment.*

264 Measured products are dominated by C₆ and C₅ compounds, as expected given that cyclohexene
265 is a C₆ species. The two products with the largest mass spectrometric signals, C₆H₁₀O₂ and
266 C₆H₁₀O₃, are the major products of the OH and O₃ initiated oxidation of cyclohexene,
267 respectively^{33,34} (see Scheme S1) (Products are detected as the analyte-NH₄⁺ adduct, and reported

268 as the analyte formula.) The ratios of the signals from the two products vary among experiments,
269 indicating differences in the relative concentrations of OH and O₃. In Figure 4b, the ratio of the
270 mass spectrometric signals of these two products is shown vs. the relative OH-to-O₃ oxidation
271 rate ratios (calculated from the experimentally-determined values of [OH] and [O₃]) for each
272 cyclohexene experiment. A strong correlation ($R^2 = 0.98$) is found between the two ratios,
273 providing further support for OH-initiated oxidation, and more generally for OH radical
274 production from irradiation by 222 nm light. The products formed in the 222 nm irradiation of
275 hexanal are also broadly consistent with OH-initiated oxidation (see Scheme S2).³⁵

276 *Secondary organic aerosol formation*

277 In all experiments, dry ammonium sulfate seed particles are added to the chamber, providing
278 surface area onto which low-volatility species may condense, and enabling the assessment of
279 potential SOA formation. SOA formation is observed in a number of experiments (Table S1 and
280 Figure S7). SOA formation is generally modest for most hexanal and cyclohexene experiments,
281 likely due to the relatively small size (C6) and low concentrations (10 ppb) of those species.
282 Higher concentrations of SOA are observed for experiments with high initial concentrations (100
283 ppb) of hexanal or cyclohexane, and for those using limonene (C₁₀H₁₆, a monoterpene commonly
284 found in fragrances and cleaning products). In fact, the GUV₂₂₂ irradiation of 100 ppb limonene
285 (a level that can be found in indoor environments immediately after cleaning events^{36,37}) results
286 in exceedingly high SOA loadings, on the order of $400 \pm 80 \mu\text{g m}^{-3}$. Additionally, the formation
287 of new particles is observed upon 222 nm irradiation under some conditions (Section S3.6 and
288 Figure S8). This effect is not observed when O₃ is added without 222 nm irradiation. GUV₂₂₂-
289 induced nucleation occurs even when no VOCs are added, and so may result from
290 photochemistry of organic species on the chamber surfaces, or even of the surface materials
291 themselves. Whether this is a general feature of the irradiation of organics on indoor surfaces is
292 unclear from the present experiments, but it does suggest that 222 nm irradiation may induce
293 new particle formation in some environments.

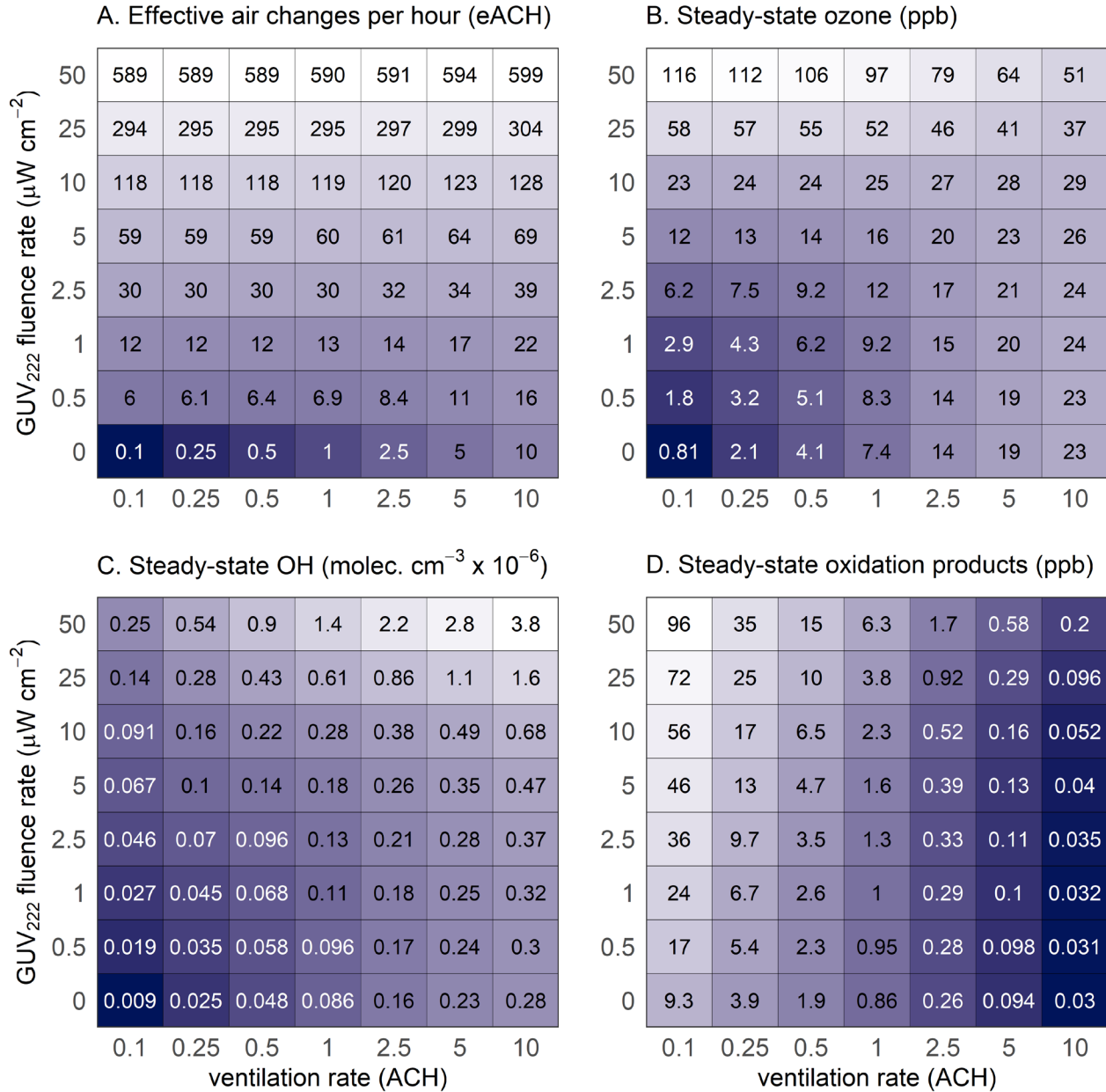
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295 *Extrapolation to indoor environments*

296 The above laboratory experiments demonstrate that GUV₂₂₂ irradiation forms ozone, OH, and a
297 range of oxidation products; measured ozone and inferred OH agree broadly with predictions by
298 a photochemical box model. However, real-world indoor environments are substantially different
299 than our simple laboratory system: they involve a large number of organic compounds,
300 depositional loss of ozone and other species, infiltration of outdoor pollutants, a wide range of
301 possible ventilation rates, and typically much lower average UV fluence rates. Here we extend
302 our photochemical model to a more realistic indoor air scenario, with the goal of understanding
303 how GUV₂₂₂ may impact indoor air quality under a range of ventilation and irradiation
304 conditions.

305 For simulations of chemistry in a more realistic indoor environment, two “lumped” VOCs are
306 included in the model: one (VOC1) that reacts with OH but not with O₃, and another (VOC2)
307 that reacts with both OH and O₃. Rate constants for VOC1 are chosen based on typical values for
308 indoor VOCs (Section S2.1 and Tables S3 and S4); rate constants for VOC2 are assumed to be
309 equal to those of limonene. OH yields from O₃ + VOC2 are assumed to be 0.86, equal to that of
310 limonene.¹¹ All oxidation reactions form lumped organic products that can also react with OH.
311 VOC emission rates (84 ppb hr⁻¹ and 4.2 ppb hr⁻¹ for VOC1 and VOC2, respectively) are
312 determined from previous measurements of OH and O₃ reactivities in indoor environments;^{38,39}
313 details of these calculations are given in Section S2.1. The model is run at 298 K, 1 atm, and
314 30% RH. We also include a background concentration of O₃ in the ventilation air (40 ppb,
315 consistent with typical outdoor O₃ concentrations), a 25% loss of O₃ to the ventilation system,
316 and an O₃ deposition constant of 3 hr⁻¹.^{10,31}

317 The range of light fluence rates chosen covers US and international guidelines on 222 nm
318 exposure limits (ranging from 0.8 to 16 μW/cm² assuming a continuous 8-hour exposure^{40,41}) as
319 well as the values in previous studies used for pathogen deactivation (average irradiance of up to
320 2.73 μW/cm² at 1.7 m above the ground from Eadie et al.⁴² and 3.5 μW/cm² from Peng et al.²³).
321 The range used in our model extends higher to take into account proposals for the use of
322 significantly higher light fluence rates,⁴³ and include the fluence rates in our experiments (~45
323 μW/cm²). Ventilation rates span a range of typical indoor values, and include the minimum
324 American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
325 recommendations for homes (0.35 ACH), offices (~2-3 ACH), and health care settings (10
326 ACH).⁴⁴



327

328 Figure 5: Effects of ventilation and GUV₂₂₂ fluence rate on modeled GUV efficacy and indoor
 329 air quality (see also Figures S9-S12). Panel A: effective air changes per hour (eACH) for indoor
 330 pathogens, based on the previously reported inactivation rate of SARS-CoV-2 at 222 nm⁴⁵
 331 (Section S4.2). Panels B-D: steady-state concentrations of (B) O₃, (C) OH, and (D) organic
 332 oxidation products, respectively, as predicted by the photochemical box model. Panel D
 333 calculations assume unit yields, and do not account for VOC production from surfaces (see
 334 Figure S11) or recycling by NO_x-HO_x interactions (Figure S12), so likely represent lower limits.
 335 Lighter colors represent larger values; note that the logarithmic color scaling is different for each
 336 panel. Additional model results are given in Figures S9 and S10.

337

338 Key model results are provided in Figure 5. Figure 5A shows the effective air change rate
339 (eACH) across a wide range of GUV_{222} fluence and ventilation rates; even modest irradiation
340 levels lead to substantial increases in eACH (see also Figure S9A). Figures 5B, C, and D show
341 the steady-state indoor concentrations of O_3 , OH, and total oxidation products (assuming unit
342 yield), respectively.

343 Steady-state ozone levels (Figure 5B) are higher with 222 nm irradiation than without. Sources
344 of O_3 include photochemistry (R1-2) and infiltration of outdoor air, while sinks include
345 deposition, ventilation, and chemical reaction (rates and contributions of individual processes are
346 given in Figures S9B-E). With low irradiation, O_3 levels are governed mainly by infiltration of
347 outdoor air, and O_3 increases are modest. Under the highest fluence rates ($>25 \mu W/cm^2$), and
348 especially under low ventilation rates (<1 ACH), indoor O_3 can reach levels exceeding that of the
349 outdoors, and can even exceed the OSHA indoor limit of 100 ppb. However, even a small
350 change in indoor O_3 levels can have a dramatic effect on people's total ozone exposure,⁴⁶ given
351 the large fraction of time people spend indoors. In most cases, deposition represents the
352 dominant sink of ozone (Figure S9D).

353 Figure 5C shows steady-state levels of OH as a function of ventilation and 222 nm light
354 intensity. Sources of OH include O_3 -alkene reactions (R3) and photochemistry (R4-5), while
355 sinks are dominated by reactive losses (see also Figures S9F-G). In the absence of GUV_{222}
356 irradiation, modeled OH is from alkene ozonolysis only, with predicted levels ($\sim 10^5$ molec cm^{-3})
357 overlapping but falling on the low end of measured and modeled OH in indoor spaces (which
358 range from 6×10^4 - 1.6×10^6 molec cm^{-3}),⁴⁷⁻⁵⁶ this underestimate may arise from the omission of
359 photolysis of trace species such as nitrous acid (HONO) or aldehydes, which may be important
360 in some environments.⁵⁷ As with O_3 , GUV_{222} irradiation leads to increases in indoor levels of
361 OH. At low to moderate irradiation levels, this increase in OH is mostly due to the alkene
362 ozonolysis reaction, while at higher levels, ozone photolysis plays a larger role (Figure S9G).
363 OH increases with increasing photochemistry (higher GUV_{222} fluence rates and ozone
364 concentrations), but is substantially modulated by losses from reaction with VOCs. VOC
365 concentrations are higher at low ventilation rates (see Figure S9H), due to the buildup of emitted
366 VOCs, which suppresses OH concentrations. At high light intensities, steady-state OH levels can
367 approach outdoor levels, matching or exceeding indoor OH measurements during transient
368 events such as cleaning or cooking activities.^{58,59}

369 The production of O_3 and OH by GUV_{222} -driven chemistry and their subsequent reactions with
370 VOCs leads to an increase in organic oxidation products (OVOCs and SOA). Steady-state levels
371 and production rates of such products (assuming unit yields) are shown in Figures 5D and S9I.
372 Concentrations increase with increased light intensity, and are especially high at low ventilation
373 rates. Since more than one product molecule may be formed per oxidation reaction, and OVOCs
374 may also be formed by surface reactions of O_3 or OH, these numbers likely represent lower
375 limits. Of particular concern is the production of hazardous air pollutants (HAPs, such as CH_2O)
376 and SOA, both of which may represent health hazards in the indoor environment. Concentrations
377 of SOA are challenging to predict, as SOA production depends on the amounts and identity of
378 the indoor VOCs, as well as on a host of reaction conditions. However, SOA levels on the order

379 of a few $\mu\text{g}/\text{m}^3$ might occur (Figure S10); the production of SOA from 222 nm irradiation in
380 realistic indoor settings is an important area of future research.

381 The simplicity of the model neglects some additional secondary effects, which are highly
382 uncertain. For example, volatile secondary organic products stemming from reactive surface
383 losses of O_3 (e.g., to paint, textiles, skin)^{12,60} could represent an additional secondary effect of
384 GUV_{222} on indoor air quality. Preliminary modeling suggests that this may increase OVOC
385 concentrations by as much as a factor of 100 (Figure S11). Similarly, indoor environments
386 contain NO_x , which can affect the levels and fates of oxidants. While NO_x chemistry is not
387 modeled explicitly here, due in part to uncertainties in NO_x photolysis processes, we have
388 carried out additional simulations to estimate the role of HO_x - NO_x cycling. As shown in Section
389 S4.1 and Figure S12, such cycling increases OH concentrations and OVOC product formation
390 substantially. We do not examine the role of HONO, which can be present in high (ppb) levels
391 indoors⁵⁵ and absorbs strongly at 222 nm ($\sigma = 1.35 \times 10^{-18} \text{ cm}^2 \text{ }^9$); HONO photolysis may lead to
392 even higher OH levels than predicted here. All of these effects have the potential to increase
393 OVOC formation, suggesting that the OVOC concentrations presented in Figure 5 are best
394 understood as a lower limit and that the indoor air quality impacts of 222 nm irradiation could be
395 more severe than predicted here.

396 *Implications*

397 Our laboratory studies demonstrate that GUV_{222} light leads to the production of (1) ozone, (2)
398 OH radicals, and (3) secondary organic species (OVOCs and SOA); these are in broad agreement
399 with prior model predictions.²³ The resulting concentrations of such secondary species can be
400 substantially higher than are normally found in indoor environments; in extreme cases, these
401 increases can be dramatic, leading to oxidation conditions similar to those found in outdoor
402 environments. The negative health impacts associated with the unavoidable generation of these
403 secondary species – most importantly O_3 , fine particular matter, and HAPs – thus need to be
404 taken into account (and ideally mitigated) when considering the use of 222 nm disinfection in
405 indoor spaces.

406 While a detailed analysis of the health impacts of GUV_{222} use (both the benefits from
407 inactivation of airborne pathogens and the drawbacks from secondary pollutant formation) is
408 beyond the scope of this work, our results offer some broad guidance as to the optimal use of
409 GUV_{222} in indoor environments. Most importantly, GUV_{222} disinfection alone is not a safe
410 substitute for ventilation as a means to control levels of indoor airborne pathogens, as it can lead
411 to the buildup of indoor ozone and other pollutants to dangerous levels (Figure 5). However,
412 GUV_{222} may be effectively used in conjunction with ventilation: relatively modest irradiation
413 levels combined with carefully chosen ventilation conditions can greatly enhance the effective
414 air change rate (Figure 5A), while limiting the levels of secondary pollutants (Figures 5B-D).
415 Moreover, due to the unavoidable formation of secondary pollutants, GUV_{222} lights should be
416 run at the lowest effective levels whenever possible. Further, the combination of GUV_{222}
417 irradiation with air-cleaning technologies (e.g., sorbents for ozone and OVOCs, filters for
418 particulate matter) may serve to minimize indoor secondary pollutant levels, potentially enabling

419 safer use of GUV₂₂₂ under poorly-ventilated environments. Quantifying the benefits and
420 tradeoffs of these combined approaches (ventilation, GUV₂₂₂ irradiation, and/or air cleaning) in
421 terms of pathogen transmission, air pollutant levels, human health, and cost-effectiveness, is a
422 critical next step toward ensuring healthier indoor environments.

423 **Supporting Information**

424 Experimental conditions and methods, additional modeling methods, additional results and
425 discussion (incl. ozone steady-state calculations, discussion of VOC loss pathways, discussion of
426 elevated VOC and RH experiments, more complete product distribution figures, reaction
427 schemes, and SMPS data), model results (incl. additional model output figures and calculation of
428 effective air changes per hour) (PDF)

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434 **References**

- 435 (1) Wells, W. F.; Wells, M. W.; Wilder, T. S. The Environmental Control of Epidemic
436 Contagion: I. An Epidemiologic Study of Radiant Disinfection of Air in Day Schools.
437 *American Journal of Epidemiology* **1942**, *35* (1), 97–121.
438 <https://doi.org/10.1093/oxfordjournals.aje.a118789>.
- 439 (2) Nardell, E. A. Air Disinfection for Airborne Infection Control with a Focus on COVID-19:
440 Why Germicidal UV Is Essential†. *Photochemistry and Photobiology* **2021**, *97* (3), 493–
441 497. <https://doi.org/10.1111/php.13421>.
- 442 (3) Centers for Disease Control and Prevention. *Upper Room Ultraviolet Germicidal*
443 *Irradiation (UVGI)*. [https://www.cdc.gov/coronavirus/2019-](https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation/uvgi.html)
444 [ncov/community/ventilation/uvgi.html](https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation/uvgi.html) (accessed 2023-05-17).
- 445 (4) Blatchley, E. R.; Brenner, D.; Claus, H.; Cowan, T. E.; Linden, K.; Liu, Y.; Mao, T.; Park,
446 S.-J.; Simons, R.; Sliney, D. *Far UV-C Radiation: Current State-of-Knowledge*; White
447 paper; International Ultraviolet Association Task Force.
- 448 (5) Buonanno, M.; Welch, D.; Shuryak, I.; Brenner, D. J. Far-UVC Light (222 Nm) Efficiently
449 and Safely Inactivates Airborne Human Coronaviruses. *Sci Rep* **2020**, *10* (1), 10285.
450 <https://doi.org/10.1038/s41598-020-67211-2>.
- 451 (6) Collins, D. B.; Farmer, D. K. Unintended Consequences of Air Cleaning Chemistry.
452 *Environ. Sci. Technol.* **2021**, *55* (18), 12172–12179.
453 <https://doi.org/10.1021/acs.est.1c02582>.
- 454 (7) Ye, Q.; Krechmer, J. E.; Shutter, J. D.; Barber, V. P.; Li, Y.; Helstrom, E.; Franco, L. J.;
455 Cox, J. L.; Hrdina, A. I. H.; Goss, M. B.; Tahsini, N.; Canagaratna, M.; Keutsch, F. N.;
456 Kroll, J. H. Real-Time Laboratory Measurements of VOC Emissions, Removal Rates, and
457 Byproduct Formation from Consumer-Grade Oxidation-Based Air Cleaners. *Environ. Sci.*
458 *Technol. Lett.* **2021**, *8* (12), 1020–1025. <https://doi.org/10.1021/acs.estlett.1c00773>.
- 459 (8) Turner, M. C.; Jerrett, M.; Pope, C. A.; Krewski, D.; Gapstur, S. M.; Diver, W. R.;
460 Beckerman, B. S.; Marshall, J. D.; Su, J.; Crouse, D. L.; Burnett, R. T. Long-Term Ozone

- 461 Exposure and Mortality in a Large Prospective Study. *Am J Respir Crit Care Med* **2016**,
462 *193* (10), 1134–1142. <https://doi.org/10.1164/rccm.201508-1633OC>.
- 463 (9) Burkholder, J.; Sander, S. P.; Abbatt, J. P. D.; Barker, J. R.; Cappa, C.; Crouse, J. D.;
464 Dibble, T. S.; Huie, R. E.; Kolb, C. E.; Kurylo, M. J.; Orkin, V. L.; Percival, C. J.;
465 Wilmouth, D. M.; Wine, P. H. *Chemical Kinetics and Photochemical Data for Use in*
466 *Atmospheric Studies*; 19–5; NASA Jet Propulsion Laboratory, 2020.
- 467 (10) Nazaroff, W. W.; Weschler, C. J. Indoor Ozone: Concentrations and Influencing Factors.
468 *Indoor Air* **2022**, *32* (1). <https://doi.org/10.1111/ina.12942>.
- 469 (11) Calvert, J. G. *The Mechanisms of Atmospheric Oxidation of the Alkenes*; Oxford University
470 Press, 2000.
- 471 (12) Wisthaler, A.; Weschler, C. J. Reactions of Ozone with Human Skin Lipids: Sources of
472 Carbonyls, Dicarboxyls, and Hydroxycarbonyls in Indoor Air. *Proceedings of the National*
473 *Academy of Sciences* **2010**, *107* (15), 6568–6575. <https://doi.org/10.1073/pnas.0904498106>.
- 474 (13) Kroll, J. H.; Seinfeld, J. H. Chemistry of Secondary Organic Aerosol: Formation and
475 Evolution of Low-Volatility Organics in the Atmosphere. *Atmospheric Environment* **2008**,
476 *42* (16), 3593–3624. <https://doi.org/10.1016/j.atmosenv.2008.01.003>.
- 477 (14) US EPA. *Dose-Response Assessment for Assessing Health Risks Associated with Exposure*
478 *to Hazardous Air Pollutants*. [https://www.epa.gov/fera/dose-response-assessment-](https://www.epa.gov/fera/dose-response-assessment-assessing-health-risks-associated-exposure-hazardous-air-pollutants)
479 [assessing-health-risks-associated-exposure-hazardous-air-pollutants](https://www.epa.gov/fera/dose-response-assessment-assessing-health-risks-associated-exposure-hazardous-air-pollutants) (accessed 2023-05-02).
- 480 (15) Dockery, D. W.; Pope, C. A.; Xu, X.; Spengler, J. D.; Ware, J. H.; Fay, M. E.; Ferris, B. G.;
481 Speizer, F. E. An Association between Air Pollution and Mortality in Six U.S. Cities. *New*
482 *England Journal of Medicine* **1993**, *329* (24), 1753–1759.
483 <https://doi.org/10.1056/NEJM199312093292401>.
- 484 (16) Burnett, R.; Chen, H.; Szyszkowicz, M.; Fann, N.; Hubbell, B.; Pope, C. A.; Apte, J. S.;
485 Brauer, M.; Cohen, A.; Weichenthal, S.; Coggins, J.; Di, Q.; Brunekreef, B.; Frostad, J.;
486 Lim, S. S.; Kan, H.; Walker, K. D.; Thurston, G. D.; Hayes, R. B.; Lim, C. C.; Turner, M.
487 C.; Jerrett, M.; Krewski, D.; Gapstur, S. M.; Diver, W. R.; Ostro, B.; Goldberg, D.; Crouse,
488 D. L.; Martin, R. V.; Peters, P.; Pinault, L.; Tjepkema, M.; van Donkelaar, A.; Villeneuve,
489 P. J.; Miller, A. B.; Yin, P.; Zhou, M.; Wang, L.; Janssen, N. A. H.; Marra, M.; Atkinson,
490 R. W.; Tsang, H.; Quoc Thach, T.; Cannon, J. B.; Allen, R. T.; Hart, J. E.; Laden, F.;
491 Cesaroni, G.; Forastiere, F.; Weinmayr, G.; Jaensch, A.; Nagel, G.; Concin, H.; Spadaro, J.
492 V. Global Estimates of Mortality Associated with Long-Term Exposure to Outdoor Fine
493 Particulate Matter. *Proceedings of the National Academy of Sciences* **2018**, *115* (38), 9592–
494 9597. <https://doi.org/10.1073/pnas.1803222115>.
- 495 (17) Pye, H. O. T.; Ward-Caviness, C. K.; Murphy, B. N.; Appel, K. W.; Seltzer, K. M.
496 Secondary Organic Aerosol Association with Cardiorespiratory Disease Mortality in the
497 United States. *Nat Commun* **2021**, *12* (1), 7215. [https://doi.org/10.1038/s41467-021-27484-](https://doi.org/10.1038/s41467-021-27484-1)
498 [1](https://doi.org/10.1038/s41467-021-27484-1).
- 499 (18) Donahue, N. M.; Drozd, G. T.; Epstein, S. A.; Presto, A. A.; Kroll, J. H. Adventures in
500 Ozoneland: Down the Rabbit-Hole. *Phys. Chem. Chem. Phys.* **2011**, *13* (23), 10848–10857.
501 <https://doi.org/10.1039/C0CP02564J>.
- 502 (19) Levy, H. Normal Atmosphere: Large Radical and Formaldehyde Concentrations Predicted.
503 *Science* **1971**, *173* (3992), 141–143. <https://doi.org/10.1126/science.173.3992.141>.
- 504 (20) Bender, E. Disinfecting the Air with Far-Ultraviolet Light. *Nature* **2022**, *610* (7933), S46–
505 S47. <https://doi.org/10.1038/d41586-022-03360-w>.

- 506 (21) Link, M. F.; Shore, A.; Hamadani, B. H.; Poppendieck, D. Ozone Generation from a
507 Germicidal Ultraviolet Lamp with Peak Emission at 222 Nm. *Environ. Sci. Technol. Lett.*
508 **2023**, *10* (8), 675–679. <https://doi.org/10.1021/acs.estlett.3c00318>.
- 509 (22) Peng, Z.; Day, D. A.; Symonds, G. A.; Jenks, O. J.; Stark, H.; Handschy, A. V.; de Gouw,
510 J. A.; Jimenez, J. L. Significant Production of Ozone from Germicidal UV Lights at 222
511 Nm. *Environ. Sci. Technol. Lett.* **2023**, *10* (8), 668–674.
512 <https://doi.org/10.1021/acs.estlett.3c00314>.
- 513 (23) Peng, Z.; Miller, S. L.; Jimenez, J. L. Model Evaluation of Secondary Chemistry Due to
514 Disinfection of Indoor Air with Germicidal Ultraviolet Lamps. *Environ. Sci. Technol. Lett.*
515 **2023**, *10* (1), 6–13. <https://doi.org/10.1021/acs.estlett.2c00599>.
- 516 (24) Ushio, Inc. Care222 Technical Specification Sheet.
517 [https://www.ushio.com/files/specifications/care222-filtered-far-uv-c-excimer-lamp-module-](https://www.ushio.com/files/specifications/care222-filtered-far-uv-c-excimer-lamp-module-technical-data-sheet.pdf)
518 [technical-data-sheet.pdf](https://www.ushio.com/files/specifications/care222-filtered-far-uv-c-excimer-lamp-module-technical-data-sheet.pdf) (accessed 2023-05-03).
- 519 (25) Krechmer, J.; Lopez-Hilfiker, F.; Koss, A.; Hutterli, M.; Stoermer, C.; Deming, B.;
520 Kimmel, J.; Warneke, C.; Holzinger, R.; Jayne, J.; Worsnop, D.; Fuhrer, K.; Gonin, M.; de
521 Gouw, J. Evaluation of a New Reagent-Ion Source and Focusing Ion–Molecule Reactor for
522 Use in Proton-Transfer-Reaction Mass Spectrometry. *Anal. Chem.* **2018**, *90* (20), 12011–
523 12018. <https://doi.org/10.1021/acs.analchem.8b02641>.
- 524 (26) Zaytsev, A.; Breitenlechner, M.; Koss, A. R.; Lim, C. Y.; Rowe, J. C.; Kroll, J. H.;
525 Keutsch, F. N. Using Collision-Induced Dissociation to Constrain Sensitivity of Ammonia
526 Chemical Ionization Mass Spectrometry (NH₄⁺ CIMS) to Oxygenated Volatile Organic
527 Compounds. *Atmos. Meas. Tech.* **2019**, *12* (3), 1861–1870. [https://doi.org/10.5194/amt-12-](https://doi.org/10.5194/amt-12-1861-2019)
528 [1861-2019](https://doi.org/10.5194/amt-12-1861-2019).
- 529 (27) DeCarlo, P. F.; Kimmel, J. R.; Trimborn, A.; Northway, M. J.; Jayne, J. T.; Aiken, A. C.;
530 Gonin, M.; Fuhrer, K.; Horvath, T.; Docherty, K. S.; Worsnop, D. R.; Jimenez, J. L. Field-
531 Deployable, High-Resolution, Time-of-Flight Aerosol Mass Spectrometer. *Anal. Chem.*
532 **2006**, *78* (24), 8281–8289. <https://doi.org/10.1021/ac061249n>.
- 533 (28) Stewart, D. J.; Almarok, S. H.; Lockhart, J. P.; Mohamed, O. M.; Nutt, D. R.; Pfrang, C.;
534 Marston, G. The Kinetics of the Gas-Phase Reactions of Selected Monoterpenes and Cyclo-
535 Alkenes with Ozone and the NO₃ Radical. *Atmospheric Environment* **2013**, *70*, 227–235.
536 <https://doi.org/10.1016/j.atmosenv.2013.01.036>.
- 537 (29) Aschmann, S. M.; Arey, J.; Atkinson, R. Kinetics and Products of the Reactions of OH
538 Radicals with Cyclohexene, 1-Methyl-1-Cyclohexene, *Cis* -Cyclooctene, and *Cis* -
539 Cyclodecene. *J. Phys. Chem. A* **2012**, *116* (38), 9507–9515.
540 <https://doi.org/10.1021/jp307217m>.
- 541 (30) D’Anna, B.; Andresen, Ø.; Gefen, Z.; J. Nielsen, C. Kinetic Study of OH and NO₃ Radical
542 Reactions with 14 Aliphatic Aldehydes. *Physical Chemistry Chemical Physics* **2001**, *3* (15),
543 3057–3063. <https://doi.org/10.1039/B103623H>.
- 544 (31) Grøntoft, T.; Raychaudhuri, M. R. Compilation of Tables of Surface Deposition Velocities
545 for O₃, NO₂ and SO₂ to a Range of Indoor Surfaces. *Atmospheric Environment* **2004**, *38*
546 (4), 533–544. <https://doi.org/10.1016/j.atmosenv.2003.10.010>.
- 547 (32) Saunders, S. M.; Jenkin, M. E.; Derwent, R. G.; Pilling, M. J. Protocol for the Development
548 of the Master Chemical Mechanism, MCM v3 (Part A): Tropospheric Degradation of Non-
549 Aromatic Volatile Organic Compounds. *Atmospheric Chemistry and Physics* **2003**, *3* (1),
550 161–180. <https://doi.org/10.5194/acp-3-161-2003>.

- 551 (33) Hansel, A.; Scholz, W.; Mentler, B.; Fischer, L.; Berndt, T. Detection of RO₂ Radicals and
552 Other Products from Cyclohexene Ozonolysis with NH₄⁺ and Acetate Chemical Ionization
553 Mass Spectrometry. *Atmospheric Environment* **2018**, *186*, 248–255.
554 <https://doi.org/10.1016/j.atmosenv.2018.04.023>.
- 555 (34) Aschmann, S. M.; Tuazon, E. C.; Arey, J.; Atkinson, R. Products of the Gas-Phase Reaction
556 of O₃ with Cyclohexene. *J. Phys. Chem. A* **2003**, *107* (13), 2247–2255.
557 <https://doi.org/10.1021/jp022122e>.
- 558 (35) Barua, S.; Iyer, S.; Kumar, A.; Seal, P.; Rissanen, M. An Aldehyde as a Rapid Source of
559 Secondary Aerosol Precursors: Theoretical and Experimental Study of Hexanal
560 Autoxidation. *EGUsphere* **2023**, 1–24. <https://doi.org/10.5194/egusphere-2023-128>.
- 561 (36) Singer, B. C.; Coleman, B. K.; Destailats, H.; Hodgson, A. T.; Lunden, M. M.; Weschler,
562 C. J.; Nazaroff, W. W. Indoor Secondary Pollutants from Cleaning Product and Air
563 Freshener Use in the Presence of Ozone. *Atmospheric Environment* **2006**, *40* (35), 6696–
564 6710. <https://doi.org/10.1016/j.atmosenv.2006.06.005>.
- 565 (37) Wainman, T.; Zhang, J.; Weschler, C. J.; Liroy, P. J. Ozone and Limonene in Indoor Air: A
566 Source of Submicron Particle Exposure. *Environmental Health Perspectives* **2000**, *108*
567 (12), 1139–1145. <https://doi.org/10.1289/ehp.001081139>.
- 568 (38) Price, D. J.; Day, D. A.; Pagonis, D.; Stark, H.; Algrim, L. B.; Handschy, A. V.; Liu, S.;
569 Krechmer, J. E.; Miller, S. L.; Hunter, J. F.; de Gouw, J. A.; Ziemann, P. J.; Jimenez, J. L.
570 Budgets of Organic Carbon Composition and Oxidation in Indoor Air. *Environ. Sci.*
571 *Technol.* **2019**, *53* (22), 13053–13063. <https://doi.org/10.1021/acs.est.9b04689>.
- 572 (39) Mattila, J. M.; Arata, C.; Abeleira, A.; Zhou, Y.; Wang, C.; Katz, E. F.; Goldstein, A. H.;
573 Abbatt, J. P. D.; DeCarlo, P. F.; Vance, M. E.; Farmer, D. K. Contrasting Chemical
574 Complexity and the Reactive Organic Carbon Budget of Indoor and Outdoor Air. *Environ.*
575 *Sci. Technol.* **2022**, *56* (1), 109–118. <https://doi.org/10.1021/acs.est.1c03915>.
- 576 (40) International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidelines on
577 Limits of Exposure to Ultraviolet Radiation of Wavelengths between 180 Nm and 400 Nm
578 (Incoherent Optical Radiation). *Health Phys* **2004**, *87* (2), 171–186.
579 <https://doi.org/10.1097/00004032-200408000-00006>.
- 580 (41) American Conference of Governmental Industrial Hygienists. *2023 Threshold Limit Values*
581 *(TLVs) and Biological Exposure Indices (BEIs)*; 2023.
- 582 (42) Eadie, E.; Hiwar, W.; Fletcher, L.; Tidswell, E.; O'Mahoney, P.; Buonanno, M.; Welch, D.;
583 Adamson, C. S.; Brenner, D. J.; Noakes, C.; Wood, K. Far-UVC (222 Nm) Efficiently
584 Inactivates an Airborne Pathogen in a Room-Sized Chamber. *Sci Rep* **2022**, *12* (1), 4373.
585 <https://doi.org/10.1038/s41598-022-08462-z>.
- 586 (43) Esvelt, K. M. Delay, Detect, Defend: Preparing for a Future in Which Thousands Can
587 Release New Pandemics. *The Geneva Centre for Security and Policy*. November 2022.
- 588 (44) ASHRAE/ANSI Standard 62.1-2022. Ventilation and Acceptable Indoor Air Quality, 2022.
- 589 (45) Ma, B.; Linden, Y. S.; Gundy, P. M.; Gerba, C. P.; Sobsey, M. D.; Linden, K. G.
590 Inactivation of Coronaviruses and Phage Phi6 from Irradiation across UVC Wavelengths.
591 *Environ. Sci. Technol. Lett.* **2021**, *8* (5), 425–430.
592 <https://doi.org/10.1021/acs.estlett.1c00178>.
- 593 (46) Weschler, C. J. Ozone's Impact on Public Health: Contributions from Indoor Exposures to
594 Ozone and Products of Ozone-Initiated Chemistry. *Environ Health Perspect* **2006**, *114*
595 (10), 1489–1496. <https://doi.org/10.1289/ehp.9256>.

- 596 (47) Weschler, C. J.; Shields, H. C. Production of the Hydroxyl Radical in Indoor Air. *Environ.*
597 *Sci. Technol.* **1996**, *30* (11), 3250–3258. <https://doi.org/10.1021/es960032f>.
- 598 (48) Weschler, C. J.; Shields, H. C. Measurements of the Hydroxyl Radical in a Manipulated but
599 Realistic Indoor Environment. *Environ. Sci. Technol.* **1997**, *31* (12), 3719–3722.
600 <https://doi.org/10.1021/es970669e>.
- 601 (49) Carslaw, N. A New Detailed Chemical Model for Indoor Air Pollution. *Atmospheric*
602 *Environment* **2007**, *41* (6), 1164–1179. <https://doi.org/10.1016/j.atmosenv.2006.09.038>.
- 603 (50) Waring, M. S.; Wells, J. R. Volatile Organic Compound Conversion by Ozone, Hydroxyl
604 Radicals, and Nitrate Radicals in Residential Indoor Air: Magnitudes and Impacts of
605 Oxidant Sources. *Atmospheric Environment* **2015**, *106*, 382–391.
606 <https://doi.org/10.1016/j.atmosenv.2014.06.062>.
- 607 (51) Carslaw, N.; Fletcher, L.; Heard, D.; Ingham, T.; Walker, H. Significant OH Production
608 under Surface Cleaning and Air Cleaning Conditions: Impact on Indoor Air Quality. *Indoor*
609 *Air* **2017**, *27* (6), 1091–1100. <https://doi.org/10.1111/ina.12394>.
- 610 (52) Gligorovski, S.; Weschler, C. J. The Oxidative Capacity of Indoor Atmospheres. *Environ.*
611 *Sci. Technol.* **2013**, *47* (24), 13905–13906. <https://doi.org/10.1021/es404928t>.
- 612 (53) Fiorentino, E.-A.; Chen, H.; Gandolfo, A.; Lannuque, V.; Sartelet, K.; Wortham, H.
613 Measurements and Modelling of OH and Peroxy Radicals in an Indoor Environment Under
614 Different Light Conditions and VOC Levels. *Atmospheric Environment* **2023**, *292*, 119398.
615 <https://doi.org/10.1016/j.atmosenv.2022.119398>.
- 616 (54) Mendez, M.; Amedro, D.; Blond, N.; Hauglustaine, D. A.; Blondeau, P.; Afif, C.; Fittschen,
617 C.; Schoemaeker, C. Identification of the Major HOx Radical Pathways in an Indoor Air
618 Environment. *Indoor Air* **2017**, *27* (2), 434–442. <https://doi.org/10.1111/ina.12316>.
- 619 (55) Gómez Alvarez, E.; Amedro, D.; Afif, C.; Gligorovski, S.; Schoemaeker, C.; Fittschen, C.;
620 Doussin, J.-F.; Wortham, H. Unexpectedly High Indoor Hydroxyl Radical Concentrations
621 Associated with Nitrous Acid. *Proceedings of the National Academy of Sciences* **2013**, *110*
622 (33), 13294–13299. <https://doi.org/10.1073/pnas.1308310110>.
- 623 (56) Zannoni, N.; Lakey, P. S. J.; Won, Y.; Shiraiwa, M.; Rim, D.; Weschler, C. J.; Wang, N.;
624 Ernle, L.; Li, M.; Bekö, G.; Wargocki, P.; Williams, J. The Human Oxidation Field.
625 *Science* **2022**, *377* (6610), 1071–1077. <https://doi.org/10.1126/science.abn0340>.
- 626 (57) Kowal, S. F.; Allen, S. R.; Kahan, T. F. Wavelength-Resolved Photon Fluxes of Indoor
627 Light Sources: Implications for HOx Production. *Environ. Sci. Technol.* **2017**, *51* (18),
628 10423–10430. <https://doi.org/10.1021/acs.est.7b02015>.
- 629 (58) Rosales, C. M. F.; Jiang, J.; Lahib, A.; Bottorff, B. P.; Reidy, E. K.; Kumar, V.; Tasoglou,
630 A.; Huber, H.; Dusanter, S.; Tomas, A.; Boor, B. E.; Stevens, P. S. Chemistry and Human
631 Exposure Implications of Secondary Organic Aerosol Production from Indoor Terpene
632 Ozonolysis. *Science Advances* **2022**, *8* (8), eabj9156.
633 <https://doi.org/10.1126/sciadv.abj9156>.
- 634 (59) Reidy, E.; Bottorff, B. P.; Rosales, C. M. F.; Cardoso-Saldaña, F. J.; Arata, C.; Zhou, S.;
635 Wang, C.; Abeleira, A.; Hildebrandt Ruiz, L.; Goldstein, A. H.; Novoselac, A.; Kahan, T.
636 F.; Abbatt, J. P. D.; Vance, M. E.; Farmer, D. K.; Stevens, P. S. Measurements of Hydroxyl
637 Radical Concentrations during Indoor Cooking Events: Evidence of an Unmeasured
638 Photolytic Source of Radicals. *Environ. Sci. Technol.* **2023**, *57* (2), 896–908.
639 <https://doi.org/10.1021/acs.est.2c05756>.

640 (60) Wang, H.; Morrison, G. Ozone-Surface Reactions in Five Homes: Surface Reaction
641 Probabilities, Aldehyde Yields, and Trends. *Indoor Air* **2010**, *20* (3), 224–234.
642 <https://doi.org/10.1111/j.1600-0668.2010.00648.x>.
643