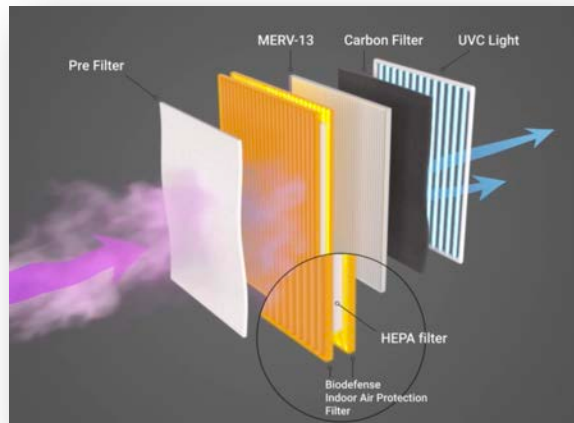# IVP Additional Information

- Specifications:

  o Mobile Units weight is ~ 150 lbs

  o Power usage is < 110V

  o Pressure drop across the HVAC retrofitted filter systems is either 0.8-1.2/500 CFM or is similar as before as it essentially replaces existing filter system with proprietary biodefense HEPA filters

  o The noise level for various settings are:

    ▪ <45 dB (Boost setting: High speed)

    ▪ <25 dB (Quiet mode: Low speed)

  o UV lamps with standard 100% 254 nm wavelength (fully enclosed within IVP mobile units), germicidal UV-C spectrum, cathode guard filament, Teflon® safety coating. [Dimensions - lamp: 8"L x 0.74" Dia., stainless steel lamp shield: 9.5" X 1", power supply: 5" x 2.5" x 1"].

  o Proprietary cutting-edge biodefense technology, for mobile units, that combines various modalities currently available (filtration, thermal and irradiation), such as IVP through its filtration (Pre-

filter, Biodefense Filter, HEPA, MERV, Carbon Filter), thermal (proprietary patent pending nickel-mesh proven to eliminate SARS-CoV-2) and irradiation (UV-C) will offer a more sound and comprehensive solution to help curb the spread of COVID-19 by eliminating the virus altogether rather than merely filtering it like HEPA offers (where the virus is not killed and rather merely secluded).

- o All IVP units have warning labels in accordance to FDA, UL, CADR, etc. certifications

    - NRTL: On-Site Field Inspections (Underwriters Laboratories: UL; ETL)

    - CA ARB certification for portable air cleaners (https://ww2.arb.ca.gov/resources/fact-sheets/complying-air-cleaner-regulation) – underway for specific products

    - Clean air delivery rate (CADR) is pending

- Additional Data from UH, TcSUH, UTMB, GNL & Texas A&M (TEES) Laboratories

    - o *Ozone Testing:* IVP's biodefense filter with augmented UV-C was tested for Ozone [O_3] under two conditions: Unheated Biodefense filter with UV as well as Heated (~200 ℃) Biodefense filter with UV. No O_3 was detected for the testing period spanning over 60 mins for either of these two conditions, as depicted in the figure.
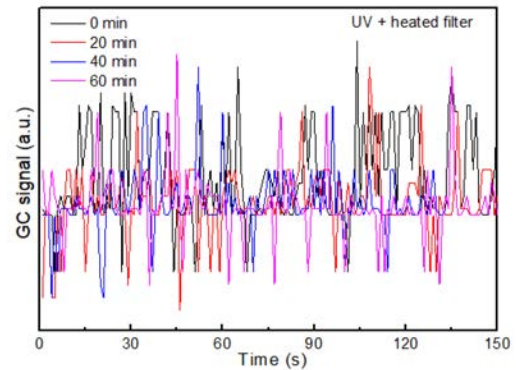
    - o *Test Rig used at TcSUH, UTMB & GNL:* The experiments were conducted using a test rig that was especially designed to be placed in the biosafety hoods of the BSL 3/4

facilities of Galveston National Laboratory. The test rig had actual proprietary

biodefense filter of IVP placed in it when the aerosolized experiments were conducted. It is correct that s1 unit itself


has not been tested for the efficacy of the virus owing to the unit's very large

dimensions which cannot be accommodated in the Galveston National Laboratory.

Regardless, the s1 units now include an even enhanced IVP's proprietary biodefense filter that is far superior than the one tested at Galveston National Laboratory. The accompanying figures depict the shape and form of the actual test rigs that were used in for the aerosolized experiments
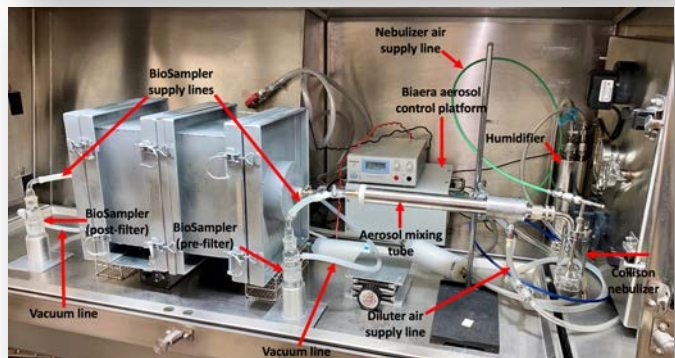
conducted on actual SARS-CoV-2 isolated from humans (SARS-CoV-2 Actual Virus

Stock ID: HPV 161 (31) SCoV2, USA WA1/2020. Prep. BK 11May20). Dimensions

of the test rig used in BSL GNL were ID: 9" wide x 12" tall x 20" long while OD: 13"

wide x 16" tall x 24" long with an overall weight of 45 lbs. Filter was assembled right in the middle of the test rig.

- Initial Results were published in:

  - Materials Today Physics

    - **Appendix A***: Full Text* – Yu L, Peel GK, Cheema FH, Lawrence WS, Bukreyeva N, Jinks CW, Peel JE, Peterson JW, Paessler S, Hourani M, Ren Z. Catching and killing of airborne SARS-CoV-2 to control spread of COVID-19 by a heated air disinfection system. Materials Today Physics. 2020 Dec;15:100249. doi: 10.1016/j.mtphys.2020.100249. Epub 2020 Jul 7. PMCID: PMC7340062.

    - **Appendix   B**: *Supplemental Information*
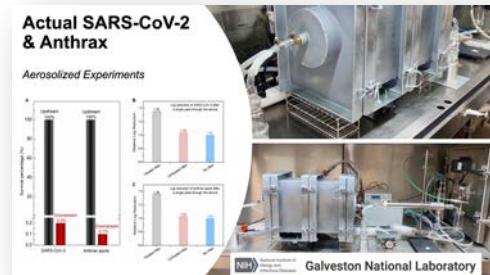
  - Preprints

    - **Appendix C**: Azimuddin, A.; Thakurdas, S.; Hameed, A.; Peel, G.; Cheema, F. Shifting Approach to Environmentally Mediated Pathways for Mitigating COVID-19: A Review of Literature on Airborne Transmission of SARS-CoV-2. Preprints 2020, 2020070194 (doi: 10.20944/preprints202007.0194.v1).

- White Paper:

  - **Appendix D:** Conventional HEPA alone is insufficient to address the COVID-19 pandemic. This white paper discusses the particular reasons why

conventional HEPA alone is not the solution, rather IVP proprietary biodefense technology powered indoor protection is the only promising solution. Below is a succinct summary of the scientific literature review as to why HEPA filtration alone, without an adjunct technology that kills the various, shall remain insufficient to counter the indoor spread of COVID-19.

- Scientific community has convincingly established airborne transmission of SARS-CoV-2 that finally both CDC and WHO now acknowledge this fact as well.

- High Efficiency Particulate Air (HEPA) filtration is a mechanism for purifying air from dust, pollen, mold, bacteria, and any airborne particles with a size of 0.3 microns (μm).

- Many viruses are small enough to pass right through HEPA filters.

- SARS-CoV-2 virions are around $60 - 140$ nanometers $(0.06 - 0.12\,\mu\text{m})$ in diameter.

- Whereas HEPA is effective against larger respiratory droplets and air pollution particles ($> 1\,\mu$m); it is not effective against transmission of smaller aerosols ($< 1\,\mu$m) that have been found to harbor the virions.

- HEPA is also not effective against volatile organic compounds (VOCs) due to their extremely smaller size.

- When viruses and bacteria are trapped in a HEPA filter, they:

   1. *Either* die and decompose to release endotoxins which are small enough to pass through a HEPA filter.

2. *Or* remain alive and continue to multiply to grow that makes the filters moldy. Thus, live pathogens can spread through HEPA in various ways, for instance:

> i. Various studies on viability of organisms (Maus et al & others) it was found that ~1/3rd of pathogens can remain alive in the filter for ~ 1 year. This high concentration of trapped organisms predisposes the live virulent bacteria/viruses to travel across and be released on the other side as high throughput of air forces pathogens across HEPA filter.

> ii. Majchrzycka et al. (2016) proved that the survivability of microorganisms on filter materials depends on the amount of accumulated moisture and microorganism type.

> iii. Under the working condition, microbes in the HEPA filter could be inspired into the air.

> iv. Gore et al. (2003) reported that the old HEPA-filter vacuum cleaner markedly increases the inspired cat allergen in operation compared with baseline.

v. Spores were also detected downstream of the filters after a longer period of conditioning when ventilation was restarted.

vi. These all indicated the microbes in the HEPA filter could be an important exposure source. Given the fact that SARS-CoV-2 is much smaller in size compared to these microbes reported in these studies, it is clear that viruses can pass through the HEPA with much ease.

vii. Changing of the filters leads to another source of spread of live bacteria/viruses trapped within HEPA.

- With approximately 60-140 nanometers (0.125-micron) in diameter, SARS-CoV-2 will only be partially captured by 300 nanometers (0.3-micron) HEPA test standard. Whereas HEPA filters with extraordinary efficiency of 10 nanometers (0.01 micron) and above are actually most efficient against SARS-CoV-2 but at that level of efficiency the flow of air and static drop in pressure makes them practically impossible to be used in standard HVAC and other devices where high throughput of air is critically needed given the size of the closed indoor spaces where their use is intended. HEPA purifiers, therefore, will prove only marginally useful in the fight against coronavirus. These all facts indicate the microbes in the HEPA filters could in fact be an important source of exposure and unless killed

while trapped, they could lead to more harm if and when the pass through on the other side of the HEPA filter as aforementioned.

- Filtration only captures and does not kill the virus. Therefore, in order for complete effectiveness, mere filtration would not be sufficient. When compared to IVP technology which offers filtration (through HEPA), irradiation (through UV-C) and thermal (through proprietary nickel-foam), it is clear that HEPA only will fall way short as it does not kill the virus and therefore must not be considered a first line of defense against the COVID-19 virus.

- In conclusion, whereas various technological solutions are coming forth amidst this pandemic to ensure clean indoor environments, mere filtration (through HEPA/MERV) remains widely insufficient as they do not kill rather only filter SARS-CoV-2. Furthermore, several studies have shown that HEPA filters are used for a long time which leads to a higher proportion of viable (live) bacteria and viruses trapped within. Considering the significantly increased bacterial/viral quantities trapped within the HEPA coupled with the fact that they remain alive for longer period of time and are predisposed to crossing the HEPA due to various reasons, as described above, **HEPA filters should be recognized as a new ecological niche in indoor environment and should in fact be included in evaluation of indoor environmental health risk factor.**

- Unpublished results from UTMB & GNL

    - **Appendix E:** Since the original manuscript was actually focused on physics and not biology; therefore, we have since repeated experiments and validated results and those subsequent studies (currently unpublished data) have all shown that with a 240-fold increase in the starting viral concentration compared to our published viral counts, a 99.99% kill of the virus was achieved in v2.0 of IVP's biodefense filter. A 3+ log reduction was achieved in these experiments using a single pass.

- Unpublished results from Texas A& M (TEES)

    - **Appendix F:** A sub-second exposure to the heat confirms 5-6 log reduction in a quasi-coronavirus validating IVP's biodefense technology.

- Unpublished results from UTMB & GNL:

    - **Appendix G:** Aerosolized SARS-CoV-2

    - Table depicts SARS-CoV-2 aerosol droplet size distribution

Size Bin [um]:	Counts:	Rel Mass
0.542	27151	2161.492
0.583	46433	4600.472
0.626	72102	8843.829
0.673	102072	15556.856
0.723	115474	21820.721
0.777	105230	24681.561
0.835	82403	23986.808
0.898	62031	22459.899
0.965	46956	21098.085
1.04	36366	20453.402

1.11	28748	19658.328
1.2	22701	19613.664
1.29	17799	19104.459
1.38	14264	18743.41
1.49	11313	18711.414
1.6	9039	18511.872
1.72	7919	20147.71
1.84	6443	20068.347
1.98	5742	22285.827
2.13	4128	19945.664
2.29	2869	17226.895
2.46	2023	15058.136
2.64	1661	15280.987
2.84	1394	15965.694
3.05	1256	17818.008
3.28	874	15420.66
3.52	570	12430.049
3.79	451	12276.206
4.07	382	12877.056
4.37	303	12643.198
4.7	187	9707.451
5.05	99	6374.987
5.43	56	4482.884
5.83	41	4062.183
6.26	12	1471.886
6.73	3	457.232
7.23	3	566.9
7.77	6	1407.292
8.35	1	291.091
8.98	0	0
9.65	1	449.316

10.4	2	1124.864
11.1	1	683.815
12	0	0
12.9	0	0
13.8	0	0
14.9	0	0
16	0	0
17.2	0	0
18.4	0	0
19.8	0	0
Total Counts = 836509 particles		
CMAD = 0.78 um		
MMAD = 1.60 um		
GSD = 1.92		
Dilution = 100 :1		
APS Sample Completed at 00:02:33 of Run		

Appendix A
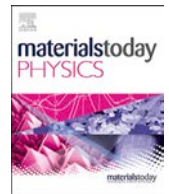
Catching and killing of airborne SARS-CoV-2 to control spread of COVID-19 by a heated air disinfection system

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ABSTRACT

Airborne transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) via air-conditioning systems poses a significant threat for the continued escalation of the current coronavirus disease (COVID-19) pandemic. Considering that SARS-CoV-2 cannot tolerate temperatures above 70 °C, here we designed and fabricated efficient filters based on heated nickel (Ni) foam to catch and kill SARS-CoV-2. Virus test results revealed that 99.8% of the aerosolized SARS-CoV-2 was caught and killed by a single pass through a novel Ni-foam—based filter when heated up to 200 °C. In addition, the same filter was also used to catch and kill 99.9% of Bacillus anthracis, an airborne spore. This study paves the way for preventing transmission of SARS-CoV-2 and other highly infectious airborne agents in closed environments.

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Coronavirus disease-2019 (COVID-19), caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), is a rapidly spreading pandemic that is severely threatening public health all over the world [1—6]. In accordance with the World Health Organization, as of June 25, 2020, there have been more than 9.4 million confirmed cases in 216 countries, areas, or territories, leading to at least 484,249 deaths [7]. The rapid spread of COVID-19 is related to SARS-CoV-2 carriers being highly infectious while asymptomatic and the high capability of the virus to survive in various environmental conditions [8—10]. The most probable SARS-CoV-2 transmission route is human-to-human [11—13], which may explain why cluster spread was the main reason for the quickly increasing cases of COVID-19 in early February 2020 in Wuhan, China [14]. In addition, the consensus among scientists is that the virus is also transmitted through aerosols and droplets that are released into the air by a carrier, especially when the person coughs, sneezes, or even talks forcefully in a closed environment [15,16]. A recent study compared simulated SARS-CoV-2 aerosols to those of SARS-CoV-1 [17], its most closely related viral strain and the cause of the 2003 SARS outbreak in Asia, and showed that, comparable with the case of SARS-CoV-1, aerosols containing SARS-CoV-2 can remain in the air for about 3 h, although their viral load continually diminishes during that time. In the same study, it was also found that the virus contained in droplets that settled on various surfaces can remain viable for several days.

Having confirmed airborne transmission of SARS-CoV-2, a mode of transmission that is relevant to several previously known respiratory viruses, including influenza, scientists are now questioning whether the virus can travel even greater distances through the air by becoming lodged in other airborne particles such as condensed water vapor or even dust. Such a mode of transmission would be extremely concerning and would call into question the adequacy of measures that are mostly designed to address issues related to proximity to an infectious individual, such as wearing masks, washing hands, and surfaces, and general social distancing. One of the earliest studies addressing this subject indicated that such transmission may be possible for SARS-CoV-2 [18]. The study looked at certain indicators of airborne viral spread in a Wuhan hospital where patients with COVID-19 were kept in isolation. With all available precautions in place to prevent viral spread through

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personnel or equipment, viral RNA was still detected in areas of the hospital that it could only have reached through the atmosphere or the ventilation system [18]. Currently, with increasing numbers of people returning to the workplace, the chances of infection resulting from aerosol transmission through central air-conditioning systems are increasing. Thus, determining how to stop the virus from spreading in air-conditioned spaces is extremely urgent. Simple filtration cannot completely stop the spread. Fortunately, most viruses, including SARS-CoV-2, are not resistant to high temperature [19,20]. It has been demonstrated that the time needed for SARS-CoV-2 inactivation is reduced to 5 min when the incubation temperature is increased to 70 °C [21]. Therefore, if a filter in an air conditioner can be heated to a high temperature (e.g. up to 250 °C), any SARS-CoV-2 in the cycling air can be efficiently killed in a very short time. An even more challenging task is to prevent the transmission of other airborne highly infectious agents that have been used for bioterrorism, such as *Bacillus anthracis* (anthrax) spores, which are large ($1-1.5$ μm $\times$ $3-10$ μm in size), aerobic, gram-positive, spores that have long been considered biological warfare agents [22].

Traditional air conditioner filters based on fiberglass or aluminum (Al) mesh are difficult to heat or have large pores (about 1 cm in size), hence they cannot effectively catch and kill the virus contained in aerosols (generally smaller than 5 μm in size) [23] or other airborne highly infectious agents, such as anthrax spores. An ideal filter should be self-heated rather than have an external heat source that would surely cause a very large rise in air temperature, which requires that the filter itself be electrically conductive. Commercial nickel (Ni) foam is electrically conductive and mechanically strong and it exhibits good flexibility, properties that have prompted its wide use in energy conversion and storage applications [24–26]. More importantly, Ni foam is highly porous with randomly located pores that are between 50 and 500 μm in size and that meander from one side of the foam to the other, resulting in a very large surface area that can effectively catch particles in the air passing through the filter due to van der Waals forces. The self-heated filter has the additional advantage that the heating is localized on the Ni foam and heat transfer to the passing air is minimal due to the short time of contact between the air and the Ni foam. Therefore, Ni foam may act as a good filter for catching and killing SARS-CoV-2 or anthrax spores in air-conditioning systems. However, it is extremely challenging to design such a filter because the resistivity of Ni foam is too small to achieve heating at a sufficiently high temperature. To realize a filter for preventing the spread of SARS-CoV-2 and anthrax spores, here we designed and fabricated a filter device consisting of folded pieces of Ni foam in multiple compartments connected electrically in series to efficiently increase the resistance to a manageable level so that a temperature up to 250 °C was able to be achieved and found that the filter device exhibits almost 100% ability to catch and kill aerosolized SARS-CoV-2 and anthrax spores in air passed once through the Ni foam heated up to 200 °C (temperature optimization will be addressed in a future study). Our study demonstrates the possibility of applying commercial Ni foam as an air conditioner filter for use in airplanes, airports, hospitals, schools, office buildings, restaurants, hotels, cruise ships, and so on. for 100% removal of SARS-CoV-2 in cycling air, thus slowing the spread of COVID-19, as well as to prevent transmission of other airborne highly infectious agents such as anthrax spores.

The optical image in Fig. 1A shows that commercial Ni foam has typical metal luster, and it is highly flexible, and hence it can be easily molded into different shapes similar to the accordion folds shown in Fig. 1B. Owing to its high porosity of $\geq$95% (Fig. S1A), Ni foam also exhibits very high air permeability, as indicated by the clear observation of light passing through Ni foam under the glare

of a fluorescent lamp (Fig. 1C). The Ni foam pore size is in the range of $\sim$50$-$500 μm, and the diameter of a single Ni wire is about 65 μm, as seen in the scanning electron microscope (SEM) images in Fig. 1D and E, respectively. The cross-section SEM (Fig. 1F) and optical (Fig. S1B) images further reveal that the thickness of the Ni foam is around 1.6 mm and that the Ni wires in the foam are randomly interconnected with one another, creating a three-dimensional (3D) network structure with many non-straight channels. Therefore, although the aerosols containing SARS-CoV-2 or anthrax spores are smaller than the pores in the Ni foam, it remains highly probable that the aerosolized SARS-CoV-2 and anthrax spores will be captured by the heated Ni wires due to the meandering path, in contrast to the straight path resulting from the well-organized wires in an Al mesh. It should be noted that the thickness, pore size, and porosity of Ni foam can all be easily controlled during the manufacturing process in case different pore sizes are required for different sizes of viruses or other infectious agents. The X-ray diffraction (XRD) pattern in Fig. 1G demonstrates the pure phase of Ni with strong diffraction peaks from the (111), (200), and (220) planes. We then calculated the electrical resistivity (ρ) of a strip of commercial Ni foam 250 mm $\times$ 10 mm $\times$ 1.6 mm in size. From the slope of the current (I)-voltage (V) curve shown in Fig. 1H, the resistance (R) of the Ni foam is about 0.178 Ω, therefore the ρ is calculated to be around 1.42×10^{-5} Ω m, indicating good conductivity. Thus, we can electrically heat a piece of Ni foam to the required temperature under a certain input power. As shown in Fig. 1I, the temperature of the Ni foam increases very quickly under increasing input power, and it reaches to about 119 °C when the input power is $\sim$6.6 W.

For use in air conditioners, we must also consider the temperature of the air after it passes through the heated Ni foam; if the air temperature becomes too high, the heated Ni foam would not be suitable for large-scale application. To test this, we blew high-purity nitrogen (N_2) gas toward one side of the heated Ni foam and measured the air temperature at different distances away from its opposite side. The distance between the N_2 gas source and the heated Ni foam was $\sim$3.5 cm and the room temperature was about 21.7 °C. From the results shown in Fig. S2, we can see that the air temperature decreases very quickly after passing through the heated Ni foam. Even for the Ni foam with a high temperature of 115.3 °C, the air temperature is close to room temperature at 4 cm away. Therefore, we do not need to be concerned about the air temperature becoming too high after passing through the hot Ni-foam filter. It should be noted that the resulting air temperature inside ductwork may be slightly higher than in an open environment as we tested.

Owing to the very low resistivity of Ni foam, it is not possible to simply use a single piece of Ni foam as a filter that satisfies both the size requirement for heating, ventilation, and air-conditioning (HVAC) systems and the U.S. residential voltage requirement (110 V). Considering the flexibility of Ni foam, we designed a folded structure (Fig. 2A) that exhibits much larger resistance due to its significantly increased length, ideally addressing both of the aforementioned requirements. In addition, compared with a flat Ni-foam filter, the folded one has two other advantages. First, as illustrated in Fig. 2B, if the thickness of the Ni foam is 1.6 mm, the distance for catching and killing viruses or other infectious agents is only 1.6 mm when it is flat. However, after folding, the effective distance can be much longer, for example, 10 times that for the flat Ni foam if considering a bending length of 1.6 cm, because the gaps within the folds retain sufficiently high temperature to kill viruses and other infectious agents efficiently. It should be noted that the bending length can be easily controlled, and the longer the bending length, the higher the temperature. Second, compared with the flat Ni foam with two main sides exposed to the air, the folded Ni foam
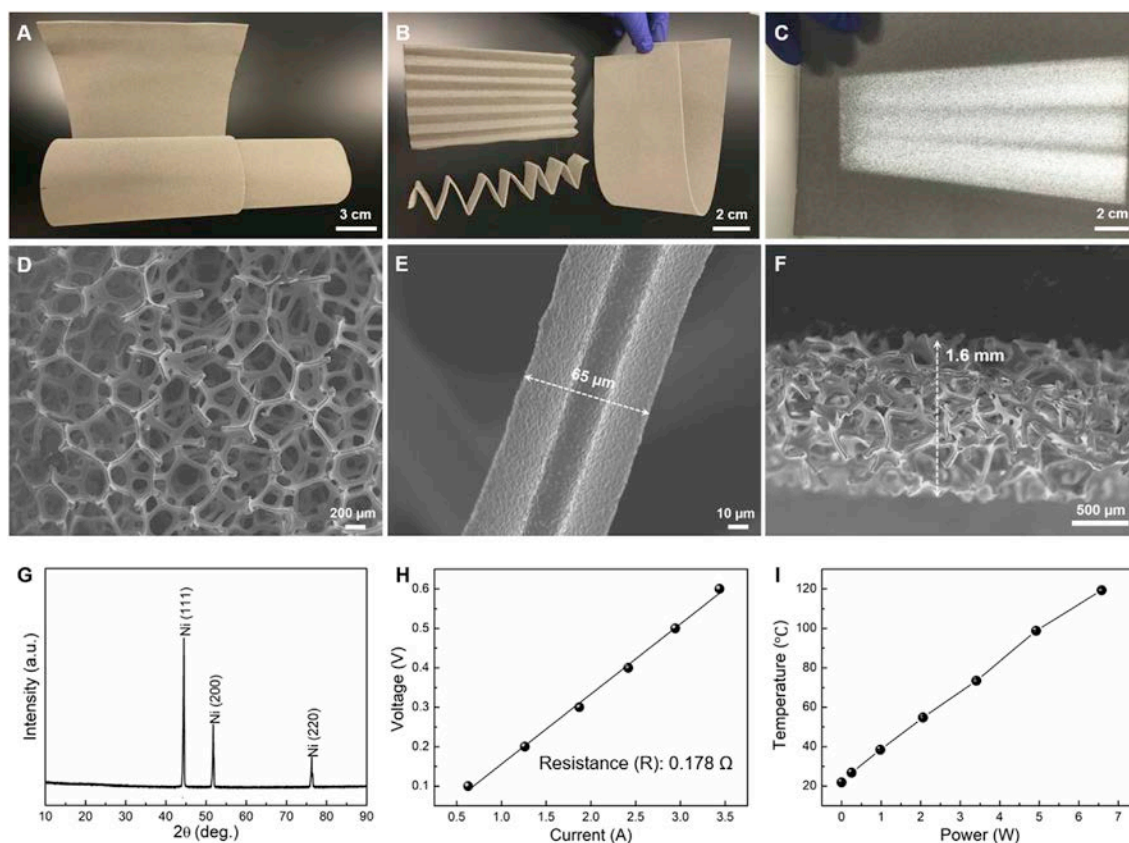
Fig. 1. Basic properties of commercial Ni foam. (A–C) Photographs under different conditions. Photograph (C) was taken under the glare of a fluorescent lamp. (D, E) Surface SEM images at different magnifications. (F) Cross-section SEM image. (G) XRD pattern. (H) I-V curve of a strip of Ni foam 1.6 mm × 250 mm × 10 mm in size. (I) T-P curve showing the relationship between the Ni foam temperature and the input power.
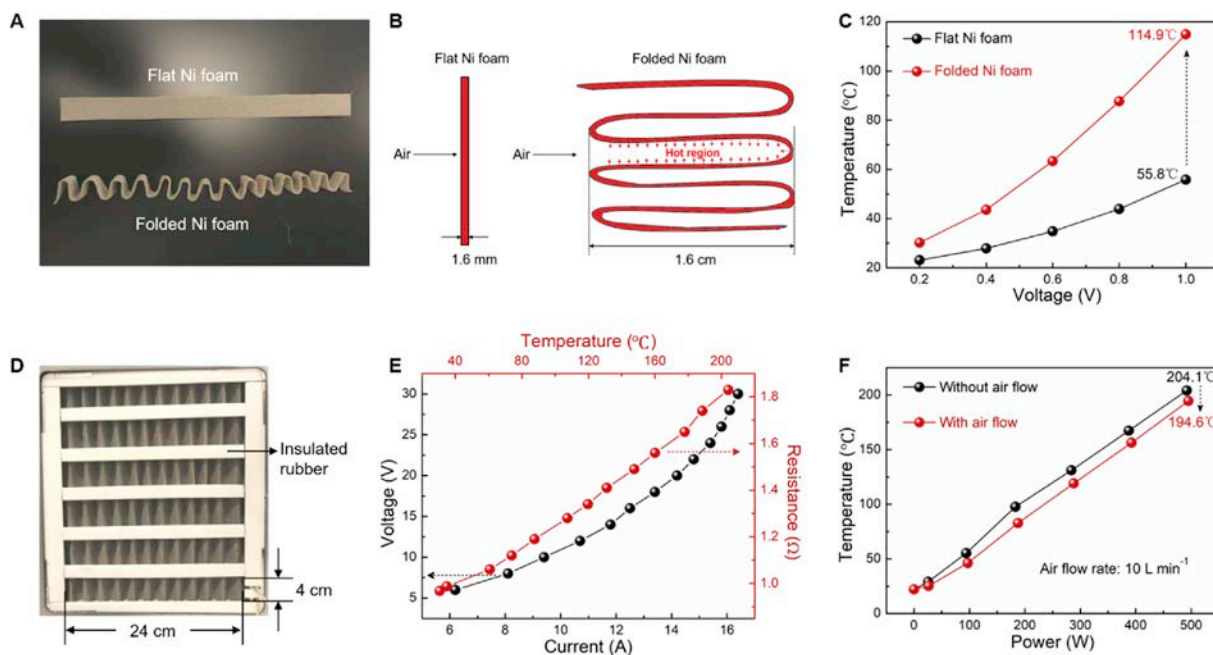

Fig. 2. Study of Ni foam as a filter. (A) Photographs and (B) side-view schematic illustrations of flat Ni foam and folded Ni foam. (C) Temperature comparison between flat Ni foam and folded Ni foam under the same voltage. The Ni foam is 20 mm × 250 mm × 1.6 mm in size, and the bending length is about 1.6 cm. (D) Photograph of the fabricated filter using six pieces of folded Ni foam connected electrically in series. (E) I-V and T-R curves of the filter. (F) T-P curves of the filter with and without air flow (high-purity N_2 gas).

has a much smaller surface area exposed to the incoming and outgoing air, which minimizes the heat loss so that the temperature of the Ni foam increases much more quickly and can reach a much higher value at the same power consumption. As shown in Fig. 2C, under the same voltage of 1.0 V, the temperature of the folded Ni foam is 114.9 °C, which is more than twice that of the flat Ni foam (55.8 °C).

Finally, we fabricated filters (Fig. 2D) that each use six pieces of folded Ni foam connected electrically in series, which effectively increases the total resistance to a manageable level so that regular gauge electrical wires can be used. To enhance the efficiency for catching and killing SARS-CoV-2 and anthrax spores, two filters were parallelly assembled inside a closed device (Fig. S3). We first studied the I-V and temperature (T)-resistance (R) curves for the filter. As the results in Fig. 2E show, the Ni-foam filter exhibits a typical metal property, in which the resistance increases with increasing temperature. We further investigated the influence of air flow on the temperature of the filter, and the results are shown in Fig. 2F. Clearly, with an air flow rate of 10 L min^{-1}, the temperature of the filter shows a slight decrease of about 10 °C under the same input power relative to that without air flow.

The prototype device was tested using aerosolized actual SARS-CoV-2, isolated from humans, and encouragingly demonstrated 99.8% viral load reduction from upstream to downstream in the device using a single passthrough when the filters were heated up to 200 °C (temperature optimization is currently being studied). As shown in Fig. 3A, by using the median tissue culture infectious dose (TCID50) method for determining viral titer reduction, we confirmed that, the heated filters significantly reduced the viral titers of SARS-CoV-2 through a single pass in this prototype device. After the successful demonstration of catching and killing almost 100% of the SARS-CoV-2, we designed similar experiments for testing the elimination of *Bacillus anthracis* (anthrax spores) in a

separate prototype device, which is more challenging. Strikingly, the heated Ni-foam filter was found to catch and kill 99.9% of the anthrax spores through a single pass in the prototype device (Fig. 3A). Compared with the unheated filter or the control without a filter, a remarkable 1.2 (Fig. 3B) or 1.21-fold log reduction (Fig. 3C) for the anthrax spores calculated by an aerosol method or a Bio-Sampler method was achieved when the Ni-foam filter was heated, indicating high efficiency in killing of anthrax spores and the SARS-CoV-2.

The deployment of these novel filter and purification units stands to have a dramatic impact on both essential workers and the general public in the current COVID-19 pandemic, as well as reducing the risk of exposure to other airborne highly infectious agents, both known and unknown. With a phased rollout, beginning with high-priority venues where essential workers are at elevated risk of exposure (particularly hospitals and health-care facilities, as well as public transit environs such as airplanes), this innovative technology will (a) improve the safety for front-line workers in essential industries by minimizing the risk of SARS-CoV-2 exposure, (b) make it possible for non-essential workers to safely return to public work spaces by reducing their risk of exposure, and (c) allow for the general public to more safely reengage with their own communities through the creation of mobile air-purification devices that can be carried on one's person to maintain clean personal air space. These outcomes will enable resilience in the battle against COVID-19, in which the front lines are everywhere and rapidly changing. This technology will also provide for safe bioagent protection gear to eliminate future bioterrorism threats from airborne infectious agents such as anthrax. The air purification and disinfection system derived from this Ni-foam–based heated filter will be a useful addition in the armamentarium of technologies available to combat future pandemics.
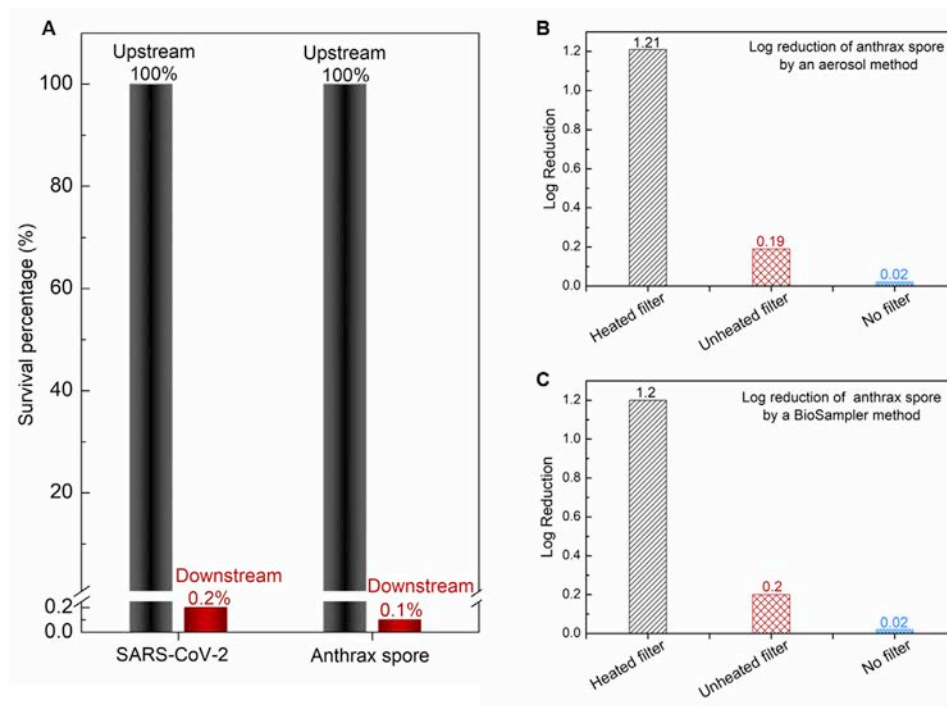

Fig. 3. Performance of prototype device on aerosolized SARS-CoV-2 and *Bacillus anthracis*. (A) Absolute reduction of TCID50 of aerosolized SARS-CoV-2 and *Bacillus anthracis* by heated filters, showing 99.8% and 99.9% reductions, respectively, between predevice and postdevice levels. Log reduction by the heated filter, unheated filter, and control (no filter) for *Bacillus anthracis* calculate by (B) an aerosol method and (C) a BioSampler method.

Author contributions

MH and GKP conceived the filter concept for eliminating the airborne viruses. ZR and LY conceived the electrically conducting porous filter idea. CJ made the testing systems. ZR, LY, GKP, JWP, SP, and FHC designed the experiments. LY performed all the temperature and power measuring experiments and collected the data. WSL, JEP, and NB conducted the virus and spore experiments, and analyzed the data. LY, ZR, GKP, and FHC analyzed all the data and results, and wrote the article. All authors contributed to the discussion of the results and commenting on the manuscript.

Declaration of competing interest

MH filed a provisional patent application on the work described here. The other authors do not have any conflict of interest to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mtphys.2020.100249.

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Appendix B

Supporting Information for

Catching and killing of airborne SARS-CoV-2 to control spread of COVID-19 by a heated air disinfection system

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Materials and Methods

Ni foam

Pieces of commercial Ni foam were purchased from MTI Corporation in USA and Kunshan Jiayisheng Electronics Co Ltd in China. Both have very similar properties in terms of purity (>99.99%), surface density (346 g m^{-2}), thickness (1.6 mm), and porosity (≥95%). The pieces of Ni foam were used without any treatment.

Morphology and nanostructure

The surface morphology and nanostructure of the Ni foam were examined by scanning electron microscopy (SEM, JEOL JSM-6330F).

Phase composition

Phase composition of the Ni foam was characterized by X-ray diffraction (PANalytical X'pert PRO diffractometer).

Current and temperature measurements

We used a programmable DC power supply (BK PRECISION, 9153, 60 V/9A) to measure the voltage (V)-current (I) curves and to heat the Ni-foam filters. The temperature was recorded using an infrared thermometer (MICRO-EPSILON, CTL-CF2-C3).

Aerosolization method

Aerosolization of SARS-CoV-2 and *Bacillus anthracis* Ames spores was accomplished using an automated aerosol control platform (Biaera AeroMP; Biaera Technologies, LLC). The bioaerosols were generated using either a 3-jet (*B. anthracis* spores) or a 6-jet (SARS-CoV-2) Collison nebulizer, both of which typically produce droplet sizes of approximately 1 μm. The total flow rate to the filtration unit, comprised of nebulizer air and diluter air, was 30 L min^{-1}. The nebulizer air flow rates to the 3- and 6-jet Collison nebulizers were 7.5 and 14 L min^{-1}, respectively. Bioaerosol samples were collected before and

after filtration for each aerosol run using S.K.C. BioSamplers (S.K.C., Inc.). The flow rate to each BioSampler was approximately 10 L min^{-1}. Aerosolization and bioaerosol sampling was performed for either 15 min (*B. anthracis* spores) or 20 min (SARS-CoV-2). All aerosolization procedures were performed in a Class III biosafety cabinet housed within the animal biosafety level 3 (ABSL-3) facility of the Galveston National Laboratory (GNL).

<u>Virus titration determination method</u>

Vero cells (ATCC Cat# CCL-81, RRID:CVCL_0059) were cultured in Dulbecco's Modified Eagle Medium (DMEM) (HyClone) supplemented with 10% fetal bovine serum and 1% penicillin/streptomycin (HyClone). SARS-CoV-2 USA-WA1/2020 was obtained from the World Reference Center for Emerging Viruses and Arboviruses (WRCEVA), which obtained the original isolate from the Centers for Disease Control and Prevention (CDC). Upon obtaining the isolate, virus titration was performed. A subsequent low multiplicity of infection (MOI) passage was performed in Vero cells (DMEM supplemented with 5% fetal bovine serum and 1% penicillin/streptomycin), and the resulting stock was titrated *via* TCID50 (median tissue culture infectious dose) in Vero cells to determine the titer prior to use.

The 96-well plate with Vero cells to be ~85-95% confluent in 24 hours was prepared. Cells were plated at 2×10^5 mL^{-1}. Growth media used was DMEM supplemented with 10% fetal bovine serum and 1% penicillin/streptomycin. The virus sample was diluted in quadruplicate at a 1:10 ratio in DMEM + 5% fetal bovine serum and 1% penicillin/streptomycin, for a total of 6 dilutions (10^{-1} to 10^{-6}). Media was removed from the cells and replaced with 100 uL of the diluted virus. Cells were incubated at 37 °C and 5% CO_2 for 4 days. On day 4, the post-infection virus inoculum was removed from the plate and the cells were fixed with 100 uL of 10% buffered formalin per well. After 30 min of fixation, the formalin was removed and the

cells were stained with 0.25% crystal violet. SARS-CoV-2 positive cells were noted and TCID50 was calculated. These experiments were conducted within approved biosafety level three (BSL-3) laboratories at the University of Texas Medical Branch (UTMB) and the GNL.

Anthrax spore production and quantitation

B. anthracis Ames spores were grown in modified Schaeffer's medium using a computer-controlled New Brunswick B-510 20-L fermentor operating within a Baker BioProtect II biosafety cabinet installed in the GNL BSL-3 Enhanced Facility. After inoculation, the fermentor was operated with aeration at pH 7.0-7.5 with pH control for approximately 4 days, after which time the crude spore content of the culture was aseptically harvested by centrifugation at 9,000 x g and washed with sterile molecular grade water. The spores were purified by density gradient centrifugation using sterile MD-76. Visual observation of the spores at 400x by phase-contrast microscopy during each step of purification was performed to ensure production of a homogeneous suspension of highly refractile spores.

The bacterial concentration of the samples was determined using an automatic serial diluter and plater (easySpiral Dilute; Interscience). The samples, diluted in sterile water, were plated onto trypticase soy agar plates containing 5% sterile sheep blood (TSAB) and incubated at 37 °C for 16-24 hours. Colonies from the plates were then enumerated using an automatic colony counter (Scan 500; Interscience).
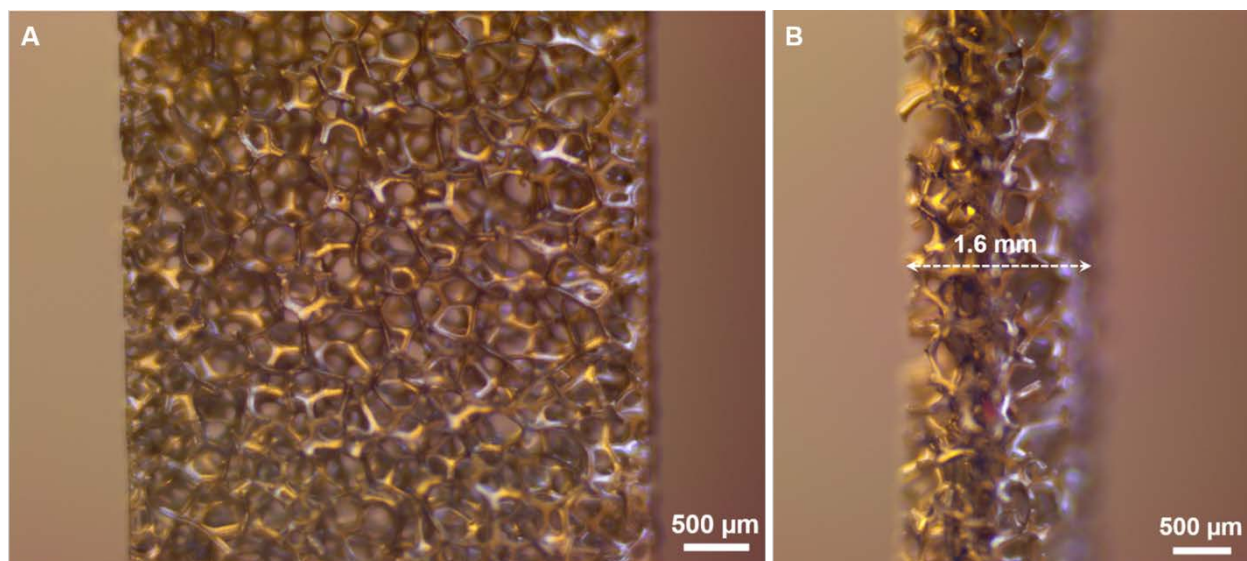
Supplementary Figures

Fig. S1. Optical images of commercial Ni foam. (A) Front view and (B) side view.
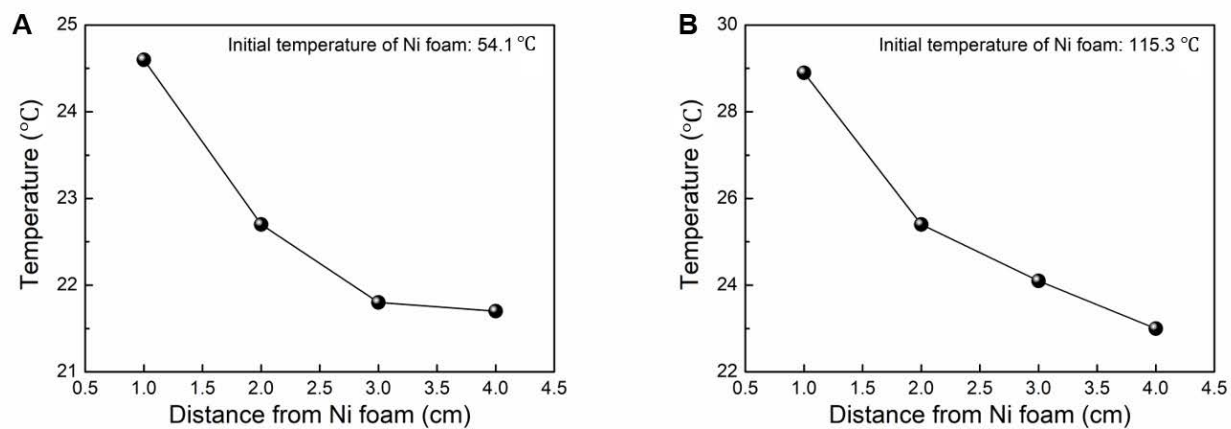
Fig. S2. Decreasing temperature of air after flowing through heated Ni foam. Initial Ni-foam temperature of (A) 54.1 °C and (B) 115.3 °C.
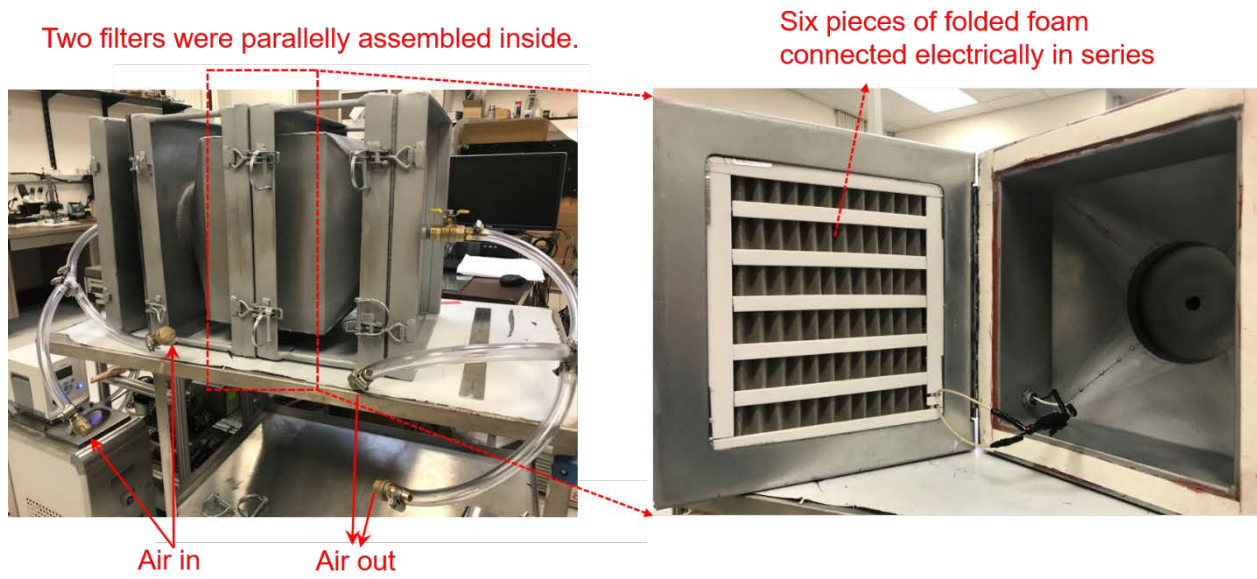
Fig. S3. Device for virus experiment. Photographs show the device details (left) and one of the two filters using folded Ni foam (right).

Appendix C

Shifting Approach to Environmentally Mediated Pathways for Mitigating COVID-19: *A Review of Literature on Airborne Transmission of SARS-CoV-2*

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ABSTRACT

Coronavirus disease 2019 (COVID-19), caused by the novel coronavirus SARS-CoV-2, has been confirmed in over 10,000,000 individuals worldwide and has resulted in more than 500,000 deaths in a few months since it first surfaced. With such a rapid spread it is no surprise that there has been a massive effort around the world to collectively elucidate the mechanism by which the virus is transmitted. Despite this, there is still no definitive consensus regarding droplet versus airborne transmission of SARS-CoV-2. Public health officials around the world have introduced guidelines within the scope of droplet transmission. However, increasing evidence and comparative analysis with similar coronaviruses, such as severe acute respiratory syndrome (SARS-CoV-1) and middle eastern respiratory syndrome (MERS), suggest that airborne transmission of SARS-CoV-2 cannot be effectively ruled out. As the data supporting COVID-19 airborne transmission grows, there needs to be an increased effort in terms of technical and policy measures to mitigate the spread of viral aerosols. These measures can be in the form of broader social distancing and facial covering guidelines, exploration of thermal inactivation in clinical settings, low-dose UV-C light implementation, and greater attention to ventilation and airflow control systems. This review summarizes the current evidence available about airborne transmission of SARS-CoV-2, available literature about airborne transmission of similar viruses, and finally the methods that are already available or can be easily adapted to deal with a virus capable of airborne transmission.

Keywords: COVID19, Airborne transmission, Droplet transmission, Aerosol transmission, SARS-CoV-2, Heat Inactivation, Infection Prevention, Ventilation system

INTRODUCTION

On March 11th, 2020, coronavirus disease 2019 (COVID-19) was designated by the World Health Organization (WHO) as a pandemic. It has since been confirmed in over 10 million cases worldwide and has resulted in more than 500,000 deaths.[1] Despite the widespread investigation of COVID-19, many aspects of the disease such as the severity, demographic preference, and transmission of the disease, are still under contention. The Centers for Disease Control and Prevention (CDC) characterizes the transmission of infectious agents via three mechanisms: direct or indirect contact, droplet, or airborne route.[2] While efficient human to human transmission of COVID-19 is undisputed,[3] the extent of this mode of transmission has yet to be fully confirmed. Current guidelines from the WHO and CDC have resigned to treat COVID-19 as a droplet transmitted disease, thereby recommending facial coverings and a distance of 2 meters between individuals.[4,5] However, analysis of previous coronaviruses, increasing evidence by way of case study, and incoming, but limited, empirical data shows that not only are droplet precautions inadequate, but airborne precautions merit aggressive implementation.[6,7,8]

There is commonly known evidence related to the aerosol transmission of various viral pathogens, such as Influenza virus, Rhinovirus, Adenovirus, Measles virus, Respiratory Syncytial virus, and Ebola virus. Of more importance, is the wealth of evidence concerning coronaviruses such as SARS-CoV and MERS. Given the high level of genetic conservation between the novel SARS-CoV-2 and previously studied coronaviruses,[9] there is mounting reason to infer that SARS-CoV-2 may also be distributed via aerosol transmission. Transmission via airborne particles 5 micrometer (μm) or less in size from asymptomatic carriers can help understand the unprecedented spread of this novel disease.[10]

Although the current evidence regarding airborne transmission needs to be interpreted with caution, it should at least encourage the adoption of simple measures that can mitigate aerosol dispersion. At a general population level, the use of face masks should be universal, as it has been associated with a decline in new cases where implemented.[11] Resourceful attempts have been made to repurpose surgical personal protective equipment (PPE), but to our knowledge, none have been successful in preventing the inhalation of potentially virulent aerosols.[12] Because of the documented susceptibility to heat of coronaviruses,[13] promising strides have been made in deactivating COVID-19 by applying high, yet tolerable, temperatures to the upper respiratory tract.[14] Because of the potential of ultraviolet light, particularly type C (UVC), in deactivating pathogenic microbes [15-17], low dose UVC is a candidate for widespread implementation in hospitals, doctors' offices, and other high-risk areas [18]. Lastly, properly designed ventilation systems inside buildings can be an effective tool to curtail airborne infection. Inventive approaches to developing portable, low cost, negative pressure systems are beginning to appear regularly.[19,20] Critical elements of ventilation that influence airborne transmission include ventilation rate, flow direction, and airflow pattern.[21]

The objective of this review has been to explore and summarize the rapidly emerging literature regarding airborne transmission of SARS-CoV-2, the available literature regarding airborne transmission of related viruses that have been involved in previous outbreaks, and finally the methods and technologies that are already available or can be easily adapted to deal with a virus capable of airborne transmission.

Transmission of Viral Pathogens

The CDC characterizes the transmission of infectious agents via three mechanisms: direct or indirect contact, droplet, or airborne route.[2] Direct or indirect contact involves transmitting the pathogen from one person to another with or without a contaminated intermediate,

respectively.[22] Droplet transmission involves the expulsion of droplet particles, 5 μm or greater in diameter, from the respiratory tract. These projected droplets can directly settle on the mucosae of an exposed individual or they can reside on surfaces, such as door knobs, to be picked up later by hand.[23] In contrast, airborne transmission results from the inhalation of droplet nuclei. These small particles are distinguished by having a diameter of 5 μm or less. Notable infectious agents that spread via the airborne route include Influenza, Measles, and Tuberculosis, among others.[23] The formation of infectious bioaerosols, in the general public, are linked to multiple processes such as expiratory activities of humans, showering or use of tap water, sewage aerosolization from toilets, and sewage transport through pipe systems, wet-cleaning of indoor surfaces, and agricultural spraying of 'gray' water.[24] Aerosol formation in healthcare settings, as listed by the CDC, is possible via specific procedures such as open suctioning of airways, sputum induction, cardiopulmonary resuscitation, endotracheal intubation and extubation, non-invasive ventilation (e.g., BiPAP, CPAP), bronchoscopy, and manual ventilation.[5] Currently, the WHO applies the greater or less than 5 μm size of droplet nuclei to differentiate between droplet transmission and airborne transmission.[25] However, this dichotomy comes with limitations. Particles capable of projecting from the respiratory tract and being inhaled by a susceptible individual can be both greater and lesser than 5 μm in size. Aerosol plumes generated from coughing, sneezing, or speaking, can range from less than 0.1 μm to greater than 100 μm and lodge directly into airway, tracheobronchial, or alveolar locations.[26] These aerosols are capable of remaining suspended in gas or air for extended periods. Furthermore, a recent review by Bahl et al. addresses various studies exploring horizontal droplet distance by presenting evidence that infectious particles may travel distances up to 26 feet.[4] While large droplets may typically settle within 3 to 6 feet of an individual, other smaller droplets are capable of remaining suspended, traveling through a room or to other rooms, and landing 20 to 26 feet away.[27]

There is already ample evidence related to the aerosol transmission of common viruses, such as Rhinovirus, Adenovirus, Measles virus, Respiratory Syncytial Virus, and Ebola Virus.[28-32] Indeed, literature regarding the aerosol transmission of Influenza virus and Coronavirus has become extensively available following the 2003 outbreak of SARS-CoV-1.[33] In the case of Influenza virus, a study by Francoise et al. confirmed the presence of airborne transmission by collecting aerosol samples in different areas of an emergency department. Their study found that, throughout the healthcare environment, airborne virus particles were present, and approximately 53% of these particles were 4 µm in size or below.[34] In the case of MERS, a viral presence was found in 4 of 7 air samples from 2 patient rooms, a patient restroom, and a common corridor.[35] Finally, in the case of SARS-CoV, a robust analysis of the first 187 cases in the Amoy Gardens housing complex found that aerosol transmission of viral particles accounted for a significant amount of the community outbreak.[36] Additional retrospective studies show the prevalence of SARS-CoV aerosol transmission within healthcare settings, housing complexes, and aircraft.[37-40]

Given the high level of genetic conservation between the novel SARS-CoV-2 and the viruses mentioned above—particularly MERS and SARS-CoV—there is mounting reason to infer that SARS-CoV-2 may also be distributed via aerosol transmission.[9]

Evidence/Characteristics of SARS-CoV-2 Airborne Transmission

Recent literature has suggested that an increasing number of SARS-CoV-2 cases occur via inhalation of aerosols produced by asymptomatic carriers.[10] These aerosols, produced by way of coughing, sneezing, and even speaking, can linger in indoor air for some time and be inhaled later by other individuals.[41] This stability of the virus poses a challenge to healthcare workers and the general population to limit the proliferation of the disease.

SARS-CoV-2 has an initial tropism for the upper respiratory tract, where it exhibits a large amount of active viral pharyngeal shedding in contrast to SARS-CoV.[42] This affinity for the upper respiratory tract presents with mild-to-asymptomatic symptomology and increases the potential dispersion of fine aerosolized infectious particles. To further explicate the similarities between SARS-CoV-2 and SARS-CoV, van Doremalen et al. investigated the aerosol and surface stability of each virus. Their results not only indicated that aerosol transmission of SARS-CoV-2 was plausible, but that the virus could remain suspended in the air for over 3 hours, similar to SARS-CoV.[41] Together these findings suggest that populations may be susceptible to SARS-CoV-2 superspreading events via aerosol, similar to the SARS-CoV Amoy Gardens housing complex incident.

Indeed a small but growing number of case reports are beginning to appear in support of airborne transmission.[8] Many of these reports originate in China, which experienced a high caseload early in the pandemic, while a few high profile "superspreading" events appear in the United States.[43-46] Of note, was a choir practice event that resulted in 45 of 60 choir members being infected.[45] Interestingly, choirs have been linked to multiple outbreak events in the United States, possibly due to both an increase in droplet projection and an increase in droplet nuclei dissemination through aerosolization.[47] These "superspreading" events are likely the result of a few asymptomatic individuals, presumably in the early pharyngeal shedding stage, expelling aerosolized droplet nuclei while simply speaking or breathing. As asymptomatic individuals, it is less likely that these "silent shedders" are coughing or sneezing at a rate to justify only droplet transmission.[10] A plausible explanation for their high infectivity lies in the ability of SARS-CoV-2 to aerosolize in droplets smaller than 5 μm. Indeed, a study by Leung et al. showed that seasonal coronaviruses were more commonly emitted as aerosols, even in ordinary tidal breathing.[48] Furthermore, it is estimated that merely 1 minute's worth of loud speaking, let alone singing, could create over 1000 virion-containing aerosol particles.[49] A report published by Li et

al., found that 79% of SARS-CoV-2 cases in China were via an asymptomatic carrier, which makes it unlikely that they were producing large infectious droplets and further support aerosolization as a mechanism for the transmission of SARS-CoV-2. [50]

As stated in a commentary of aerosolized transmission by Anderson et al., little empirical data exists, and a broader initiative is needed regarding the exact aerodynamics of SARS-CoV-2 airborne transmission.[8] This is bolstered by a statement made by the National Academy of Science that while little SARS-CoV-2 specific research is available for airborne transmission, the current studies comply with the idea that the virus is aerosolized via normal tidal breathing.[51]

Mitigation of Airborne Transmission

Methods to mitigate the spread of infectious SARS-CoV-2 aerosols are wide-ranging in ease, time, cost, and universality of implementation. Currently, the CDC, WHO, and European Centre for Disease Prevention and Control have issued guidelines primarily intended to limit the spread of SARS-CoV-2 droplets.[4] While the CDC has recommended precautions for airborne transmission, it only advocates for them in healthcare settings during aerosol-generating procedures.[5] For the general public, a 2-meter spatial separation is recommended to limit the possibility of droplet transmission. Unfortunately, even droplets (> 5 μm) have been shown to spread up to 8 meters,[4,52] suggesting that the current recommendation of 2-meter distance may have limited effectiveness even for droplet transmission.

The use of face masks by the general population has been associated with mitigation in the spread of SARS-CoV-2. A recent retrospective analysis by Lyu & Wehby of 15 states and Washington D.C. showed that after mandating public use of face coverings, the SARS-CoV-2 growth rate decreased by 0.9, 1.1, 1.4, 1.7, and 2.0 percentage points in 1-5, 6-10, 11-15, 16-20, and 21+ days respectively.[11] Although this may have averted an estimated 230,000-450,000

cases in the general population, simple face coverings are not enough to adequately protect high-risk individuals such as health care workers from aerosol exposure. Because of reported aerosol spread in previous coronavirus outbreaks, SARS-CoV, and MERS, the WHO at the time recommended masks in low-risk situations and respirators in high-risk situations while the CDC recommended respirators in both situations.[53-56] Nevertheless, this time round, in spite of the evidence supporting aerosol transmission of SARS-CoV-2, the CDC recommends only masks for low-risk situations and reserves respirators for high-risk, aerosol-generating procedures. These procedures are listed as open suctioning of airways, sputum induction, cardiopulmonary resuscitation, endotracheal intubation and extubation, non-invasive ventilation (e.g., BiPAP, CPAP), bronchoscopy, and manual ventilation.[5] Much of the hesitancy to universally mandate respirator devices in healthcare settings comes from the worry of supply shortages.[24]

Methods of Viral Inactivation

One pathway to eliminate aerosol transmission of SARS-CoV-2 is available via heat inactivation. Rabenau et al. investigated the stability and inactivation of SARS-CoV in 2004 and found that a temperature of 60°C was highly effective in reducing virus titers to below detectability.[13] Using this information, Knio et al. developed a thermal treatment for inactivating SARS-CoV-2 that resides in droplet nuclei.[14] They showed that air heated to 80-90 degrees Celsius is tolerable to the respiratory tract and successfully demonstrated a proof of concept worthy of further exploration in the battle against SARS-CoV-2 and potential future viral pandemics – although the widespread acceptance and implementation of their proposed method is likely to be challenging.

Another approach to virus inactivation is ultraviolet light (UV). Of the many types of UV light, UVC, at the range of 315-380 nm, has the most potent antimicrobial and antiviral properties.[15,16] A recent review by Heßling et al analysing data from 30 publications concluded that UVC radiation has been effective against all previous coronavirus strains. Although none of the publications deal

with the novel SARS-CoV-2 strain, the structural similarities of the coronavirus family are strong enough to believe that UVC will be an effective weapon against SARS-CoV-2 and any subsequent mutations.[17] Indeed, previous technological innovations in the delivery of bactericidal and virus inactivating UVC to an infected area without damage to mammalian skin are worth revisiting. For example, in 2017, Welch et al. developed the use of far-UVC light (207-222 nm) to inactivate over 95% of the aerosolized H1N1 influenza virus.[18] Using a continuous low dose, they were able to avoid the carcinogenic and cataractogenic effects of UV radiation and sufficiently reduce the spread of airborne-mediated microbial disease. Developments such as this hold value in public settings such as hospitals and doctors' offices, schools, airports, and beyond. However, if direct exposure to the human can be avoided, by engineering devices that contain UVC inside the device when treating air with it, a higher 254 nm UVC can be used as they have minimal ozone production, if any. Continuous progress in developing UV mediated solutions should garner much attention in future attempts toward pandemic mitigation.

Improving ventilation and air disinfectant techniques are also viable ways to explore SARS-CoV-2 aerosol mitigation.[57] Observational evidence of a case in Guangzhou, China has shown that air conditioning played a role in the transmission of SARS-CoV-2 between an infected carrier and three family clusters while eating in a restaurant. Investigators concluded that transmission of the virus was facilitated by the ventilation system.[58] The role of ventilation systems has immense implications in viral spread, given the growing evidence supporting airborne transmission of SARS-CoV-2 . Therefore, interior ventilation rate and air purification in an enclosed space are of crucial importance in restricting the spread of aerosolized viruses.[59] Following the appearance of an infection cluster in a call center in Seoul, South Korea, the Korean Ministry of Employment and Labor proposed the installation of air purifiers at the floor of the call center area with exhausts at face level.[60]

In recognition of the importance, and scarcity, of adequately ventilated patient areas, Lynch & Goring published a five-step guide to transforming standard patient rooms to negative pressure spaces. These five steps involve estimating total room volume, ventilation and differential pressure, installing supplemental exhaust ventilation through dedicated exhaust portals, increasing efficiency of filtration, keeping doors closed, and following the Infectious Disease Prevention Guidelines for health care workers.[61] Additionally, many ingenious portable isolation chambers have begun to appear to prevent airflow amongst individual patients. For example, Cubillos et al. created a cubic chamber made of widely accessible materials that produce an enclosed continuous negative airflow environment through vacuum mechanisms around the patient.[19] Adir et al. have created a similar negative pressure canopy with multiple filtering units. This contraption allows the administration of noninvasive ventilation, continuous positive airway pressure, and high-flow nasal cannula, to SARS-CoV-2 patients with minimal risk to healthcare workers.[20] Innovative filtering materials involving electrostatically charged nanofibers are also being developed that have potential applications to reduce aerosol spread via building ventilation.[62] Higher ventilation rates are believed to reduce the transmission of disease by diluting contaminated air inside a space.[63] The current recommended minimum ventilation rate for airborne infection isolation rooms by the CDC is 12 air changes per hour.[64] Properly directing airflow from clean zones to dirty zones is vital to prevent virulent aerosols from traversing between rooms.[61] Airflow patterns can be further subdivided into downward ventilation, displacement ventilation, and mixing ventilation, with an improved downward ventilation system having the greatest performance in eliminating droplet nuclei that could cause infection.[65] Conceptual framework for this has been laid down by Luo *et al* who have elicited the absolute reduction of actual SARS-CoV-2 by treating the air with a specialized biodefense indoor air protection system.[66]

CONCLUSION

There is sufficient evidence that confirms airborne transmission of SARS-CoV-2. Quantitative studies to directly measure concentrations of aerosolized SARS-CoV-2 face numerous limitations. It is incredibly challenging to address the multiple variables that affect the production and airborne transmission of respiratory viruses. These include airflow, humidity, temperature, spatial patterns, and minimum virus titers, and length of exposure needed to cause infection among susceptible individuals. While further research is necessary in all these areas, the aforementioned studies, comparisons with other viruses, and growing cases warrant a more urgent action beyond simply relegating transmission to being purely droplet spread. Therefore, guidelines accounting for airborne transmission of SARS-CoV-2 should be established and technology deployed immediately. Leveraging research advancements in UV, heat inactivation, and improved ventilation technologies are vital to creating sustainable methods in virus spread mitigation indoors. Search for cutting-edge applied physics based inventions with biodefense characteristics will find a place in future pandemics.

Data Availability

No data are associated with this article

Competing Interests

No competing interests were disclosed.

Grant Information

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Appendix D

HEPA filters leave a lot to be desired for!

___ *Integrated Viral Protection, Houston, TX* ___

High Efficiency Particulate Air (HEPA) filtration is a mechanism for purifying air of dust, pollen, mold, bacteria, and any airborne particles with a size of 0.3 microns (μm). When bacteria are trapped in a HEPA filter, they either die and decompose to release endotoxins which are small enough to pass through a HEPA filter, or remain alive and continue to multiply, making the filters moldy. Thus, live pathogens can spread through HEPA filters in a number of ways. For instance, studies done on viability of various bacteria and fungal spores found that nearly a third of these pathogens can remain alive in the filter for approximately one year. When the filters are handled during maintenance, microbes in the HEPA filter can be re-aerosolized. Furthermore, the high concentration of trapped organisms predisposes the live virulent pathogens to travel across the HEPA filter and be released on the other side.[1,2] Majchrzycka *et al.* showed that the survivability of microorganisms on filter materials depends on the amount of accumulated moisture and microorganism type.[3] It should be noted that the effectiveness of a HEPA filter is not always determined by the filter itself, but also the design of the entire system that it is a part of. This is best exemplified by the publication from Gore *et al.* who reported that the use of vacuum cleaners with new HEPA-filters (demonstrated to be more efficient in experimental chambers), resulted in an increased exposure to cat allergen similar to old vacuum cleaners.[4]

The scientific community has convincingly established airborne transmission of SARS-CoV-2 and finally both the Centers for Disease Control (CDC) and the World Health Organization (WHO) now acknowledge this fact as well. Many viruses are small enough to theoretically pass through HEPA filters. SARS-CoV-2 virions are around $60 - 140$ nanometers ($0.06 - 0.14$ μm) in diameter but larger respiratory droplets and air pollution particles (> 1 μm) are needed to transport the virus and this is

accepted to be the primary mode of airborne transmission.[5] However, the presence of viral particles in smaller aerosols ($< 1 \, \mu m$) cannot be positively ruled out. Even though these aerosol sizes are larger than the Minimum Efficiency Reporting Values (MERV) of most commonly used HEPA filters, previous studies have shown that viable virions can penetrate HEPA filters when challenged with a variety of viral aerosols.[6] Whereas HEPA filters with MERV of 10 nanometers (0.01 micron) and above are likely to filter SARS-CoV-2, the flow of air and static drop in pressure at that level of efficiency makes them impractical in standard Heating, Ventilation, and Air Conditioning (HVAC) systems and other applications where high throughput of air is needed in closed indoor spaces of considerable size. Moreover, filtration such as HEPA and MERV only "capture" and do not "kill" the virus. Therefore, improvements in filtration alone cannot completely eliminate airborne transmission of the virus.

Whereas a number of technological solutions are coming forth amidst this pandemic to ensure clean indoor environments, HEPA filtration by itself is unlikely to be sufficient as it does not kill SARS-CoV-2, rather only traps it. Furthermore, if HEPA filters are not maintained/replaced for long periods of time it can lead to an accumulation of viable bacteria and viruses trapped within, and an increased risk of these pathogens crossing over and causing infection. For this reason, HEPA filters could in fact be considered a favorable environmental niche for airborne transmission of COVID-19, if not properly maintained.

In comparison, IVP filtration technology combines filtration (through HEPA), irradiation (through UV-C) and thermal (proprietary patent pending nickel-mesh proven to eliminate SARS-CoV-2), to create a more effective and comprehensive HVAC system that eliminates the virus altogether rather than merely filtering it. The proprietary, patent pending, next generation of HEPA that is resulted from combining the biodefense technology along with the filtration offers a solution that "catches" and "kills"

the SARS-CoV-2. Based on scientific and epidemiological understanding, only a cutting-edge technology such as the proprietary biodefense indoor air protection system of IVP – which combines various currently available and newly developed modalities, can most efficiently curb the airborne transmission of SARS-CoV-2 and thereby keeping in check the spread of COVID-19.
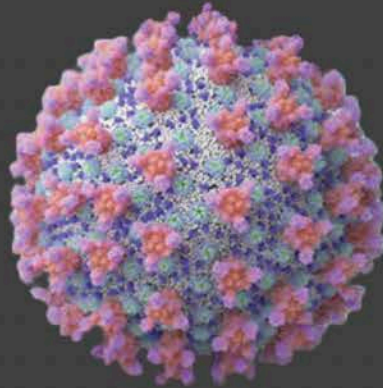
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Appendix E

SARS-CoV-2
Actual Virus Stock ID

HPV 161 (31) SCoV2, USA WA1/2020

Prep. BK 11May20

Aerosolized SARS-CoV-2 Run through IVP Biodefense Filter (v1.0)
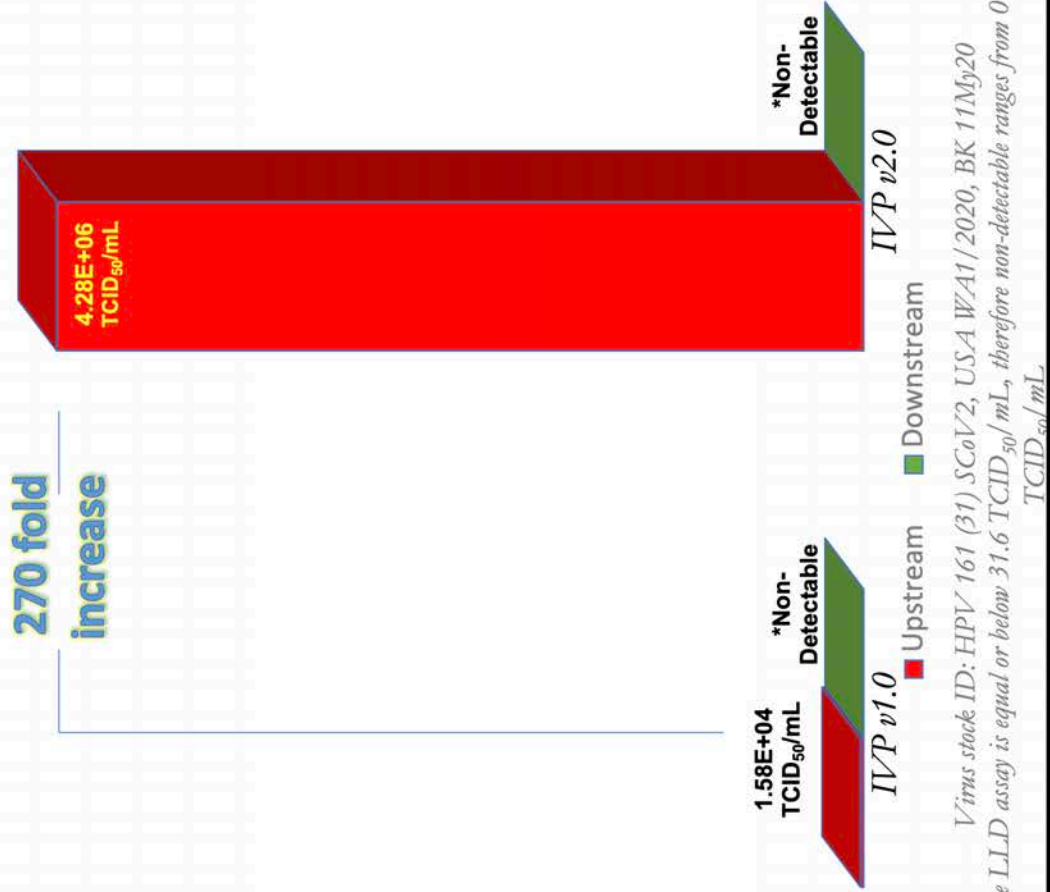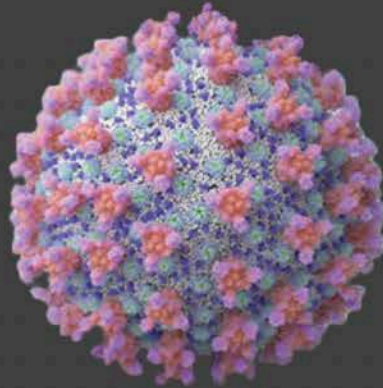
1.58E+04 $TCID_{50}$/mL

Non-Detectable*

■ Upstream ■ Downstream

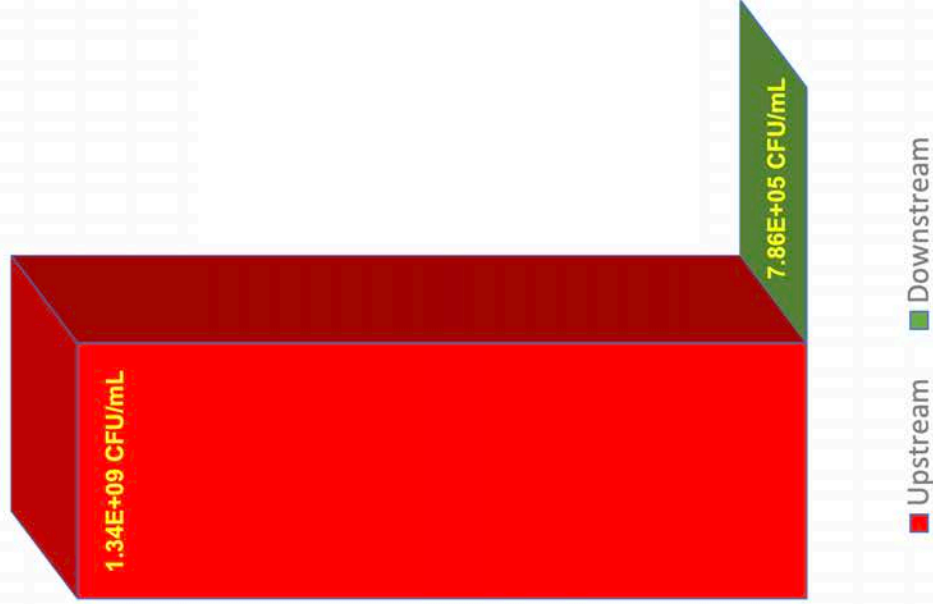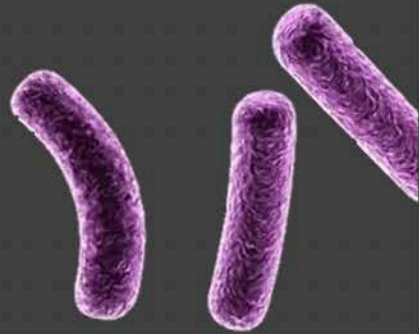*Virus stock ID: HPV 161 (31) SCoV2, USA WA1/2020, BK 11My20*

Since LLD assay is equal or below 31.6 $TCID_{50}$/mL, therefore non-detectable ranges from 0 – 31.6 $TCID_{50}$/mL
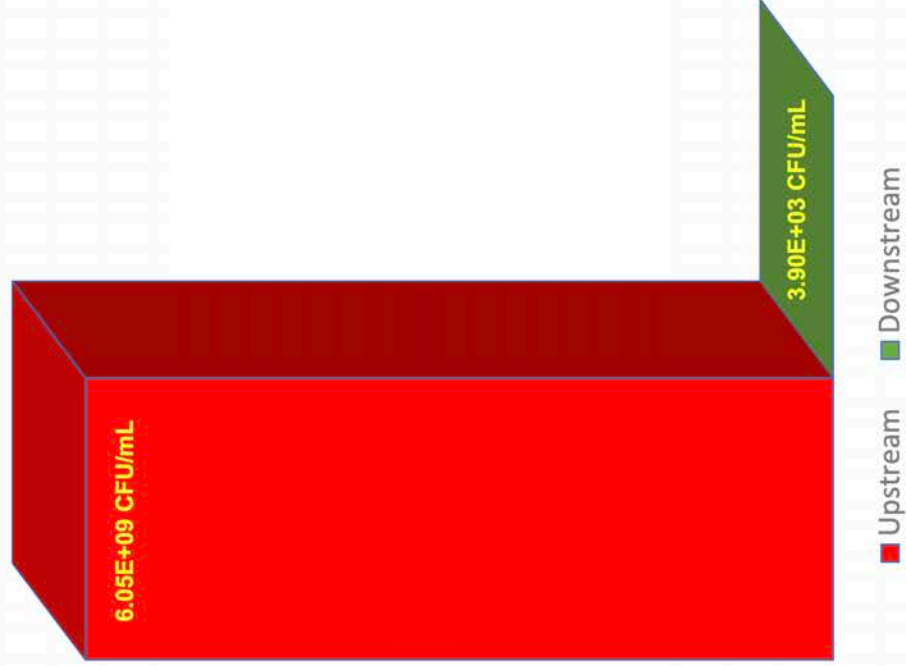
Aerosolized **SARS-CoV-2** Run through **IVP** Biodefense Filter *(v2.0)*

4.28E+06 $TCID_{50}/mL$

Non-Detectable*

■ Upstream ■ Downstream

Virus stock ID: HPV 161 (31) SCoV2, USA WA1/2020, BK 11My20

*Since LLD assay is equal or below 31.6 $TCID_{50}/mL$, therefore non-detectable ranges from 0 – 31.6 $TCID_{50}/mL$

Aerosolized **SARS-CoV-2** Run through **IVP Biodefense** Filter

270 fold increase

4.28E+06 TCID$_{50}$/mL

1.58E+04 TCID$_{50}$/mL

*Non-Detectable

*Non-Detectable

IVP v2.0

IVP v1.0

■ Upstream ■ Downstream

Virus stock ID: HPV 161 (31) SCoV2, USA WA1/2020, BK 11My20

*Since LLD assay is equal or below 31.6 TCID$_{50}$/mL, therefore non-detectable ranges from 0 – 31.6 TCID$_{50}$/mL

Aerosolized **Anthrax** Run through **IVP** Biodefense Filter *(v1.0)*

1.34E+09 CFU/mL

7.86E+05 CFU/mL

■ Upstream   ■ Downstream

Aerosolized **Anthrax** Run through **IVP** Biodefense Filter *(v2.0)*

6.05E+09 CFU/mL

3.90E+03 CFU/mL

■ Upstream　■ Downstream

Aerosolized **Anthrax** Run through **IVP** Biodefense Filter

4.5 fold increase

IVP v1.0
1.34E+09 CFU/mL
7.86E+05 CFU/mL

IVP v2.0
6.05E+09 CFU/mL
3.09E+03 CFU/mL

■ Upstream ■ Downstream

Appendix F

Sub-Second Heat Exposure Kills Coronavirus

Texas A&M Engineering
Experiment Station

Experimental Setup Allows Rapid Heating/Cooling of Coronavirus

No heat 100%

1.36 sec
0%

Survival percentage (%)
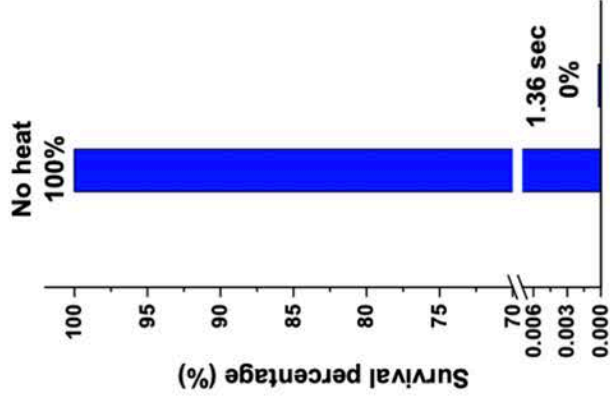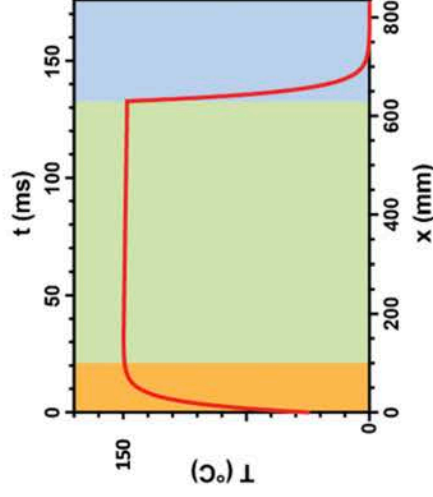
At 115°C need 1.36 sec to completely kill coronavirus

No heat 100%

0.7 sec
0.006%

Survival percentage (%)

0.7 sec treatment (at 150°C) kills coronavirus to near zero (10^5-10^6 fold) drop

5-6 Log Reduction

Project Status Overview

- **Conducted large sets of experimentation conditions, varying temperature and exposure time, to assess heat inactivation of coronavirus**

- **Conducted extensive simulation and experimental validation to understand the difference between temperature applied and actual temperature virus solution experiences**

- **Complete heat inactivate of CoV at 89°C 0.95 sec exposure**

- **Four orders of magnitude drop in CoV infectivity at 89°C 0.48 sec exposure**

- **Conclusion: Heat inactivation at much lower temperature than previously thought possible**

Method Overview

Coronavirus solution

PEEK tubing

Syringe pump for flow rate control

Flow direction

Stainless steel capillary tubing

Oil bath with temperature control (95–200 °C)

Ice bath for rapid cooling

PEEK tubing

Plaque assay for remaining infectivity
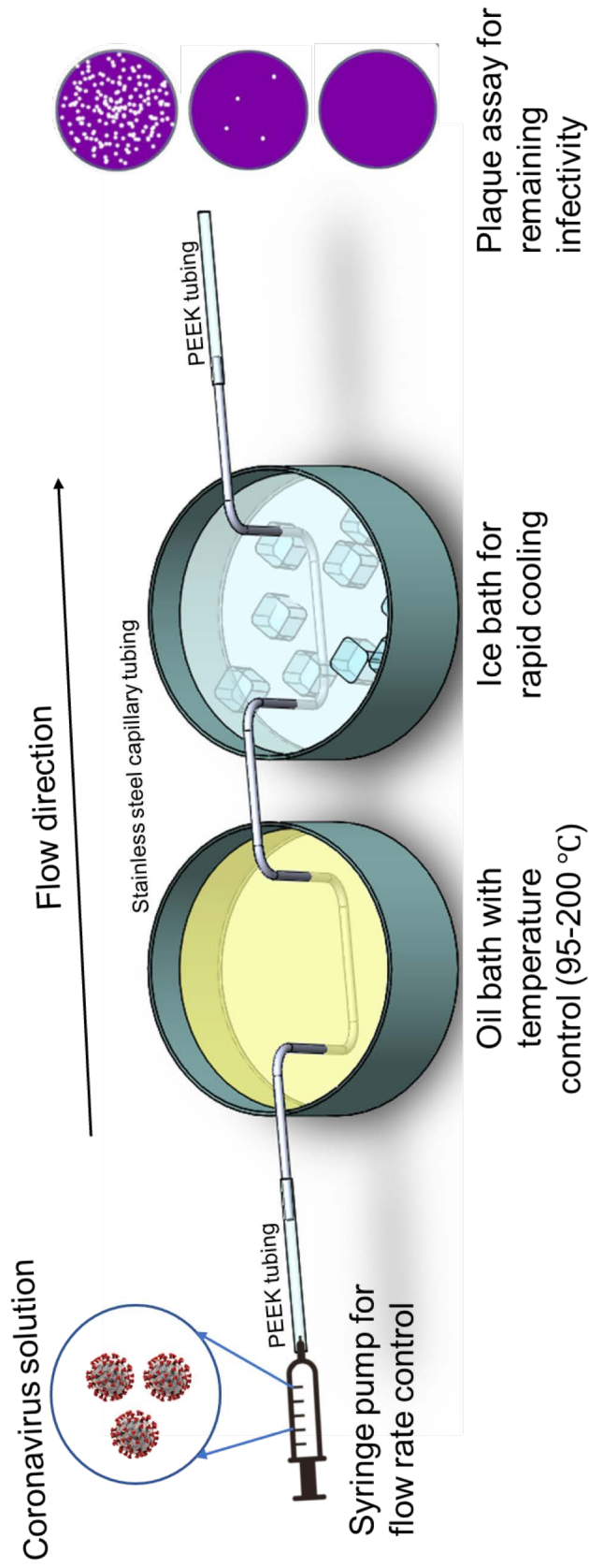
Thermal Simulation to Validate Experimental Condition

Example

125°C oil bath, 0.5 sec
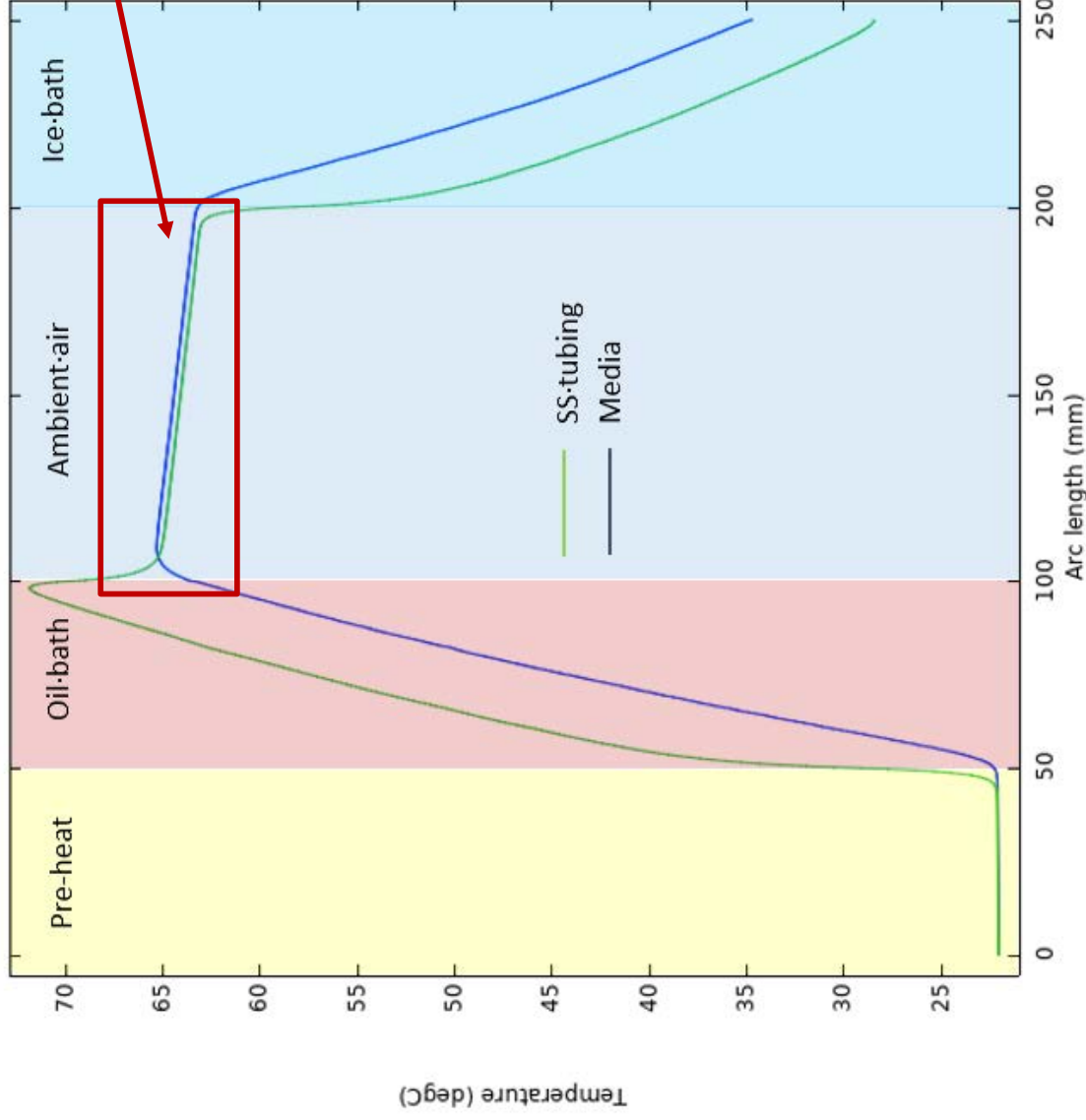
Effective virus solution temperature and exposure duration: 65°C, 0.95 sec

Due to high speed of virus solution flow, solution temperature is significantly lower than the applied oil bath temperature

Validate Direct Temperature Measurement Method
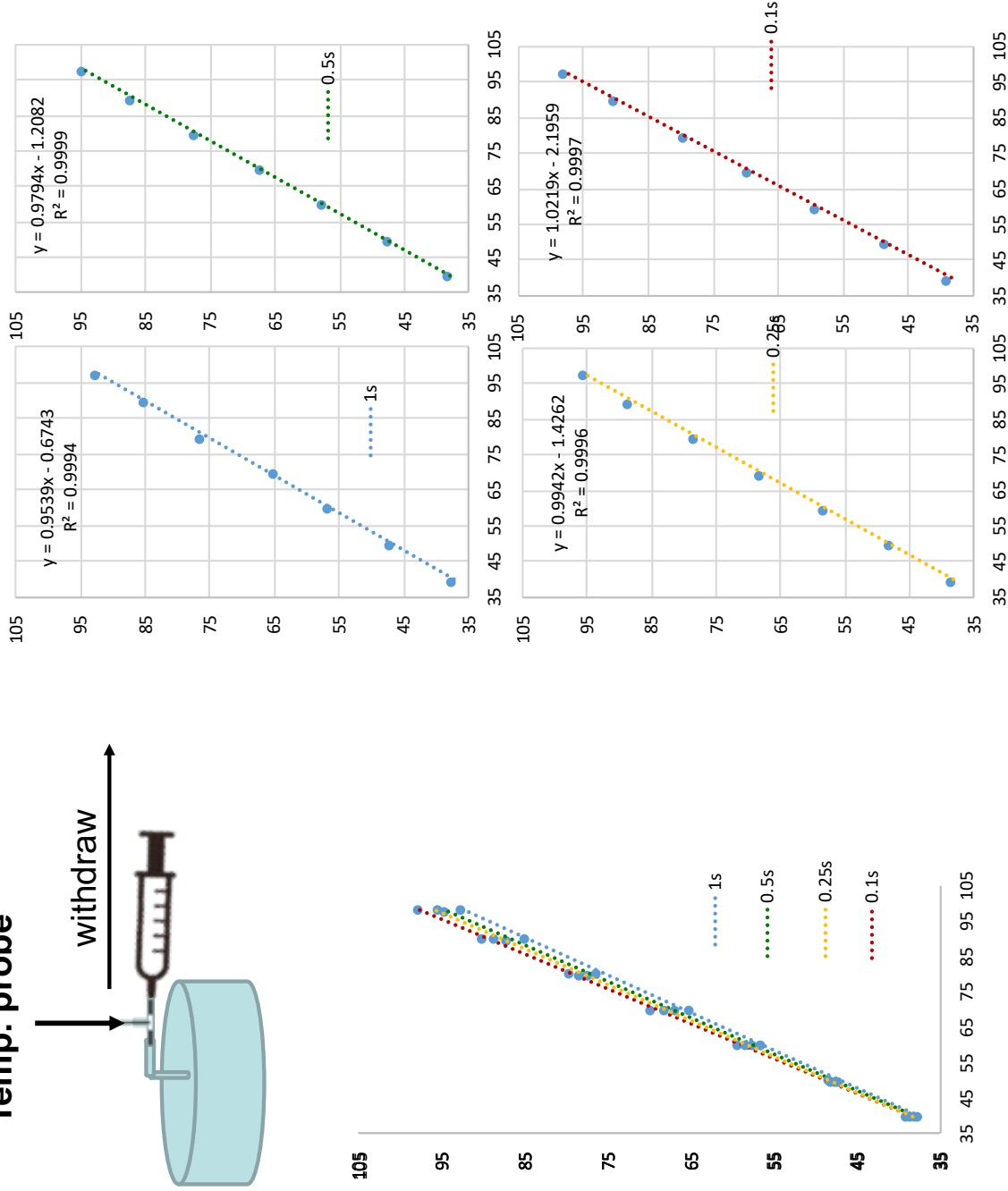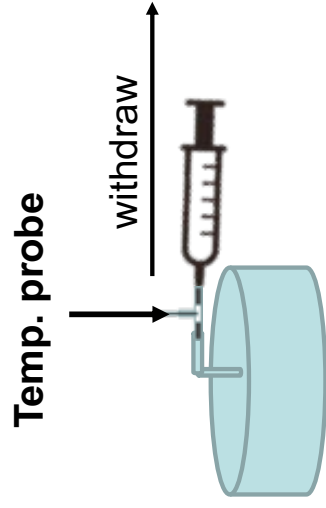
Used temperature probe to directly measure solution temperature at various flow speed

Conclusion: Experimental method utilized is indeed correct

Temp. probe

withdraw

$y = 0.9794x - 1.2082$
$R^2 = 0.9999$

0.5s

$y = 0.9539x - 0.6743$
$R^2 = 0.9994$

1s

$y = 1.0219x - 2.1959$
$R^2 = 0.9997$

0.1s

$y = 0.9942x - 1.4262$
$R^2 = 0.9996$

0.25s

1s
0.5s
0.25s
0.1s

5

Summary of CoV Heat Inactivation

Applied Conditions

Actual Conditions CoV Experience
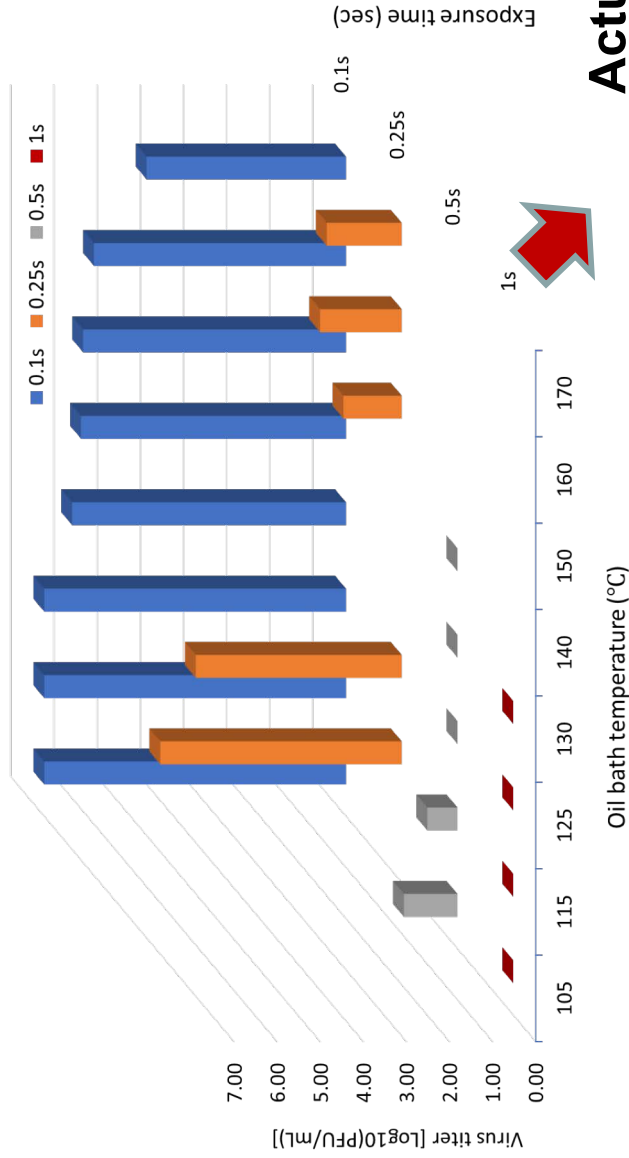
Due to high speed movement of liquid, significant difference between the oil bath temperature applied vs. actual temperature CoVs experience
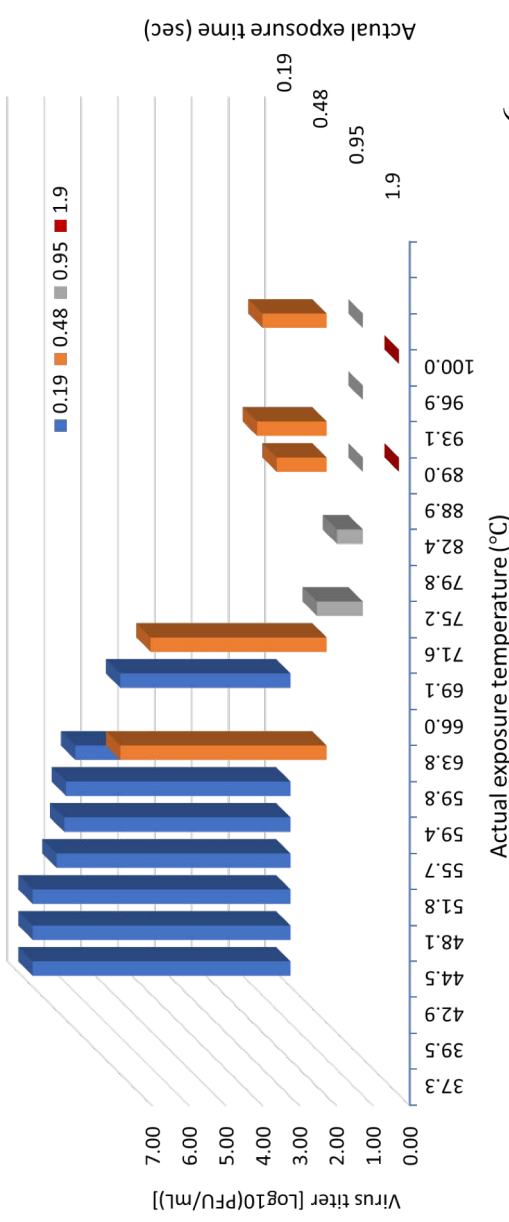
At 0.95sec, 89°C sufficient to completely heat inactivate CoV

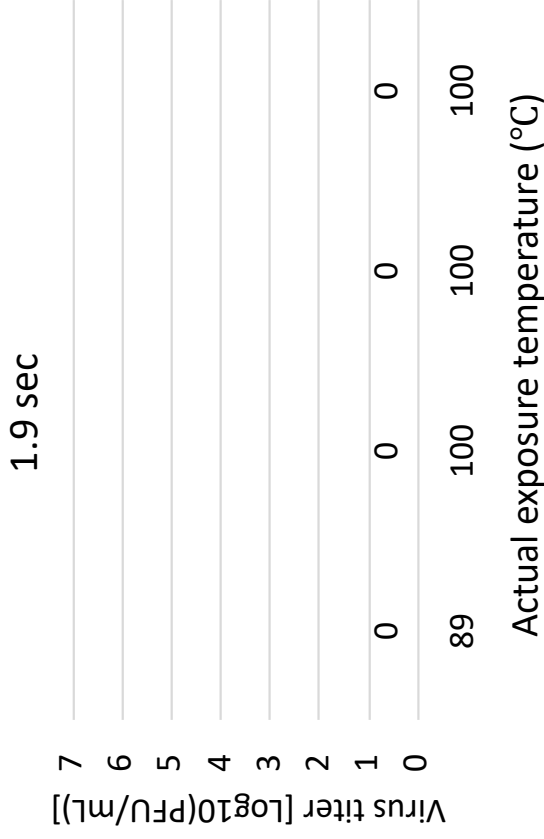**At 0.48sec, 89°C sufficient to reduce viral infectivity by 4 orders of magnitude**

9

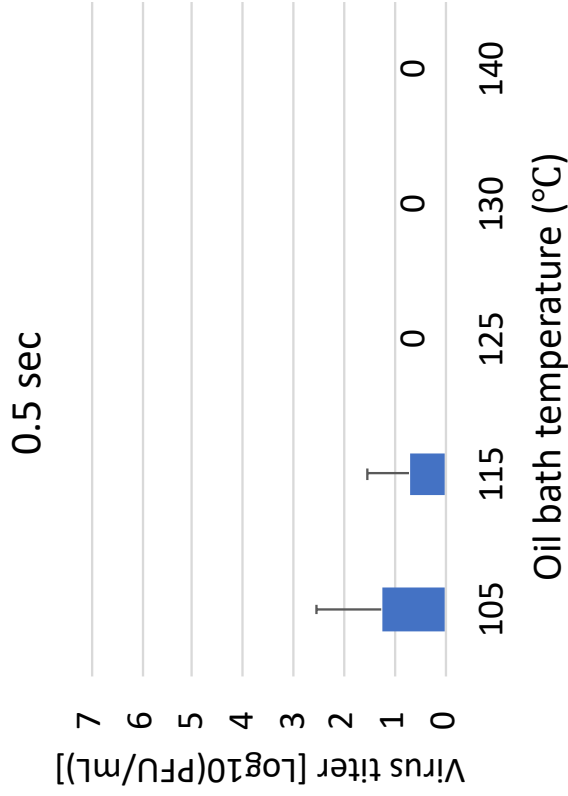# Exposure: 1 Second Applied (actual: 1.9 sec)

Applied duration: 1 sec

1 sec

Virus titer [Log10(PFU/mL)]
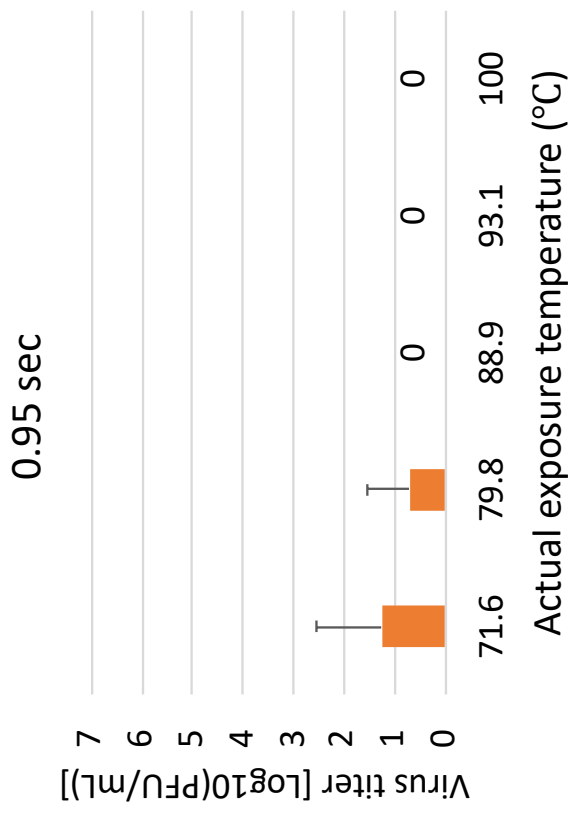
7 6 5 4 3 2 1 0

0   0   0   0   0

105   115   125   130
        115   125

Oil bath temperature (°C)

Actual duration: 1.9 sec

1.9 sec

Virus titer [Log10(PFU/mL)]

7 6 5 4 3 2 1 0

0   0   0   0   0

89   100   100   100   100
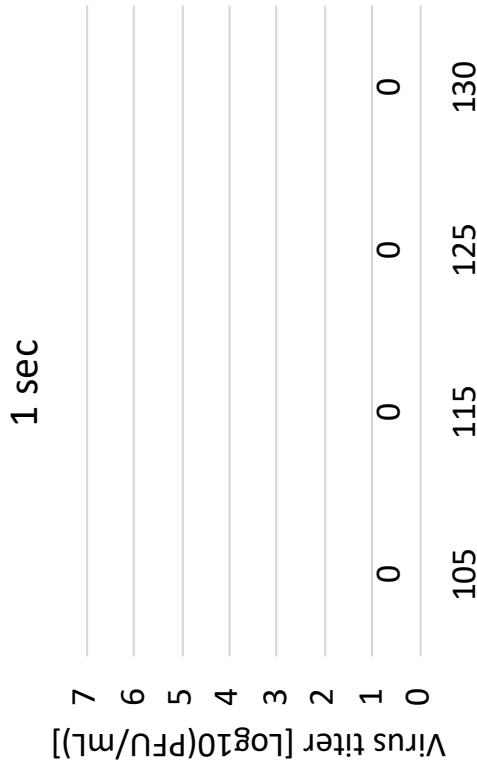
Actual exposure temperature (°C)

Exposure: 0.5 Second Applied (actual: 0.95 sec)

Applied duration: 0.5 sec

0.5 sec

Oil bath temperature (°C)

Virus titer [Log10(PFU/mL)]

Actual duration: 0.95 sec

0.95 sec

Actual exposure temperature (°C)

Virus titer [Log10(PFU/mL)]

Exposure: 0.25 Second Applied (actual: 0.48 sec)

Applied duration: 0.25 sec

0.25 sec
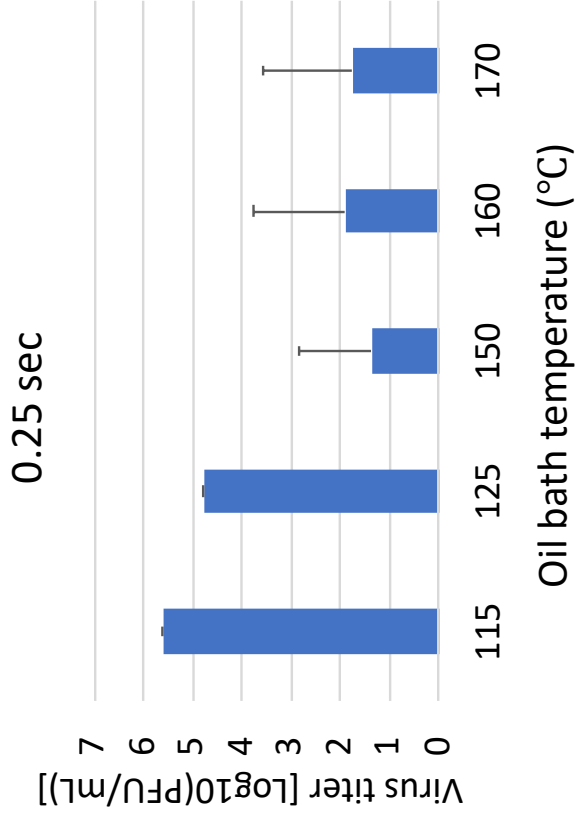
Actual duration: 0.48 sec

0.48 sec
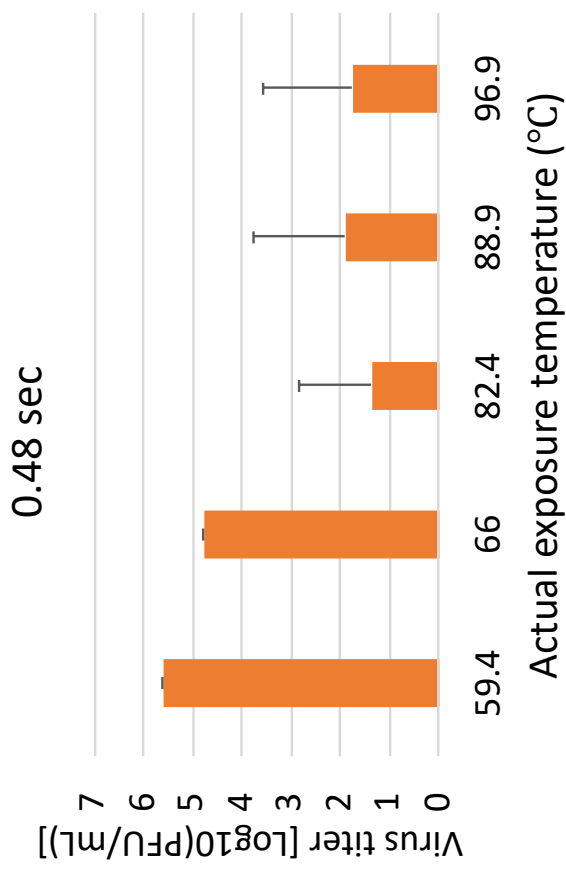
Exposure: 0.1 Second Applied (actual: 0.19 sec)

Actual duration: 0.19 sec

0.19 sec

Virus titer [Log10(PFU/mL)] vs Actual exposure temperature (°C): 37.3 39.5 42.9 44.5 48.1 51.8 55.7 59.8

Applied duration: 0.1 sec

0.1 sec

Virus titer [Log10(PFU/mL)] vs Oil bath temperature (°C): 105 115 125 130 140 150 160 170
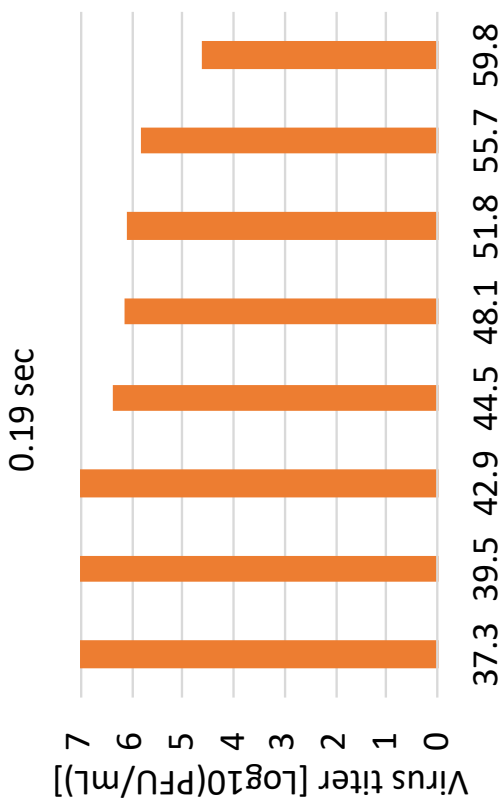
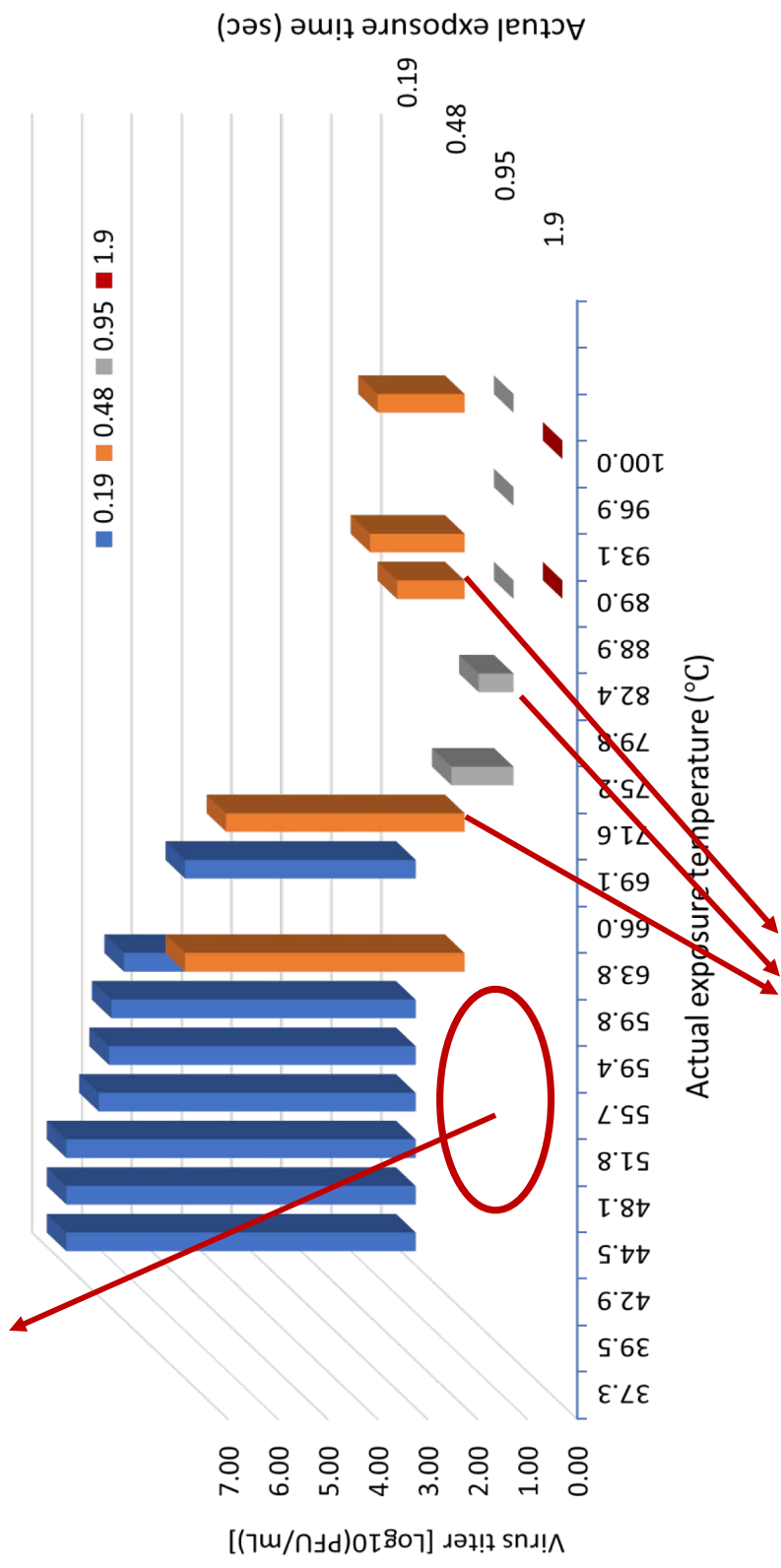**Current experimental setup does not allow testing this short exposure time at higher temperature => Require designing and creating a microfluidic setup.**

Ongoing Work

- **Test conditions at these boundary conditions**

- **Retest several critical conditions to ensure data accuracy**
- **Testing at <0.48 sec exposure, applying higher temperature not possible with current setup => Need a new microfluidic device/setup to be built. Would this be of interest?**
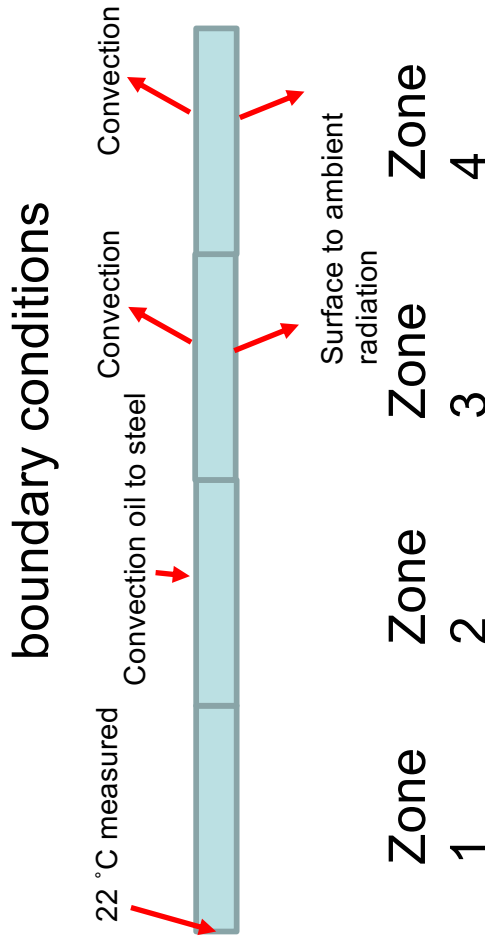
Appendix 1: Raw Data All Conditions Tested

Each experiment takes several hours, followed by a 2-day virus infectivity testing experiment

set temperature (°C)	exposure time (s)	flowrate used (ul/hr)	real oil temperature (°C)	ss tubing temperature (°C)	Real-time temperature (°C)	Simulation (°C)	H	mean of titers (cfu/ml)
95	0.5	92304			61.3	63.8	380	1.25
105	1	46152	105.1	80.2	81.1	89	420	0
	0.5	92304	104.3	68.8	69.9	71.6	420	17.5
	0.25	184594	104.6	57.6	56.4	54.9	420	
	0.1	461485	104.7	47.6	40.7	37.3	420	1×10^7
115	1	46152	115.3	86.5	87.3	100	460	0
	0.5	92304	114.3	74	76.9	79.8	460	5
	0.25	184594	114.9	65.3	62.0	59.4	460	4×10^5
	0.1	461485	114.7	47.6	42.7	39.5	460	1×10^7
125	1	46152	124.9	94.7	96.5	100	500	0
	0.5	92304	124.8	80.5	83.4	88.9	500	0
	0.25	184594	124.9	67.2	65.6	66	500	6×10^4
	0.1	461485	124.9	52.3	45.8	42.9	500	1×10^7
130	1	46152	129.5	91.9	97.0	100	520	0
	0.5	92304	129.5	84.4	86.7	93.1	520	0
	0.25	184594	129.7	68.5	67.9	69.1	520	2.5
	0.1	461485	129.5	52.4	46.5	44.5	520	2.25×10^8
140	1	46152	139.6	92.5	103.5	100	560	
	0.5	92304	139.6	90.5	92.4	100	560	0
	0.25	184594	139	73.6	71.8	75.2	560	
	0.1	461485	139.7	57.3	48.4	48.1	560	1.4×10^6
150	1	46152	149.3	93.9	103.8	100	600	
	0.5	92304	149.4	94.4	102.0	100	600	
	0.25	184594	149.4	78.1	77.8	82.4	600	22.5
	0.1	461485	149.4	66.1	55.7	51.8	600	1.25×10^8
160	1	46152	159.3	96.1	104.2	100	640	
	0.5	92304	159.5	96	102.5	100	640	0
	0.25	184594	159.5	85.4	85.2	88.9	640	
	0.1	461485	159.5	68.5	56.6	55.7	640	78
170	1	46152	169.1	99.2	103.8	100	680	7×10^5
	0.5	92304	168.7	97.8	101.3	100	680	
	0.25	184594	168.9	92.6	91.8	96.9	680	55
	0.1	461485	169	70.5	60.2	59.8	680	4.2×10^4

Appendix 2: Details of Simulation

COMSOL simulation and boundary conditions

boundary conditions

22 °C measured

Convection oil to steel

Convection

Convection

Convection

Surface to ambient radiation

Zone 1   Zone 2   Zone 3   Zone 4

Use of Vegetable Oils and Animal Oils as Steel Quenchants: A Historical Review—1850-2010

ABSTRACT: Vegetable oils and animal oils have been used as quenchants for metals for thousands of years; however, it hasn't been until relatively recently that their cooling properties have been studied in a thorough, quantitative manner. This review will focus on the published data relating to the use of triglycerides from various animal and vegetable sources to quench-harden steels. Particular focus will be on the traditional selection and use of different vegetable and animal oils for steel hardening applications and the cooling time-temperature behavior of these fluids to characterize their quenching performance. This information has not been previously reviewed in this manner.

KEYWORDS: quenchants, vegetable oils, animal oils, oxidative stability, cooling curves, hardening

quenching properties was conducted by Rose in 1940 with rapeseed oil [1]. The cooling curve results obtained showed that the heat transfer coefficients for rapeseed oil were 1744 to 2092 W/m^2K in the transition nucleate boiling region, 2906 to 3486 W/m^2K in the nucleate boiling region and 464 to 697 W/m^2K in the convective cooling region *versus* 697 to 1394 W/m^2K for film boiling, 2325 to 3486 W/m^2K nucleate boiling and 233 to 580 W/m^2K for convective cooling for a so-called petroleum "heavy oil". The higher cooling rates for rapeseed oil were attributed to the relatively poor stability of the vapor blanket formed by the rapeseed oil [1].

Temperature dependent
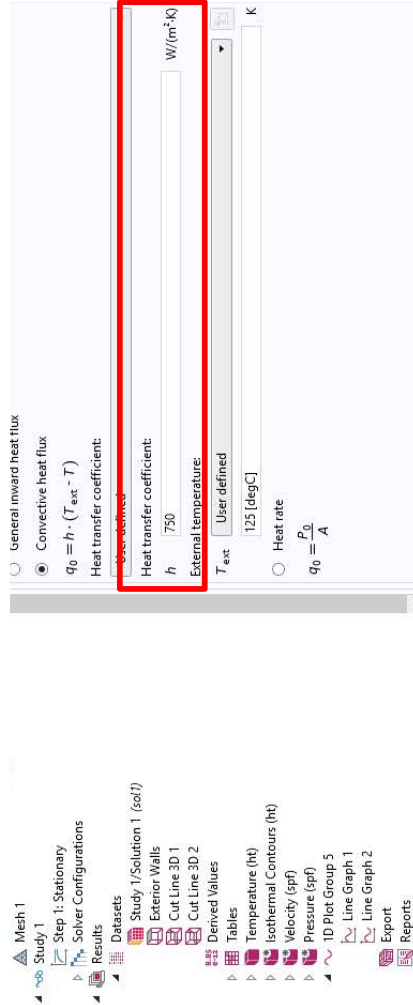
Heat transfer coefficient (A)

$$H \times A \times (T_{oil} - T_{ss}) = C_w \times Q_w \times \rho \times (T_{in} - T_{out})$$

A: surface area where the heat transfer takes place

Toil: temperature of the surrounding oil

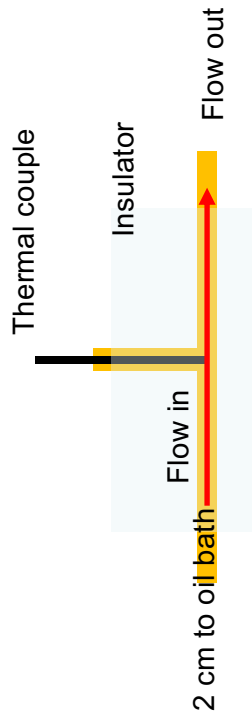Tss: temperature of the solid surface

C: heat capacity of water

Qw: flow rate of water

ρ: Density of water

Tin: water temperature at inlet (20 C)

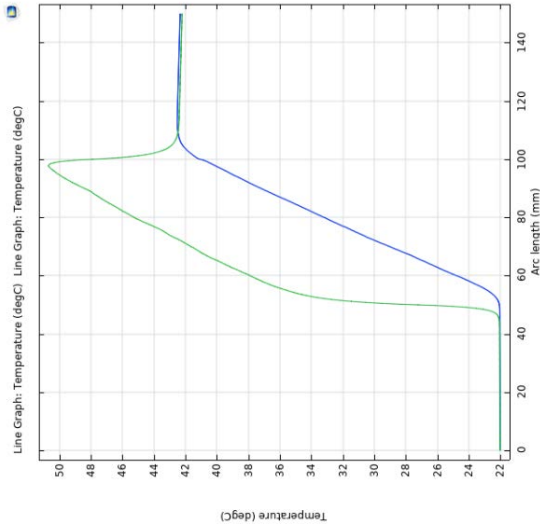Tout: Water temperature at outlet

Temperature measurement

Thermal couple

Insulator

Flow out

Flow in

2 cm to oil bath

set temperature (C)	exposure duration (s)	flowrate used (ul/hr)	real oil temperature ©	ss tubing (C)(about 2 cm to oil)	flowing solution temperature (C)
105	1	46152	105.1		76.7
	0.5	92304	104.3		69.2
	0.25	184594	104.6		54.6
	0.1	461485	104.7		39.4
115	1	46152	115.3	86.5	82.6
	0.5	92304	114.3	74	74.1
	0.25	184594	114.9	65.9	60
	0.1	461485	114.7	47.6	41.4
125	1	46152	124.9	94.7	91.4
	0.5	92304	124.8	80.5	80.5
	0.25	184594	124.9	67.2	63.8
	0.1	461485	124.9	52.3	44.6
130	1	46152	129.5	91.9	98
	0.5	92304	129.5	84.4	83.7
	0.25	184594	129.7	68.5	66.1
	0.1	461485	129.5	52.4	45.3
140	1	46152	139.6	92.5	98.1
	0.5	92304	139.6	90.5	89.3
	0.25	184594	139	73.6	70
	0.1	461485	139.7	57.3	47.3
150	1	46152	149.3	93.9	98.3
	0.5	92304	149.4	94.4	98.7
	0.25	184594	149.4	78.1	75.9
	0.1	461485	149.4	66.1	54.7
160	1	46152	159.3	96.1	98.7
	0.5	92304	159.5	96	99.2
	0.25	184594	159.5	85.4	83.3
	0.1	461485	159.5	68.5	55.6
170	1	46152	169.1	99.2	98.3
	0.5	92304	168.7	97.8	98
	0.25	184594	168.9	92.6	89.8
	0.1	461485	169	70.5	59.3

Are these measurements accurate?

Simulation result H=480, and 550

#25 115C 0.1S H=480   #25 115C 0.25S H=480   #24 115C 0.5S H=480   #4 150C 0.25S H=550

Based on calculation 452   Based on calculation 599

75-80 degree for 0.5S can
be the critical condition. If
we try higher temp and
shorter time, we may end
up getting same condition
as this one

Highest temp 42.2C
Real ET around 0.2S
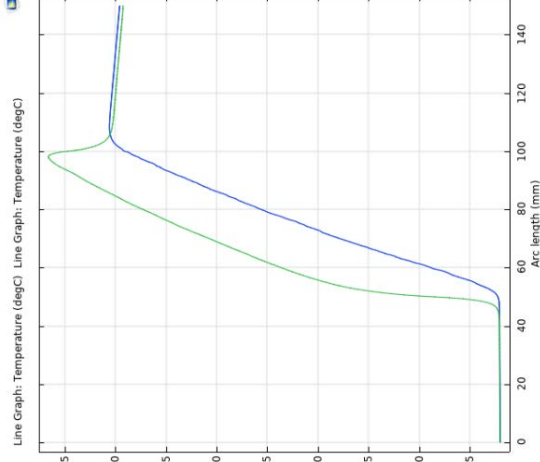
Highest temp 60.5C
Real ET around 0.5S

Highest temp 81
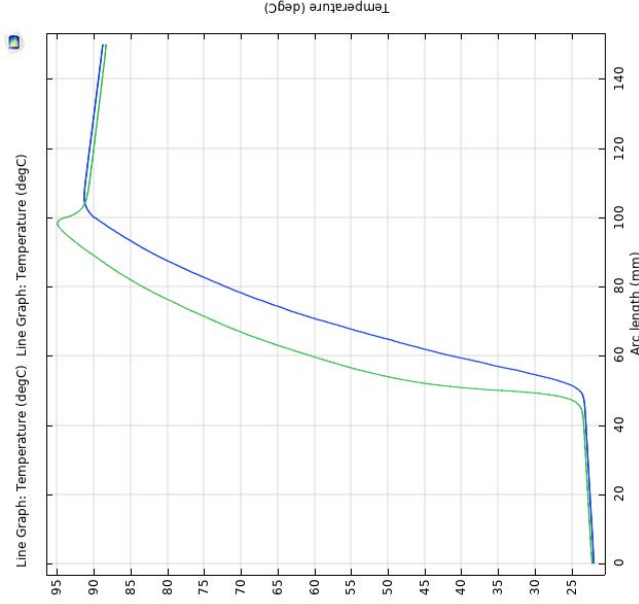Real ET around 1S
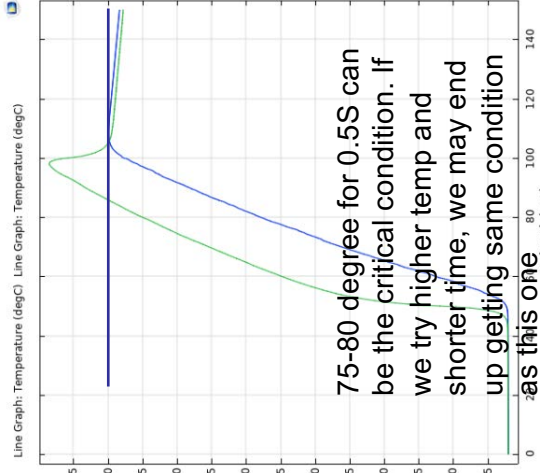
Highest temp 80
Real ET around 0.5S

Simulation result H=690
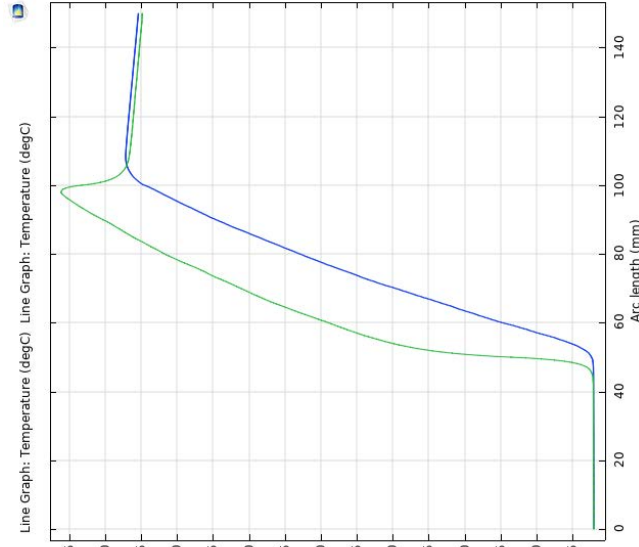
#4 150C 0.25S H=690

Highest temp 94.3
Real ET around 0.5S

#24 115C 0.5S H=690

Highest temp 91.2
Real ET around 1S

#25 115C 0.25S H=690

Highest temp 69.8
Real ET around
0.5S

Appendix G

Size Distribution of Aerosolized Particles of SARS-CoV-2
IVP's Biodefense Filter Data from Galveston National Laboratory