Ultraviolet Air Disinfection for Indoor Environments

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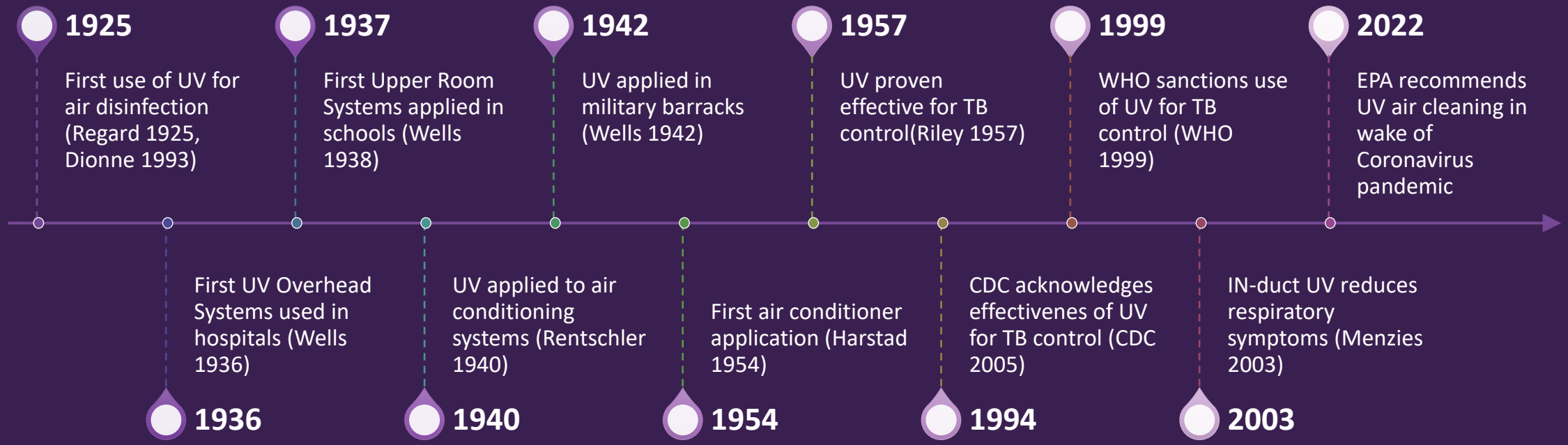
History of UV Air Disinfection



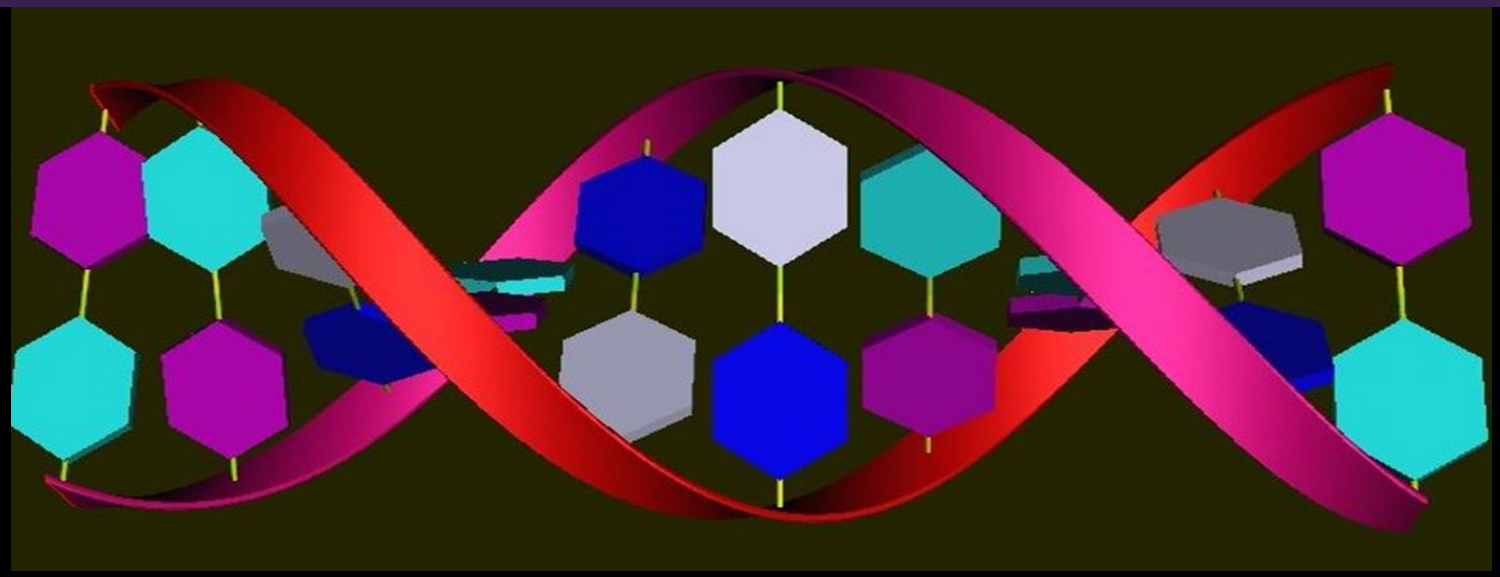
Ultraviolet Science

- **Ultraviolet Light at 254 nm is germicidal**
- **Photons are absorbed by the base pairs of the DNA double helix**
- **Disruption of the DNA inhibits DNA replication and function**
- **Photodimers are induced at pyrimidine bases T & C**

Pyrimidines

T = Thymine

C = Cytosine



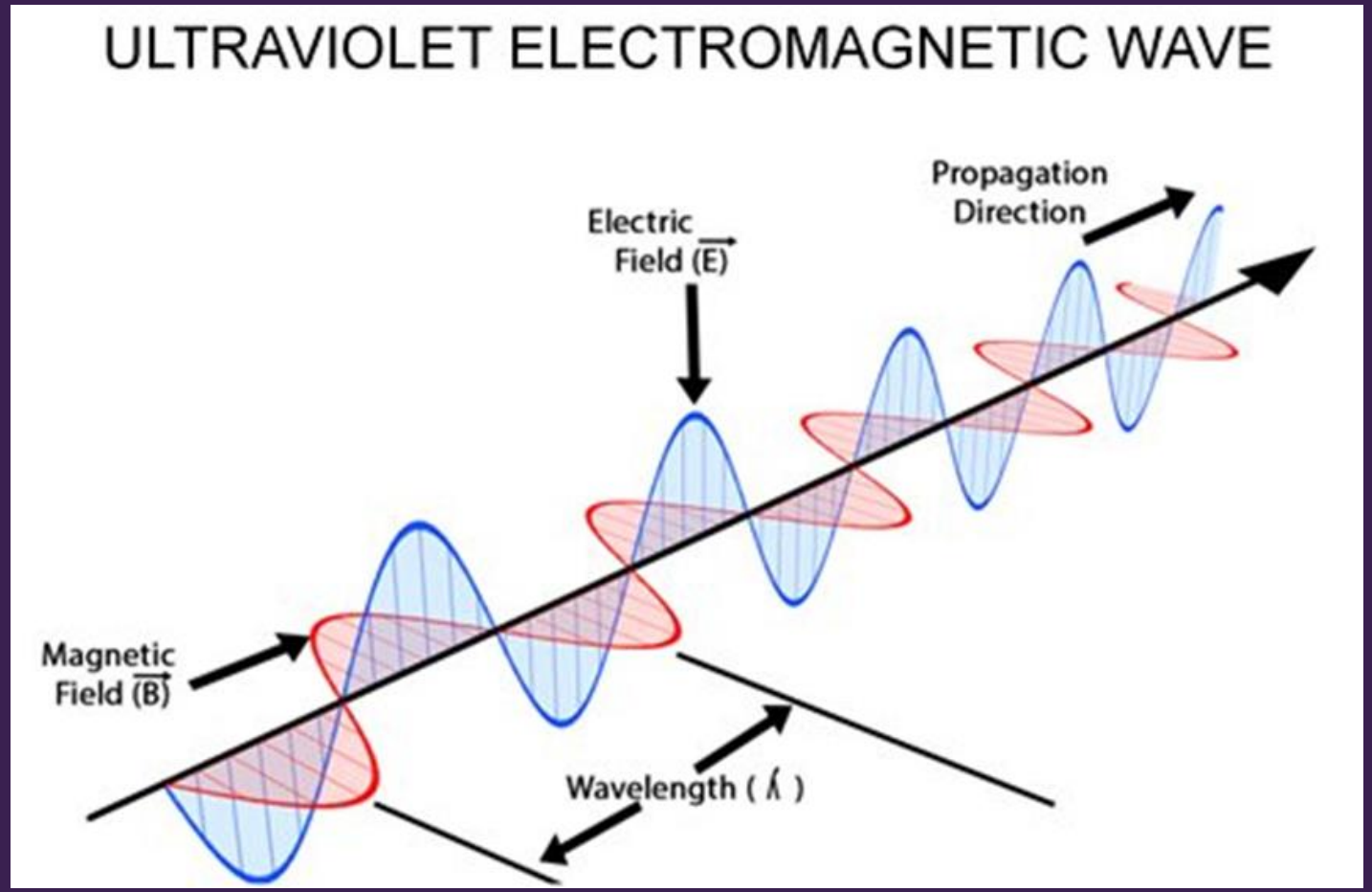
Purines

A = Adenine

G = Guanine

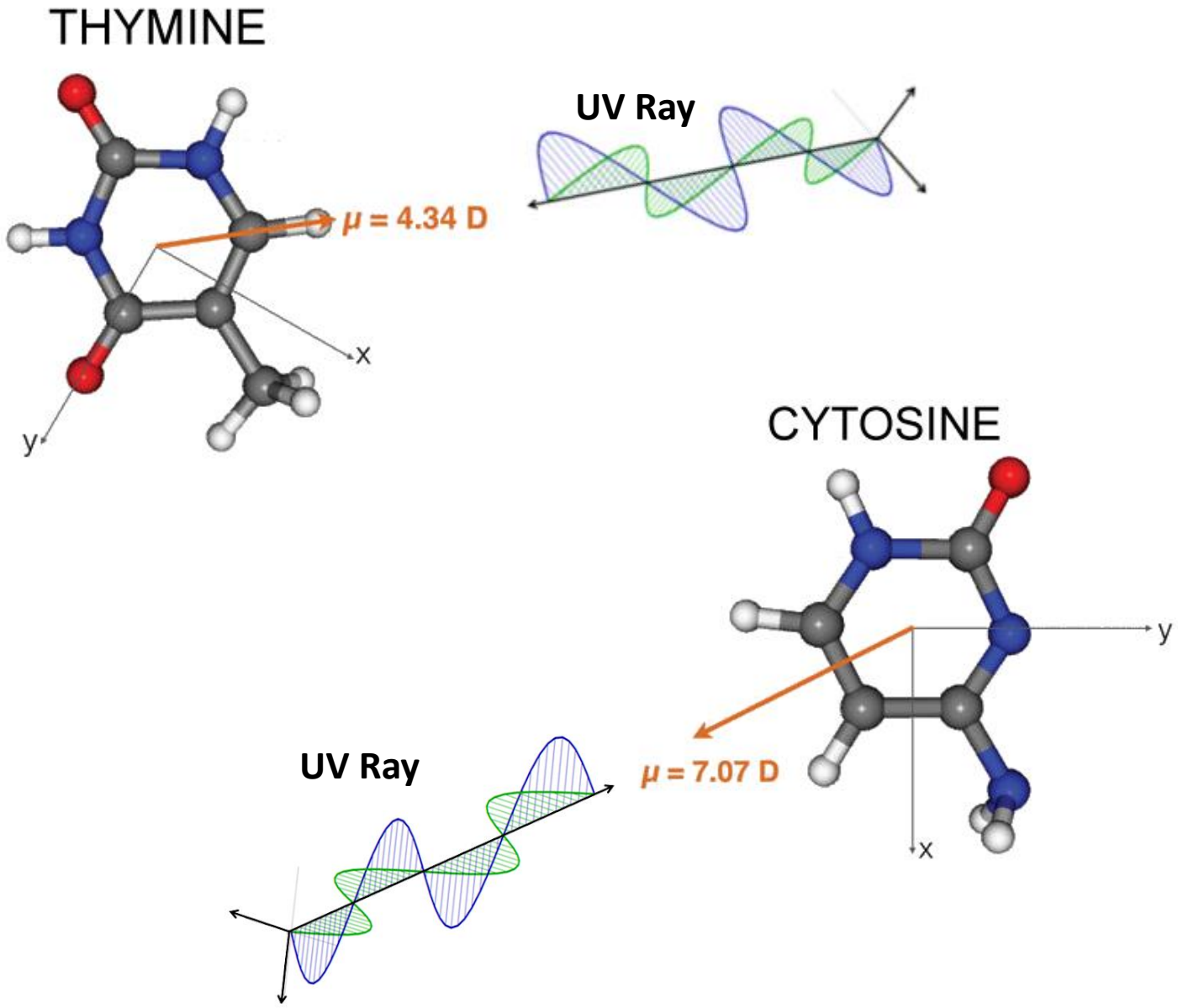
Ultraviolet Light

- Ultraviolet light is electromagnetic radiation composed of two mutually perpendicular waves travelling along an axis in the direction of propagation
- UV Rays have directionality
- Energy is absorbed in discrete quanta
- Absorption of UV energy depends on the orientation of the bases T & C relative to the incident angle of the UV rays



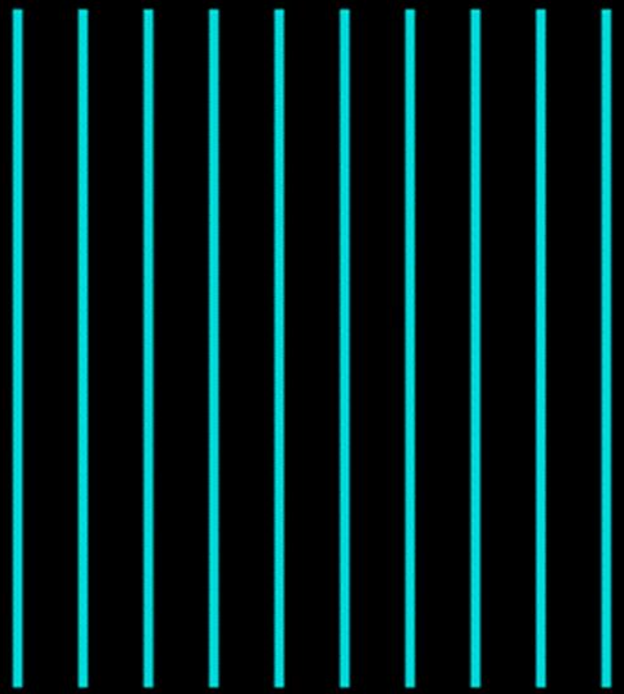
UV Electromagnetic Interaction with DNA Bases

- Thymine and Cytosine molecules have an orientation that is defined by their electromagnetic dipole moment
- Purines are much less reactive
- Absorption of a quanta of energy will occur when the dipole moments of the bases are suitably oriented with respect to the incoming UV rays (Schreier 2007)
- Energy will jump from UV waves to the molecule creating an excited state
- The excited bases will break their hydrogen bonds and fuse with adjacent pyrimidines
- This directionality accounts for higher inactivation rates in air versus surfaces.

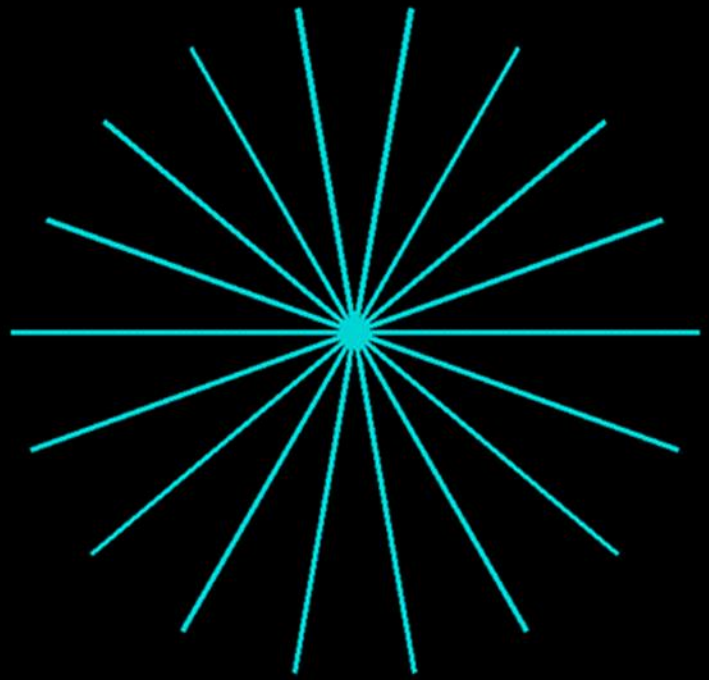


Ultraviolet Light Delivery Modes

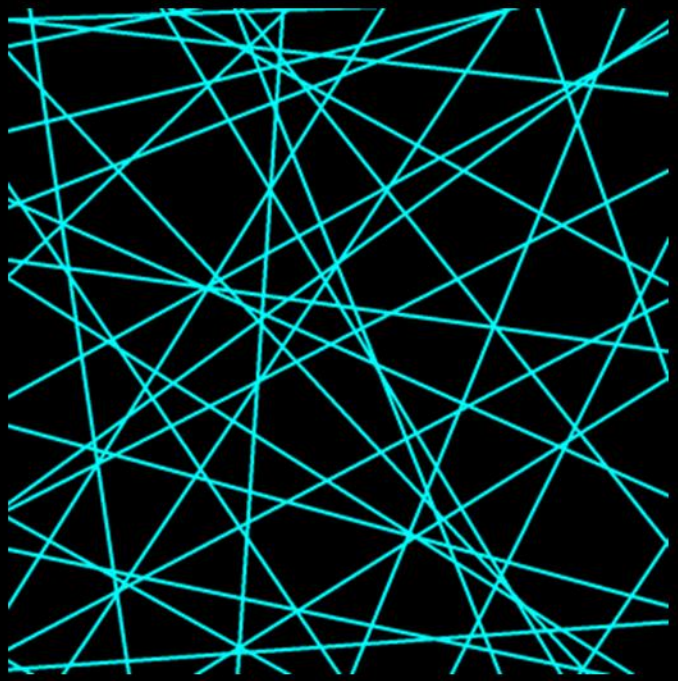
Collimated Beam
(parallel rays)



Point Source
(expanding rays)



Multivector Light
(diffuse light)



Comparing Air, Water & Surface UV Disinfection

- Airborne Microbes
  - More susceptible in air than on surfaces
  - Subject to diffusion & turbulence
  - Exposed on all sides
- Surface-borne microbes
  - No motion
  - Exposure limited by direction of light
- Waterborne Microbes
  - In dynamic motion
  - Water attenuates UV
  - Similar susceptibility to surface-borne
- Bacteria UV resistance varies with RH

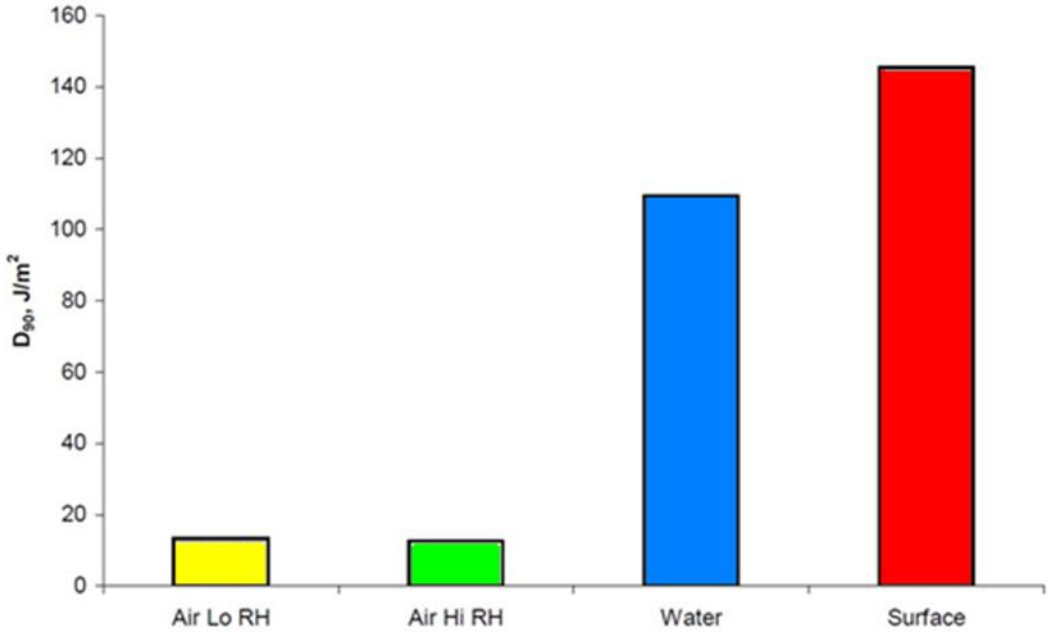
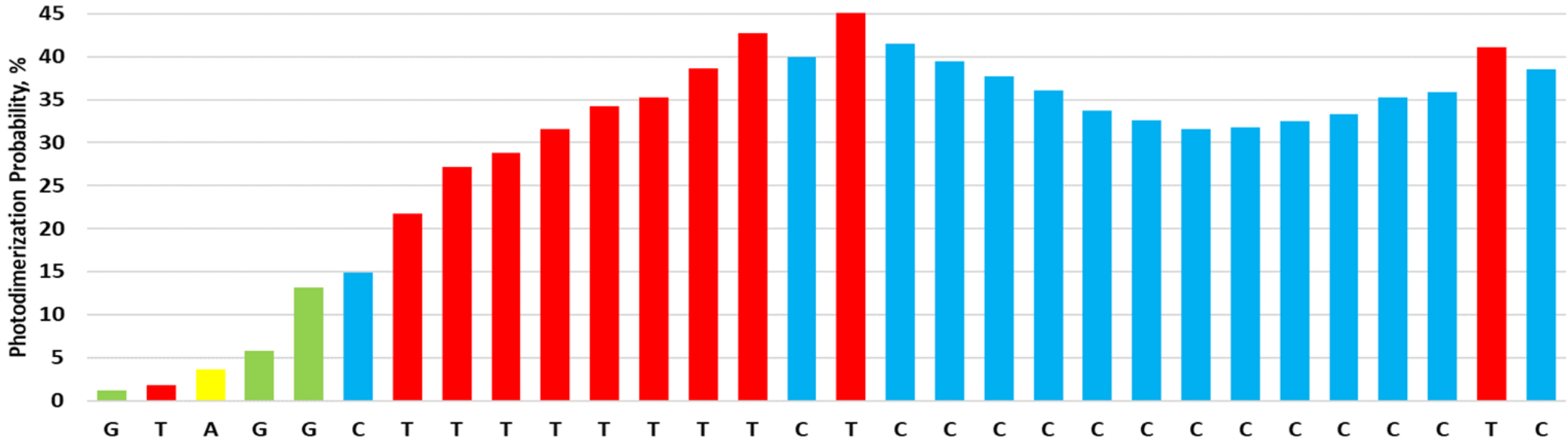
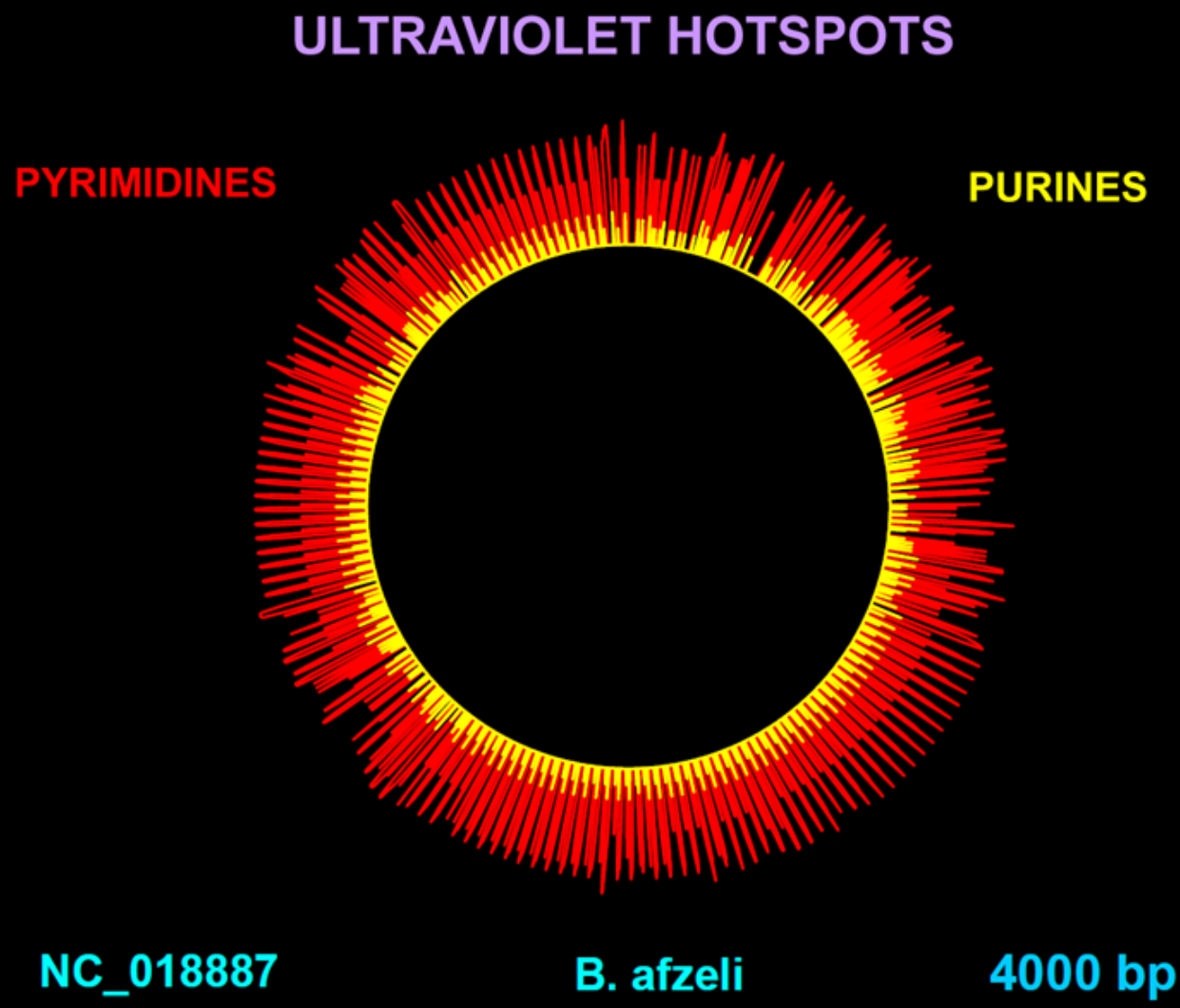


Figure 4.4: Comparison of overall averages for virus D_{90} values in various media.

Ultraviolet Genomics

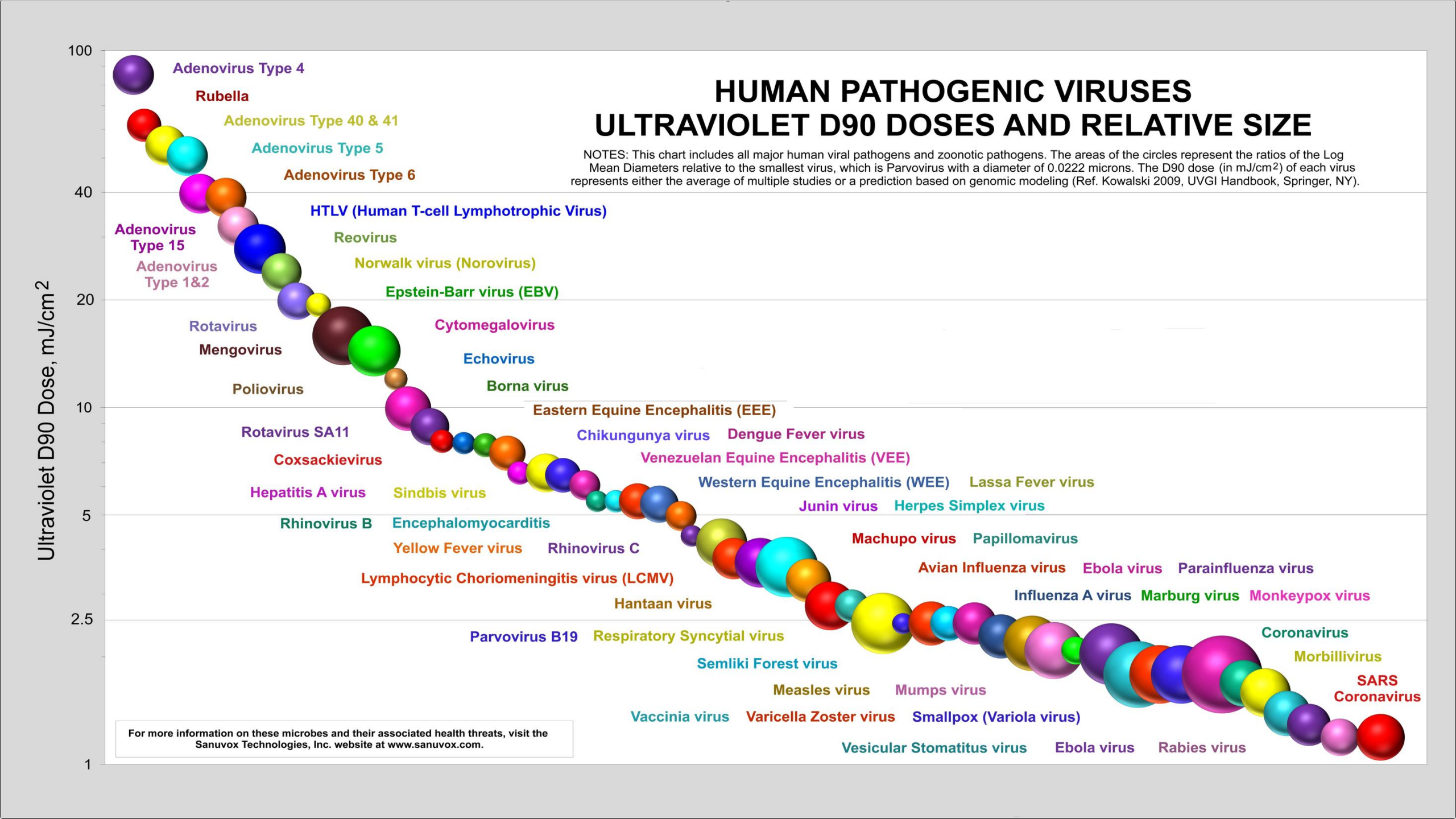


- Ultraviolet photodimerization is a sequence dependent process
- Consecutive sequences of Pyrimidines (Ts & Cs) form UV absorption hotspots
- These hotspots amplify the rate of photodimerization, with a peak occurring beyond 10-12 bases
- Sequence analyzed by Becker & Wang (1989), sea urchin DNA



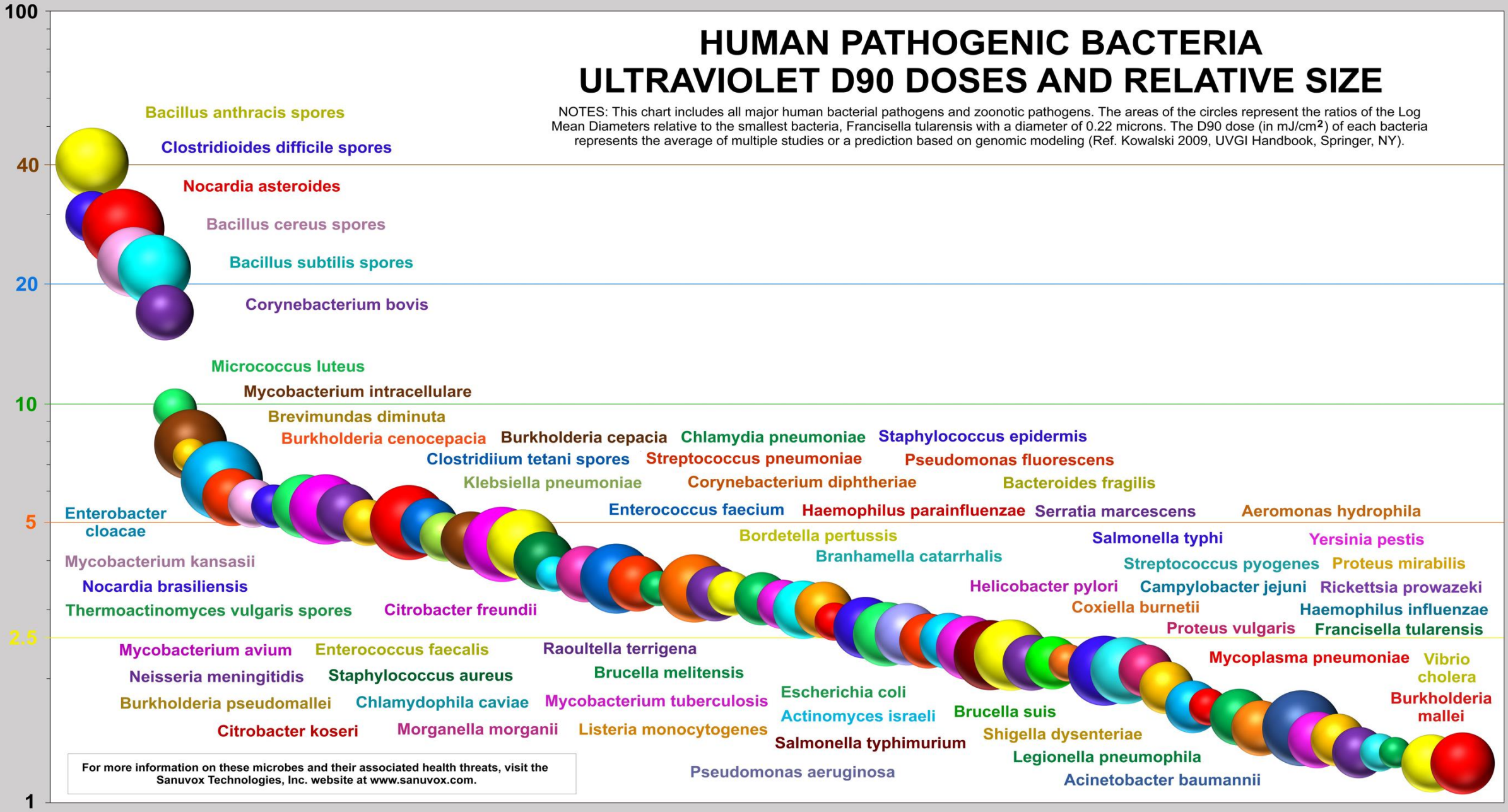
Ultraviolet Hotspots determine UV Sensitivity

- Very common in genomes
- Can occupy the majority of bases
- Can be pyrimidine or purine hotspots


HUMAN PATHOGENIC VIRUSES
ULTRAVIOLET D90 DOSES AND RELATIVE SIZE
NOTES: This chart includes all major human viral pathogens and zoonotic pathogens. The areas of the circles represent the ratios of the Log Mean Diameters relative to the smallest virus, which is Parvovirus with a diameter of 0.0222 microns. The D90 dose (in mJ/cm2) of each virus represents either the average of multiple studies or a prediction based on genomic modeling (Ref. Kowalski 2009, UVGI Handbook, Springer, NY).
Ultraviolet D90 Dose, mJ/cm 2
100
40
20
10
5
2.5
1
Adenovirus Type 4
Rubella
Adenovirus Type 40 & 41
Adenovirus Type 5
Adenovirus Type 6
HTLV (Human T-cell Lymphotrophic Virus)
Adenovirus Type 15
Reovirus
Adenovirus Type 1&2
Norwalk virus (Norovirus)
Epstein-Barr virus (EBV)
Rotavirus
Cytomegalovirus
Mengovirus
Echovirus
Poliovirus
Borna virus
Eastern Equine Encephalitis (EEE)
Rotavirus SA11
Chikungunya virus
Dengue Fever virus
Coxsackievirus
Venezuelan Equine Encephalitis (VEE)
Western Equine Encephalitis (WEE)
Lassa Fever virus
Hepatitis A virus
Sindbis virus
Junin virus
Herpes Simplex virus
Rhinovirus B
Encephalomyocarditis
Machupo virus
Papillomavirus
Yellow Fever virus
Rhinovirus C
Avian Influenza virus
Ebola virus
Parainfluenza virus
Lymphocytic Choriomeningitis virus (LCMV)
Influenza A virus
Marburg virus
Monkeypox virus
Hantaan virus
Coronavirus
Parvovirus B19
Respiratory Syncytial virus
Morbillivirus
Semliki Forest virus
SARS Coronavirus
Measles virus
Mumps virus
Vaccinia virus
Varicella Zoster virus
Smallpox (Variola virus)
Vesicular Stomatitus virus
Ebola virus
Rabies virus
For more information on these microbes and their associated health threats, visit the Sanuvox Technologies, Inc. website at www.sanuvox.com.

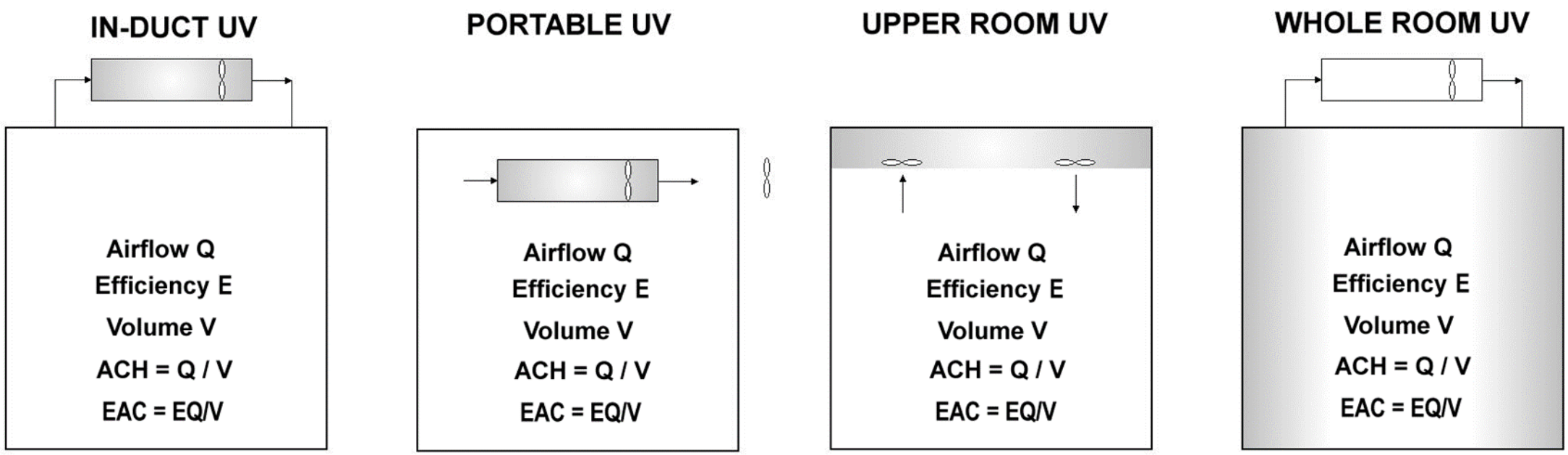
HUMAN PATHOGENIC BACTERIA
ULTRAVIOLET D90 DOSES AND RELATIVE SIZE

NOTES: This chart includes all major human bacterial pathogens and zoonotic pathogens. The areas of the circles represent the ratios of the Log Mean Diameters relative to the smallest bacteria, Francisella tularensis with a diameter of 0.22 microns. The D90 dose (in mJ/cm^2) of each bacteria represents the average of multiple studies or a prediction based on genomic modeling (Ref. Kowalski 2009, UVGI Handbook, Springer, NY).



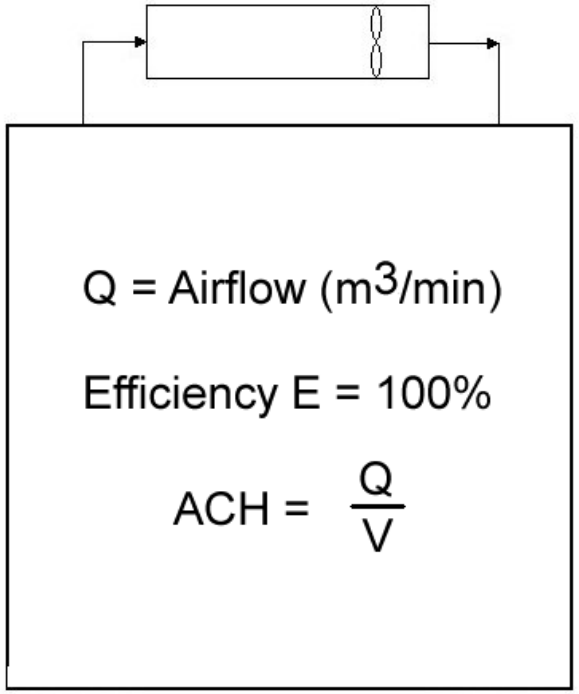
For more information on these microbes and their associated health threats, visit the Sanuvox Technologies, Inc. website at www.sanuvox.com.

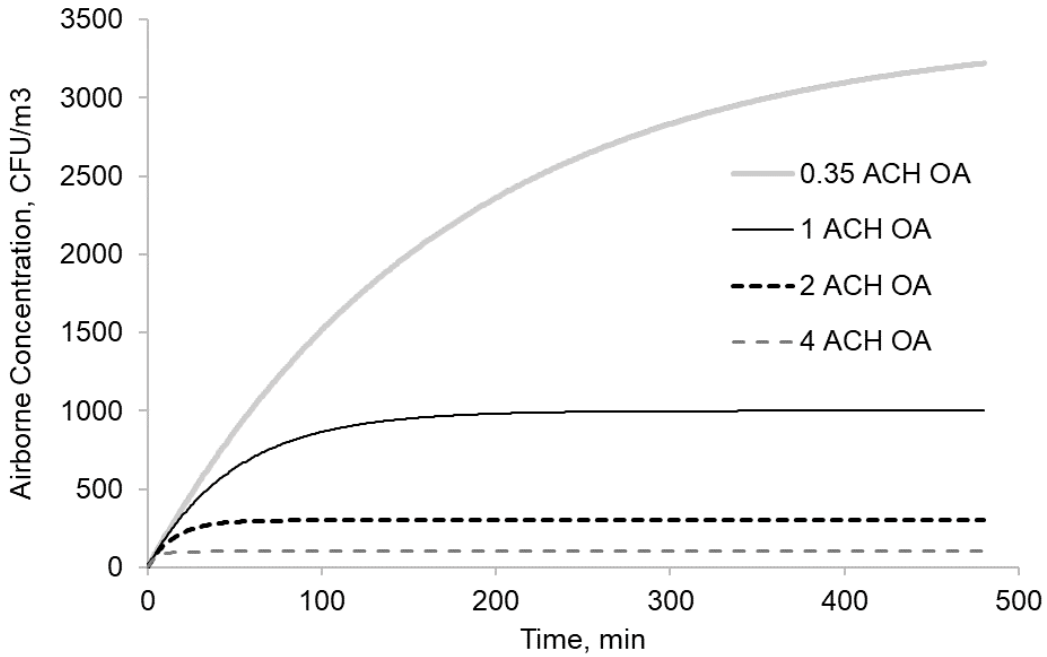
Types of UV Air Disinfection Systems



- **All air disinfection systems function according to the same principles**
- **All systems can be tested using a completely mixed steady-state model room**
- **EAC is a function of Airflow, Removal Efficiency & Room Volume**

The Standard Outside Air Model





- **Completely Mixed Model Performance Parameters are constant for any Volume V**
- **Typical test model room volume V = 50 m3**
- **Model provides a good approximation of any small to medium sized room, on the average**

The Standard Outside Air Model Performance Parameters

- **Removal rates are constant for any given ACH**
- **Can be measured/calculated per performance testing standards**
- **For corroboration any EAC must match these performance parameters**
  - **Room Removal Rate (CFU/hr, PFU/hr, etc.)**
  - **8 Hour reduction %**
  - **Minutes for 99% Removal**

Table 1: Outside Air Performance Parameters Under SS Conditions in a 50 m^3 Room

ACH	Room Rem min^{-1}	Log Removal min^{-1}	Room 8 Hour Reduction	Minutes for 99% Rem	Minutes for 99.9% Rem
0	0	0	0	-	-
0.35	0.005816	0.0025	0.992857	789	1184
1	0.016529	0.0072	0.997500	276	414
2	0.032784	0.0145	0.998750	138	207
4	0.064493	0.0290	0.999375	69	104
6	0.095163	0.0434	0.999583	46	69
10	0.153518	0.0724	0.999750	28	41
20	0.283469	0.1448	0.999875	14	21
30	0.393469	0.2171	0.999917	9.2	13.8
40	0.486583	0.2895	0.999938	6.9	10.4
50	0.565402	0.3619	0.999950	5.5	8.3
60	0.632121	0.4343	0.999958	4.6	6.9
100	0.811124	0.7238	0.999975	2.8	4.1
150	0.917915	1.0857	0.999983	1.8	2.8
200	0.964326	1.4476	0.999988	1.4	2.1
300	0.993262	2.1715	0.999992	0.92	1.4
400	0.998727	2.8953	0.999994	0.69	1.0
500	0.999760	3.6191	0.999995	0.55	0.83
600	0.999955	4.3429	0.999996	0.46	0.69
700	0.999991	5.0668	0.999996	0.39	0.59
800	0.999998	5.7906	0.999997	0.35	0.52
900	0.9999997	6.5144	0.999997	0.31	0.46
1000	0.9999999	7.2382	0.999998	0.28	0.41

Performance of In-Duct UV Systems

- Performance Parameters
  - Airflow
  - Removal Efficiency
  - Room Volume (model room)

- Performance Testing Standards
  - Test Type 1: Measure Airflow & Removal Efficiency
  - Test Type 2: Measure Airflow & Removal Efficiency in a Model Room of Volume V (typically 50 m3)

UV In-Duct Air Disinfection Unit Performance Testing Standards

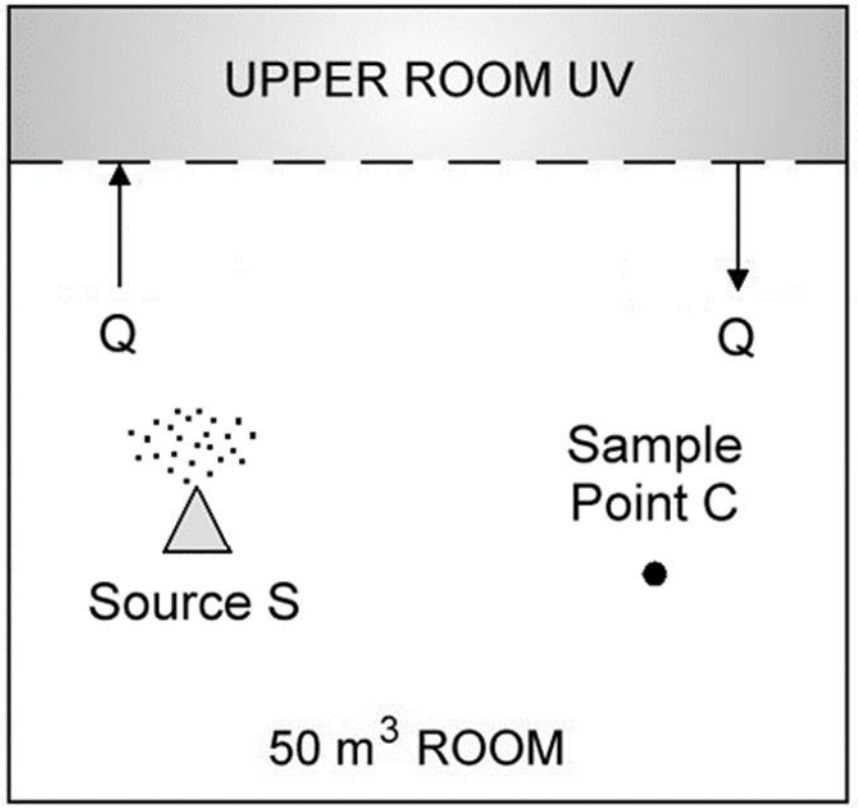
Reference	Subject	Test Setup	Measured Parameters
EPA 2006, 600/R-06/053	In-duct UV	In-Duct	Disinfection efficiency & airflow
ANSI/ASHRAE 2015, 185.1	In-duct UV	In-Duct	Disinfection efficiency & airflow
VanOsdell 2002	In-duct UV	In-Duct	Disinfection efficiency & airflow
Nakamura 1987	In-duct UV	In-Duct	Disinfection efficiency & airflow
Miller 1955	In-duct UV	In-Duct	Disinfection efficiency & airflow
Griffiths 2005	UV Air Cleaners	In-Duct	Disinfection efficiency & airflow
ISO 2019, 15714:2019	In-duct UV	In-Duct	UV Dose & airflow

UV Model Room Air Disinfection Performance Testing Standards

Reference		Subject	Test Setup	Measured Parameters
AHAM 2022	AC-5	UV Air Cleaners	Model Room	Disinfection efficiency & airflow
ASTM 2021	E3273-1	UV Air Cleaners	Model Room	Disinfection efficiency & airflow
ASHRAE 2023	185.3P	UV Air Cleaners	Model Room	Disinfection efficiency & airflow
ASHRAE 2022	185.5	Air cleaners	Model Room	Disinfection efficiency & airflow
GLA 2022	-	UV Air Cleaners	Model Room	Disinfection efficiency & airflow
Foarde 1999	-	UV air cleaners	Model Room	Disinfection efficiency & airflow
Xu 2003	-	Upper Room UV	Model Room	Disinfection efficiency & airflow

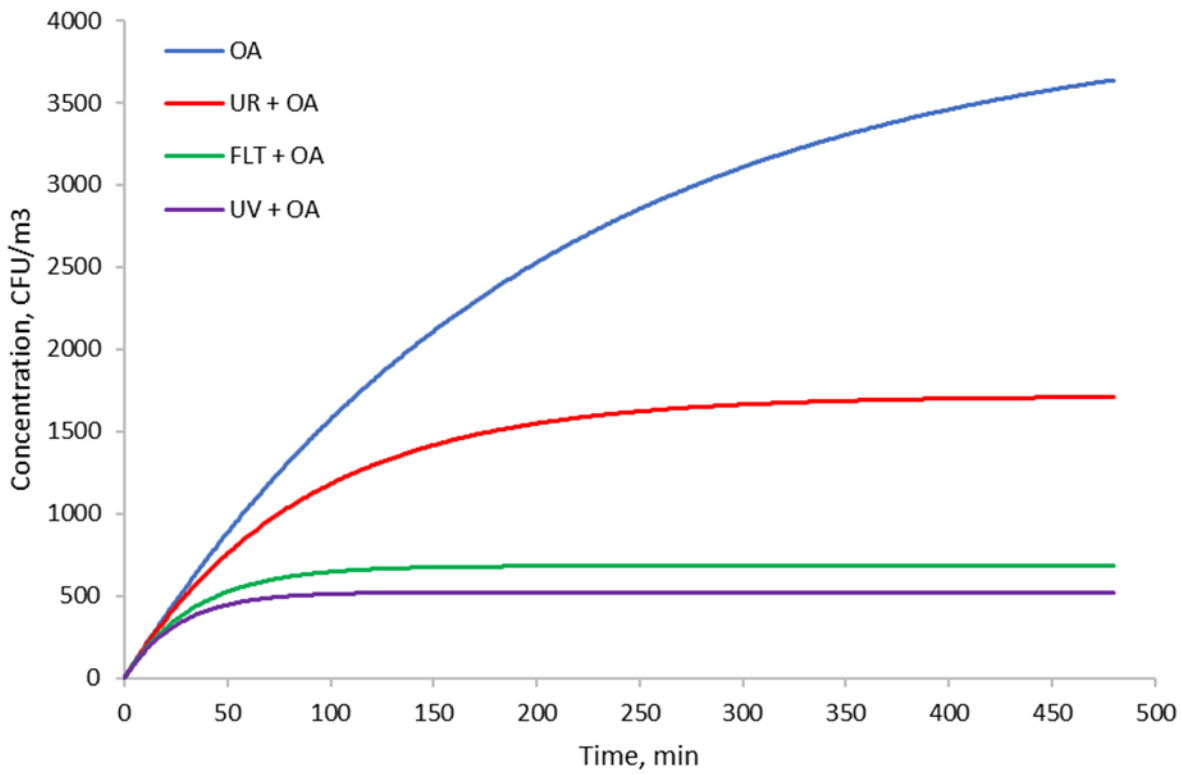
Steady State UV System Testing

- Steady State system testing works for all UV air disinfection systems; In-duct, Portable, Upper Room or Whole room
- UV Air Disinfection System testing is performed in a model room, typically 50 m3
- Airflow is measured (CFM or ACH)
- When the source is releasing microbes with the UV system OFF, a steady state is reached
- When the UV is ON major reductions will occur
- The ratio of airborne concentrations when the UV is ON to when the UV is OFF defines the system efficiency
- Theoretically the reduction in the room will match the reduction across the UV system



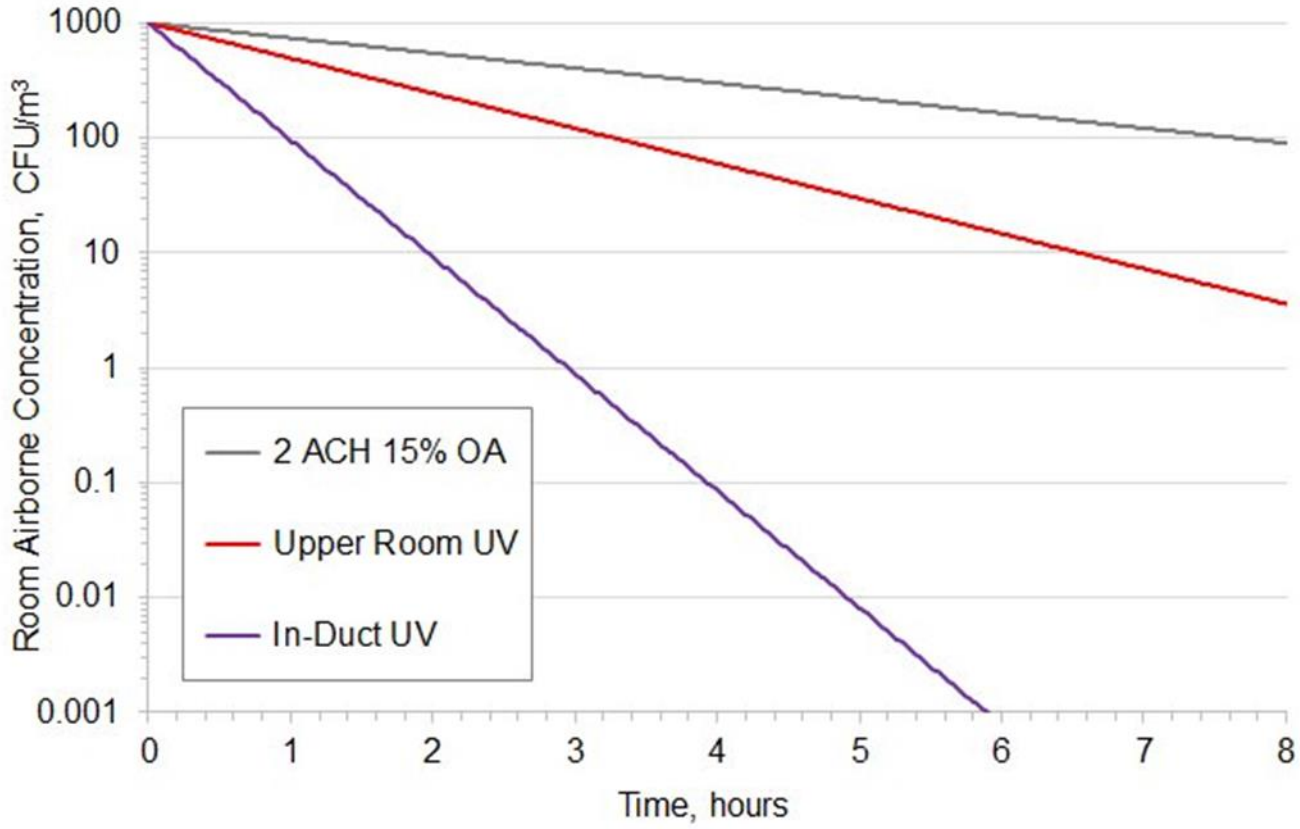
Steady State Airborne Concentrations

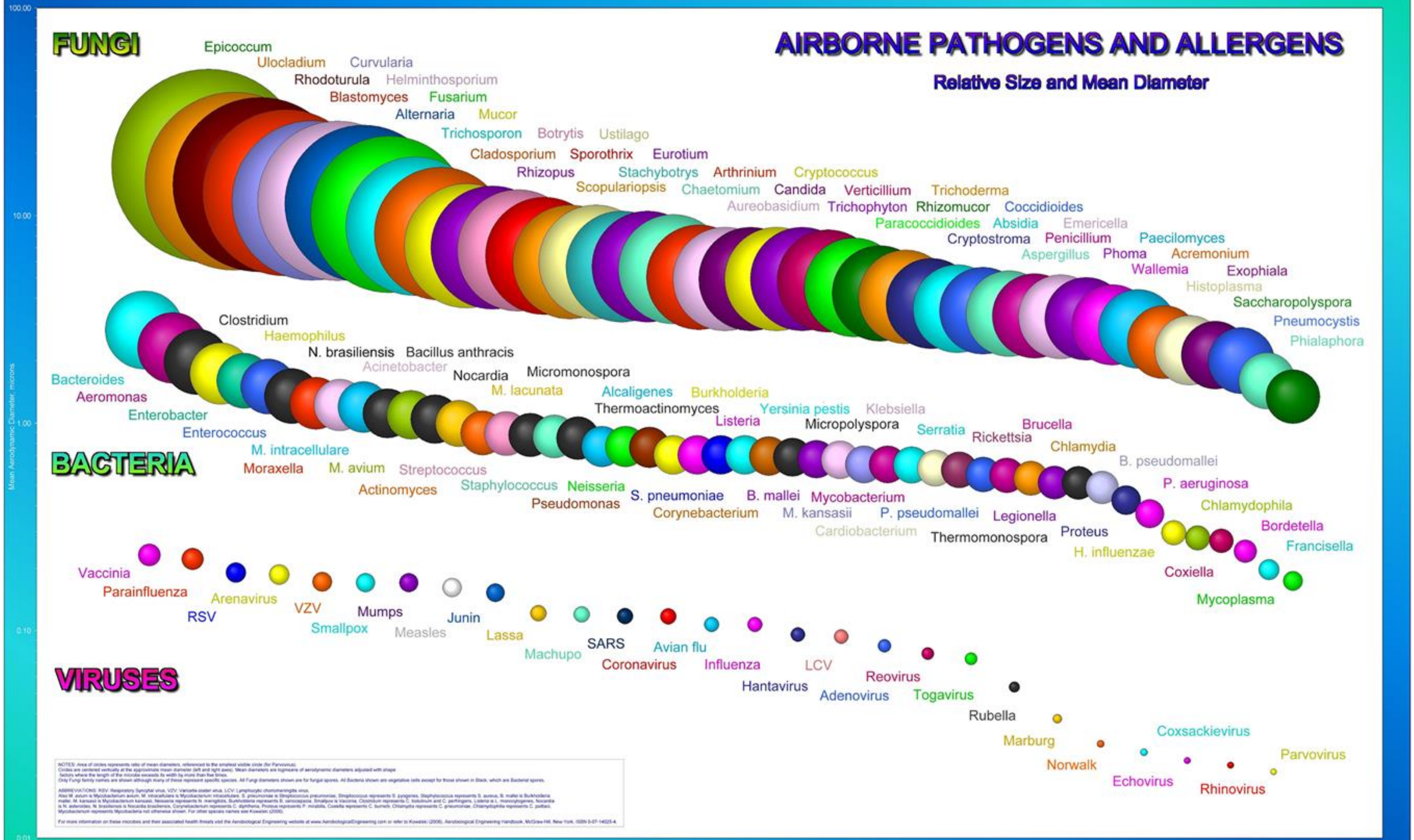
- A constant source of contaminants will cause room levels to increase until some steady state condition is reached
- Die-away tests demonstrate the rate at which microbes die off while airborne
- Completely Mixed Model results
- 2 ACH with 15% OA
- 15% Outside Air (OA) 15% Removal Efficiency (RE)
- Upper Room (UR) 87% RE + 15% OA
- MERV 13 Filter 98% RE + 15% OA
- In-duct UV 99.9% RE + 15% OA



Comparison of Outside Air, In-duct and Upper Room System Performance

- In-duct UV systems outperform typical Upper Room systems
- If power and airflow were boosted, Upper Room system performance could approach, but never exceed, the performance of an In-duct system





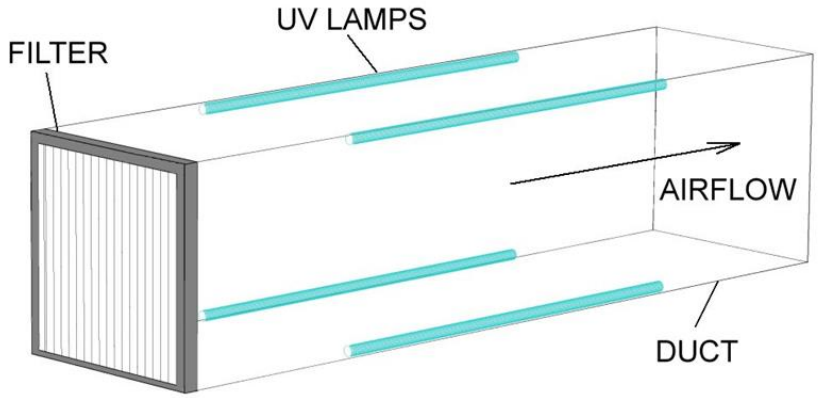
NOTES: Area of circles represents ratio of mean diameters, referenced to the smallest visible circle (for Parvovirus).
Circles are centered vertically at the approximate mean diameter (left and right axes). Mean diameters are log-means of aerodynamic diameters adjusted with shape factors where the length of the microbe exceeds its width by more than five times.
Only Fungi family names are shown although many of these represent specific species. All Fungi diameters shown are for fungal spores. All Bacteria shown are vegetative cells except for those shown in Black, which are Bacterial spores.

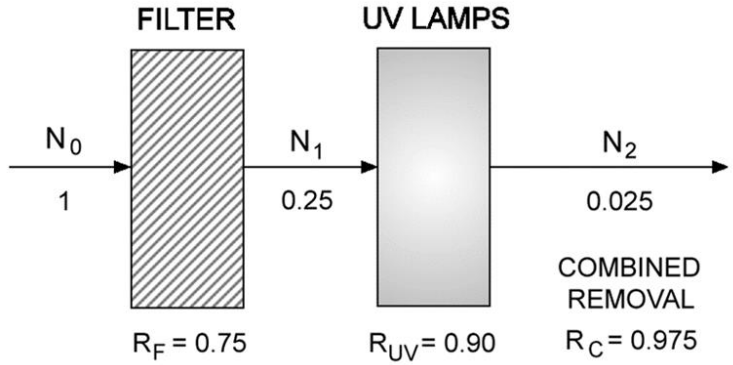
ABBREVIATIONS: RSV: Respiratory Syncytial virus, VZV: Varicella-zoster virus, LCV: Lymphocytic choriomeningitis virus.
Also M. avium is Mycobacterium avium, M. intracellulare is Mycobacterium intracellulare, S. pneumoniae is Streptococcus pneumoniae, Streptococcus represents S. pyogenes, Staphylococcus represents S. aureus, B. mallei is Burkholderia mallei, M. kansasii is Mycobacterium kansasii, Neisseria represents N. meningitidis, Burkholderia represents B. cepacia/pseudomallei, Smallpox is Vaccinia, Clostridium represents C. botulinum and C. perfringens, Listeria is L. monocytogenes, Nocardia is N. asteroides, N. brasiliensis is Nocardia brasiliensis, Corynebacterium represents C. diphtheria, Proteus represents P. mirabilis, Coxiella represents C. burnetii, Chlamydia represents C. pneumoniae, Chlamydophila represents C. psittaci, Mycobacterium represents Mycobacteria not otherwise shown. For other species names see Kowalski (2006).

For more information on these microbes and their associated health threats visit the Aerobiological Engineering website at www.AerobiologicalEngineering.com or refer to Kowalski (2006), Aerobiological Engineering Handbook, McGraw-Hill, New York, ISBN 0-07-140225-4.

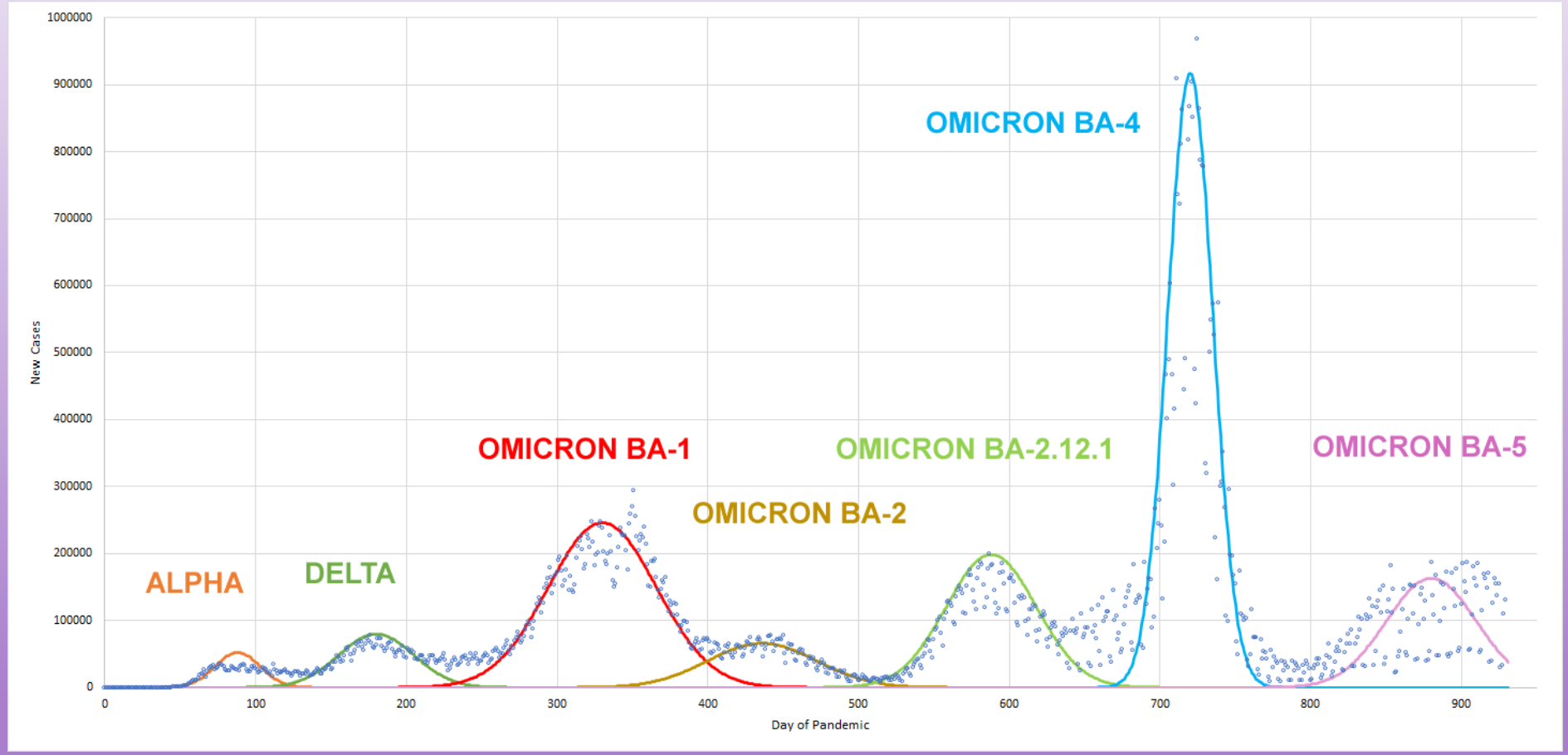
Combined Filtration & UV

- Combining filters with UV is an ideal solution for addressing the complete array of human pathogens
- Filters remove large spores, UV removes small bacteria and viruses
- MERV 13 is recommended by ASHRAE



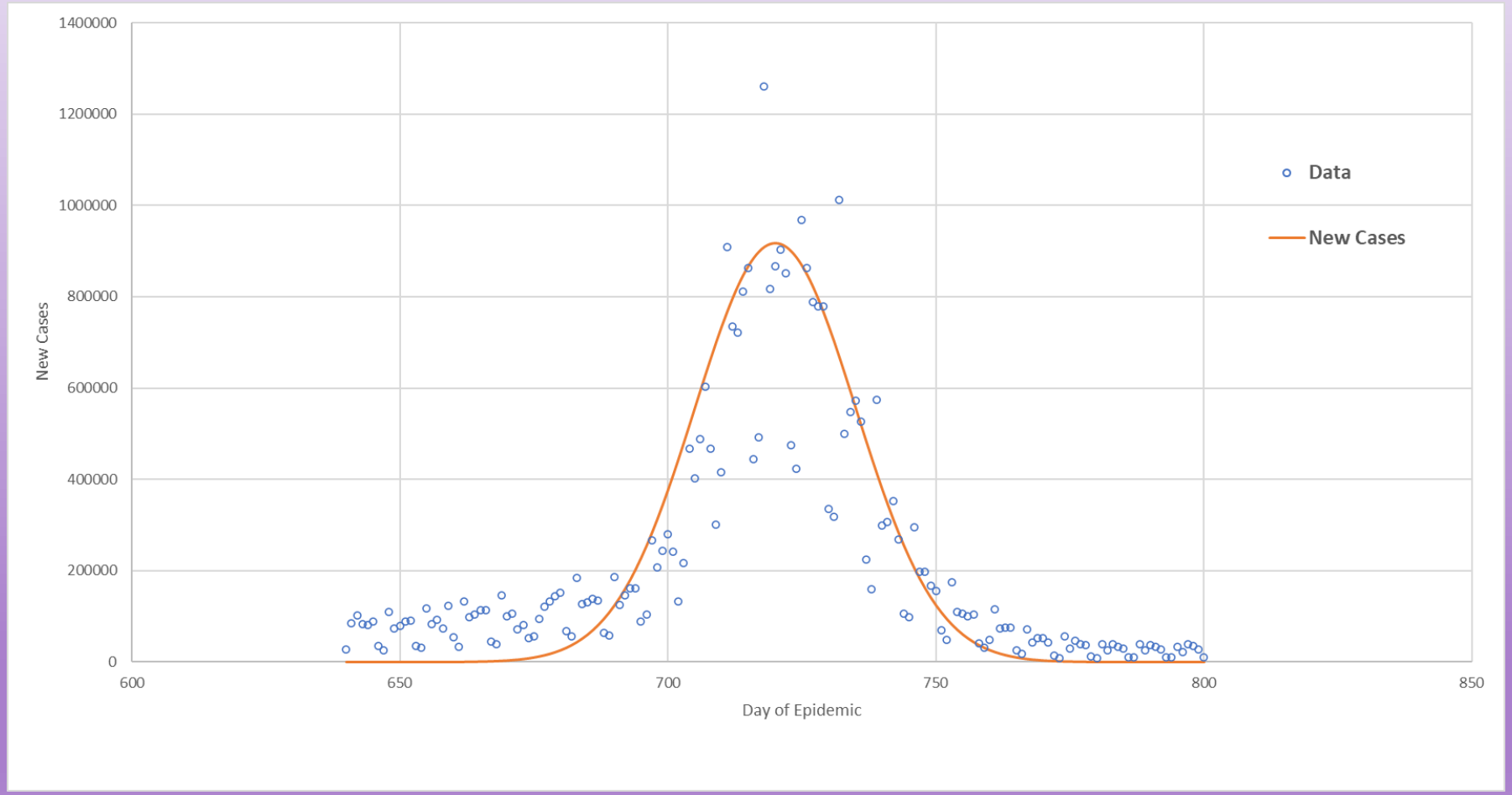


COVID-19 Epidemic Model for the USA



- 7 epidemic waves correspond to major variants
- Variant 6 is used as basis for modeling a single epidemic

COVID-19 Variant 6 Epidemic Model for the USA



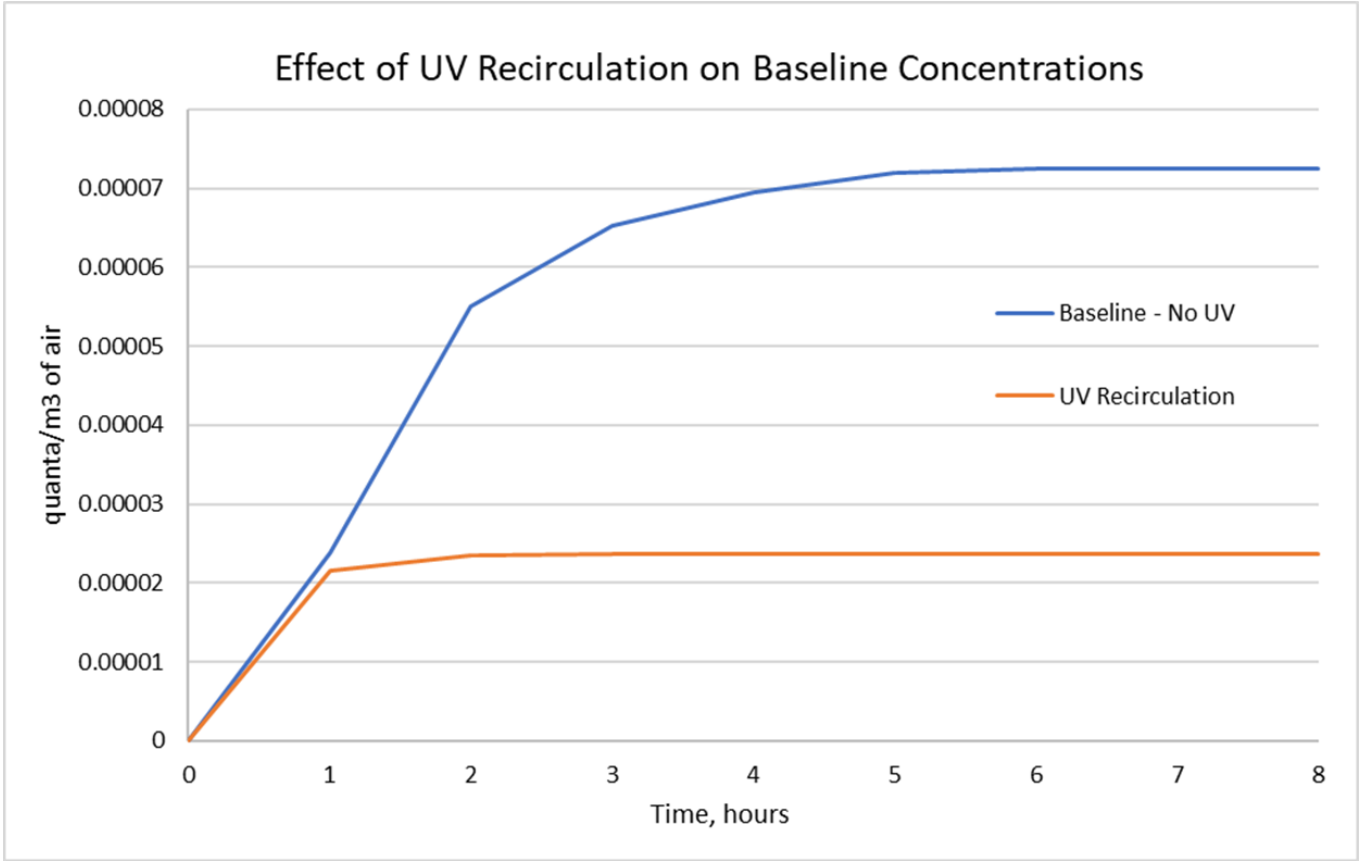
Wells-Riley/CONTAMW Model

- Model of COVID-19 Pandemic Wave 6 fit to the Wells-Riley epidemiological model
- CONTAMW provides a more detailed multizone model of epidemic wave

UV Type	Type	Number	Fraction of Population	Susceptibles	Baseline New Cases			quanta per person	ACH	ACM	ft2 per person	New Cases		% Reduction
					WR Model	Data	Contamw					Baseline	Contamw	
UV Ventilation	Office	1	0.26	86164000				502.12207	1.1	0.018333	176	8961035	10791.47	99.88
	Large	210	-	27985	2910	2908	2910.44	0.8	1.1	0.018333	160	2911	2.84	99.90
	Med	2210	-	16791	1746	1745	1746.26	0.8	1.11	0.0185	159	1746	1.87	99.89
	Small	10027.6	-	4306	448	447	447.82	0.8	1.12	0.018667	160	446	0.60	99.86
	SUM	86163805.6		49082										
Upper Room	School	1	0.23	76222000				517.97071	2	0.033333	115	7927087	50402.21	99.36
	Large	200	-	30000	3120	3117	3120	0.1135	1.24	0.020667	114.4	3106.103	0.191	99.99
	Med	6400	-	8000	832	831	832	0.1067	1.26	0.021	110	828.7868	1.13	99.86
	Small	47555	-	400	42	42	42	0.0813	1.32	0.022	100	41.54545	0.91	97.82
	SUM	76222000		38400										
Recirculation	Home	1	0.42	139188000				0.4	0.2	0.003333		23987250	835020.4	96.52
	Large	100000	-	20.0000	2.0800	2.0780	2.0800	0.019	0.1	0.001667	1800	2.079202	0.0142	99.32
	Med	8400000	-	7.0000	1.2133	1.2122	1.2133	0.0244	0.38	0.006333	800	1.212441	0.0500	95.88
	Small	26129330	-	3.0000	0.5200	0.5195	0.5200	0.00825	0.35	0.005833	424	0.520075	0.0158	96.96
	SUM	139187990		30										
				331400000								40875372	896214	97.81

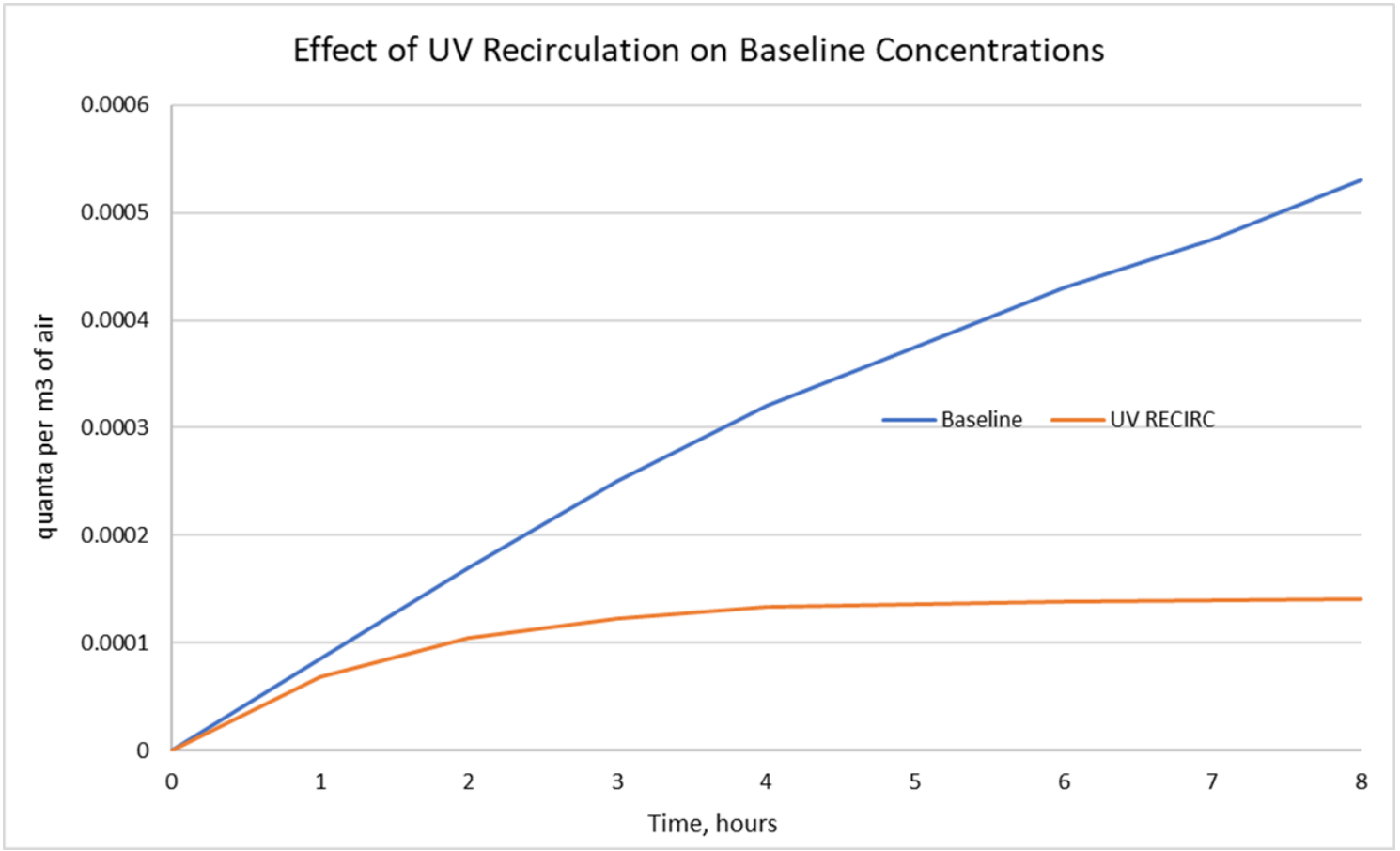
Medium Office Building CONTAMW Results

- Airborne Concentrations (quanta/m3) BEFORE vs. AFTER UV

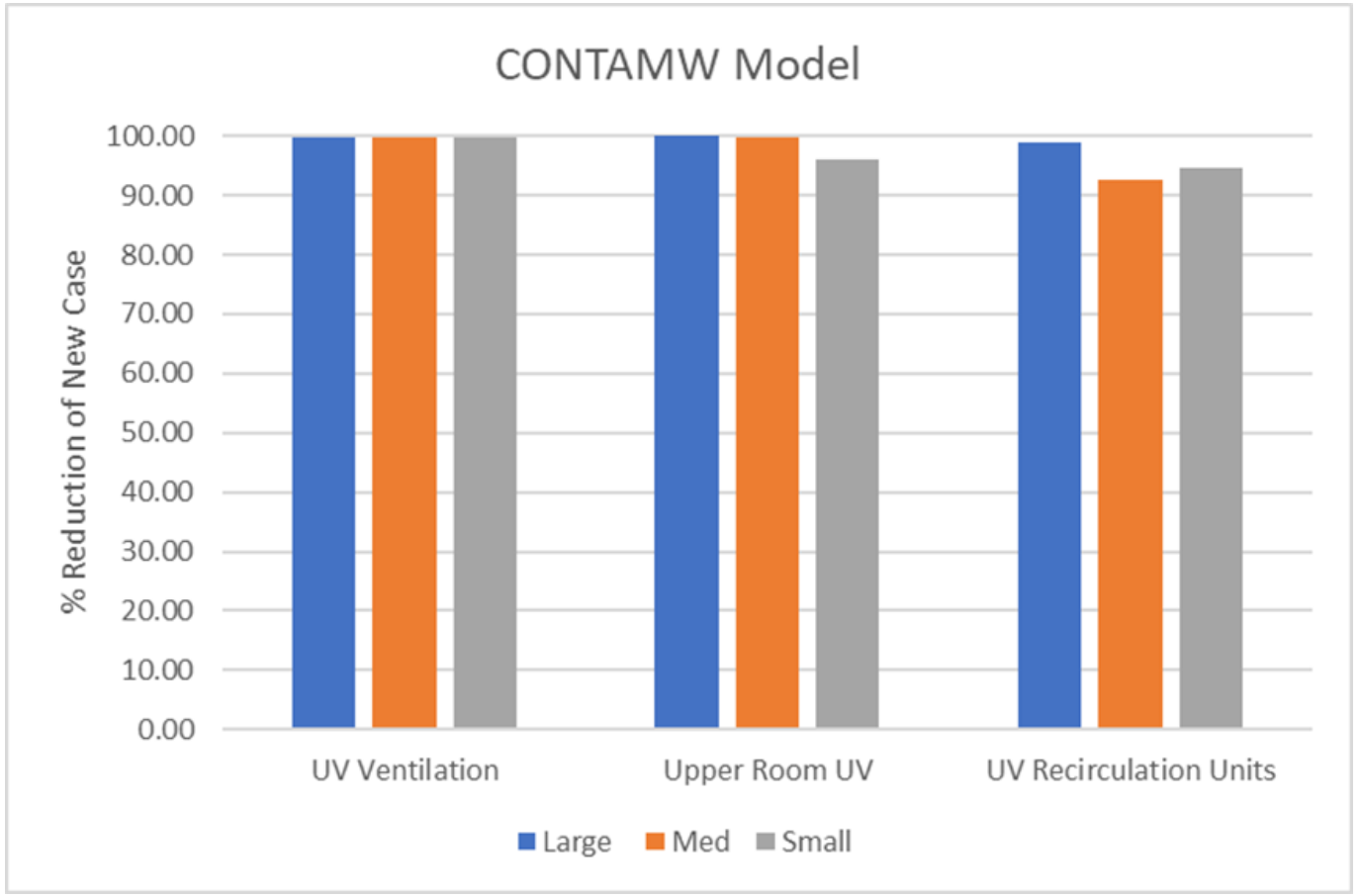


Medium Residential Building CONTAMW Results

- In these Naturally Ventilated Buildings - Concentration rises continuously for 8 hrs
- Steady State is not achieved
- Unventilated buildings may be a major contributor of New Infections

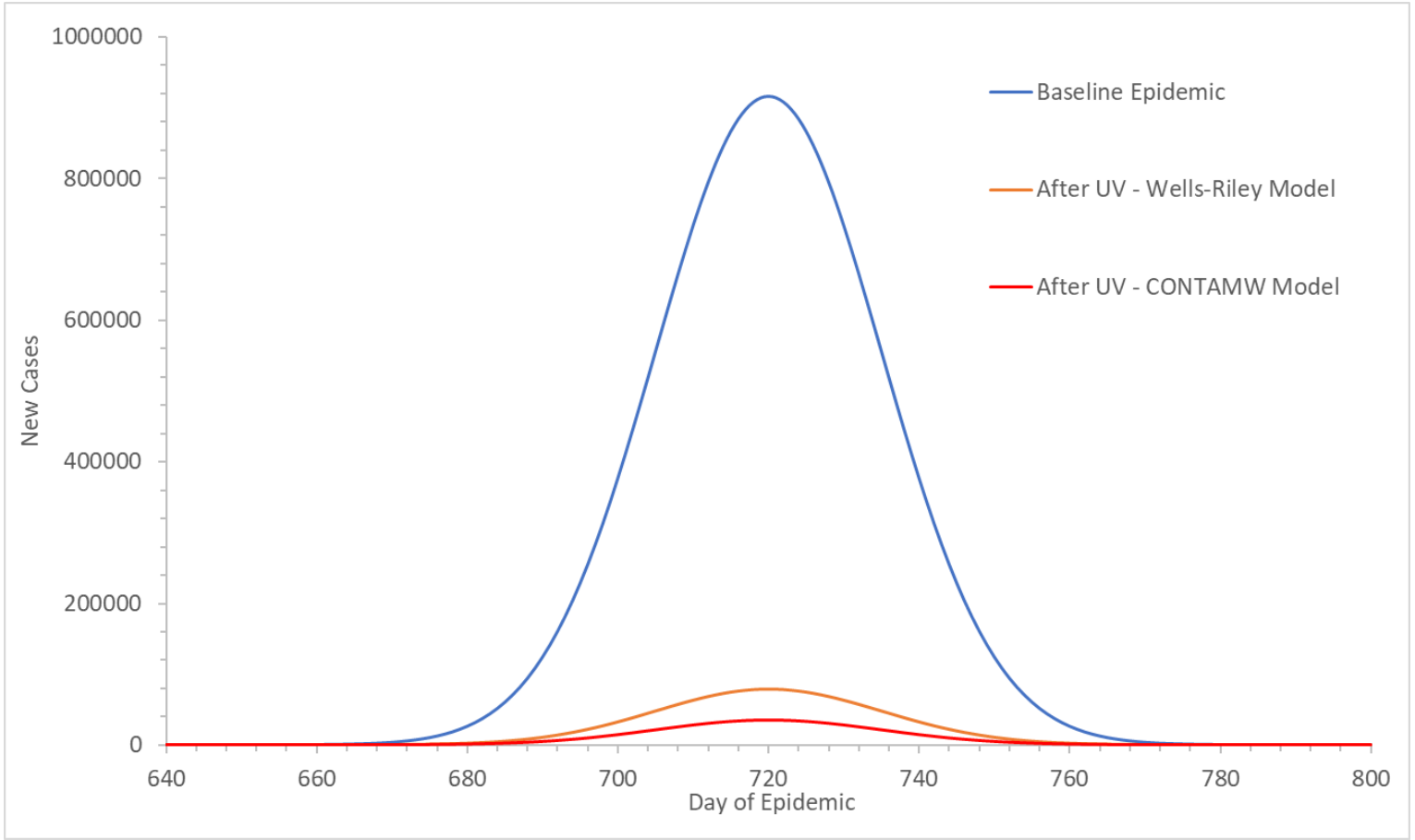


Model Predictions

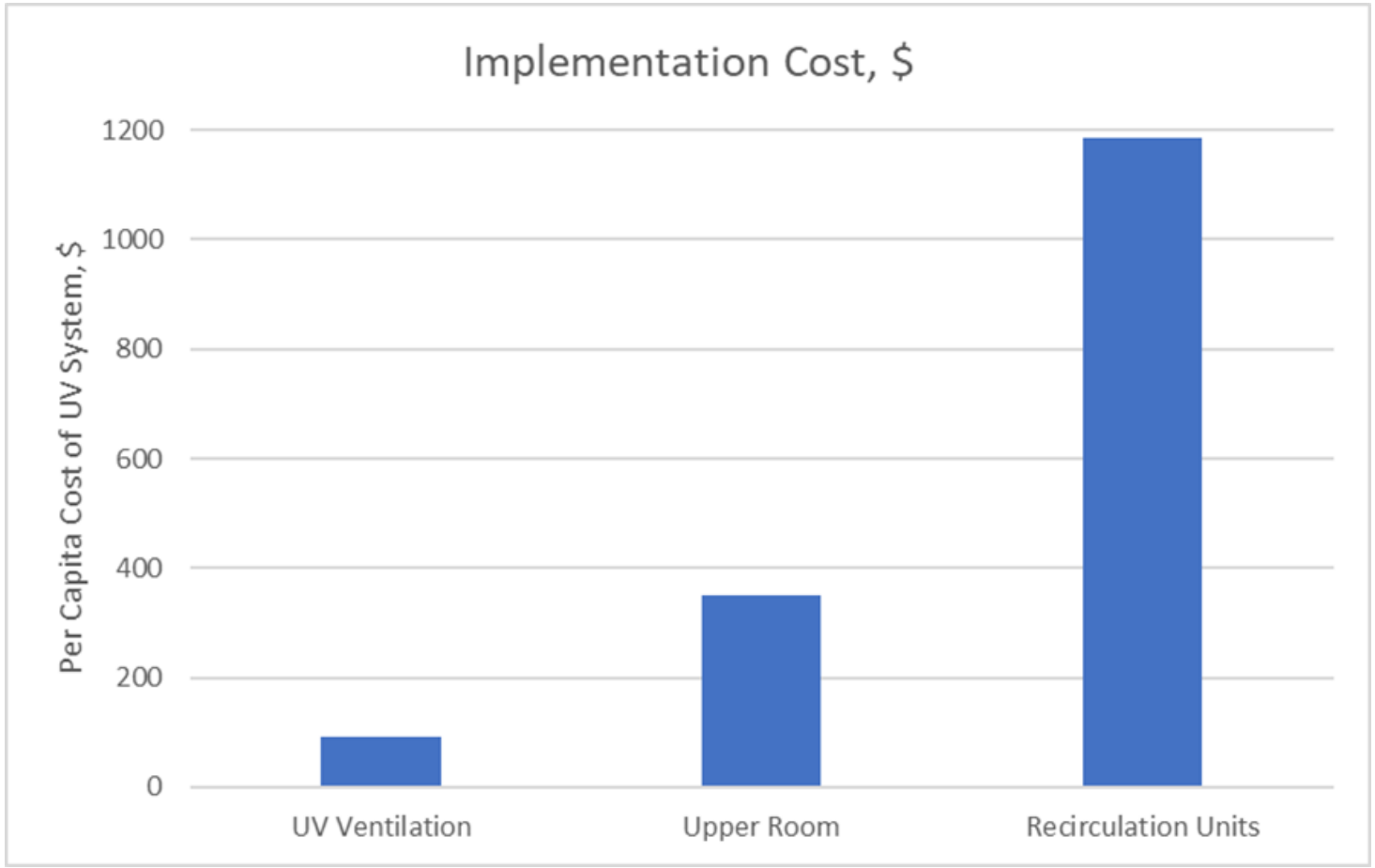


Model Predictions – ALL Buildings Combined

- All building types and sizes combined
- Wells-Riley Model: 92% Reduction of New Cases
- CONTAMW Model: 98% Reduction of New Cases



Per Capita Cost of Implementation



Questions ?