Thermal Disinfection of SARS-CoV-2 within an Airplane

Austin Hehir, Trevor Laib, Rohit Nene

Abstract

SARS-CoV-2 is a new virus in humans causing respiratory illness that can easily spread from person-to-person.[1] Breathing, talking, singing or coughing all propel particles through the air where they can then be inhaled by a nearby person, deposited on the skin or mucosal surfaces, or finally on surfaces in the surrounding area[2]. The mode of transmission is primarily through respiratory droplets, however transmission through contact with contaminated surfaces is possible.

The use of elevated temperatures (40°C to 60°C) to disinfect airplane locations that cannot be decontaminated as effectively through more traditional means, such as the flight deck, was evaluated. Boeing determined that portable recirculating air heaters were the most viable method for airline use. In collaboration with the University of Arizona, Boeing conducted lab tests on SARS-CoV-2 to determine environmental conditions and times necessary to successfully inactivate 99.9% of the SARS-CoV-2 respiratory viruses.

Operators must maintain an air temperature of 40°C for approximately 305 minutes, 50°C for 200 minutes, or 55°C for 134 minutes to achieve disinfection at expected flight deck humidity conditions (<20% RH). These times do not include the time it takes to ramp up to these temperatures (ramp up time).

Background: The Effect of Temperature on SARS-CoV-2

Boeing initially believed that the temperature range required to inactivate the SARS-CoV-2 virus was too high to be practical for use in aircraft disinfection. However, a paper released by the United States Army Medical Research Institute of Infectious Diseases (USAMRIID) came to Boeing's attention in mid-2020 which included test data showing the inactivation of the SARS-CoV-2 virus at lower temperature ranges than previously thought[6]. A vision for using thermal energy as a method for disinfecting smaller aircraft compartments, such as the flight deck, emerged.

The impact of environmental temperature on the survivability of SARS-CoV-2 on surfaces was investigated shortly after the initial discovery of the virus to determine if a seasonal effect would occur.[3] Per Chin et al.; "The virus is highly stable at 4°C, but sensitive to heat. At 4°C, there was only a 0.7 $\log_{10}$ reduction of infectious titer on day 14. With the incubation temperature increased to 70°C, the time for virus inactivation was reduced to 5 minutes."[3] As shown in Table 1, the virus can survive nearly an entire day at room (22°C) and body temperature (37°C), but became inactivated within 30 minutes at 56°C.

Copyright © 2021 Boeing. All rights reserved.

Table 1: Thermal Stability of SAR-CoV-2 in Virus Transport Medium[3]

Time	Virus titre (Log $TCID_{50}$/mL)									
	4°C		22°C		37°C		56°C		70°C	
	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
1 min	N.D.	N.D.	6.51	0.27	N.D.	N.D.	6.65	0.1	5.34	0.17
5 mins	N.D.	N.D.	6.7	0.15	N.D.	N.D.	4.62	0.44	U	-
10 mins	N.D.	N.D.	6.63	0.07	N.D.	N.D.	3.84	0.32	U	-
30 mins	6.51	0.27	6.52	0.28	6.57	0.17	U	-	U	-
1 hr	6.57	0.32	6.33	0.21	6.76	0.05	U	-	U	-
3 hrs	6.66	0.16	6.68	0.46	6.36	0.19	U	-	U	-
6 hrs	6.67	0.04	6.54	0.32	5.99	0.26	U	-	U	-
12 hrs	6.58	0.21	6.23	0.05	5.28	0.23	U	-	U	-
1 day	6.72	0.13	6.26	0.05	3.23	0.05	U	-	U	-
2 days	6.42	0.37	5.83	0.28	U	-	U	-	U	-
4 days	6.32	0.27	4.99	0.18	U	-	U	-	U	-
7 days	6.65	0.05	3.48	0.24	U	-	U	-	U	-
14 days	6.04	0.18	U	-	U	-	U	-	U	-

U: Undetectable

SD: Standard Deviation

Titer: numeric expression of viral quantity in a given fluid

Further research validated the relationship between temperature and reduction of the SARS-CoV-2.[4,5,6] Morris et al tested the half-life of viral samples at 10°C, 22°C, and 27°C and various relative humidity levels. Figure 1 shows the relationship of the virus half-life to relative humidity at various temperatures.[4] Viral half-life is defined as the time it takes to reduce the viral load by 50%. They found that the virus persists better at lower temperatures. Moreover, they found that approximately 60% relative humidity resulted in higher disinfection of the virus under thermal loading in comparison to both higher and lower relative humidity. One hypothesis proposed for the mechanistic explanation of the role humidity plays on virus reduction suggest that relative humidity affects virus inactivation by controlling evaporation and thus governs the solute concentration in a droplet containing virions. However, this has not been validated and many mechanistic principals remain elusive.[7]

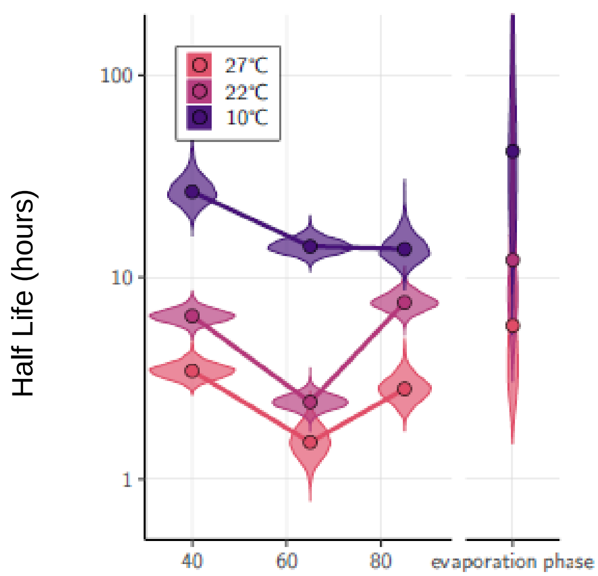

Figure 1: Relative humidity (%)[4]

Several studies were used to establish a target temperature range for airplane disinfection and to determine timeframes and environmental conditions to be evaluated through lab efficacy

Copyright © 2021 Boeing. All rights reserved.

testing.[1,3,4,5,6] However, it should be noted that most thermal disinfection methods in the scientific community use much higher temperatures than those applicable for use on airplane. This is expanded on in the Boeing airplane test section below.

Lab-Based Efficacy Testing

Comparative Surfaces for Common Flight Deck Materials

Boeing collaborated with the University of Arizona to determine the stability of SARS-CoV-2 at elevated temperatures when deposited on surfaces representative of airplane interiors. Boeing components representing three material types in the flight deck were sent for testing. An example is shown in Figure 2.

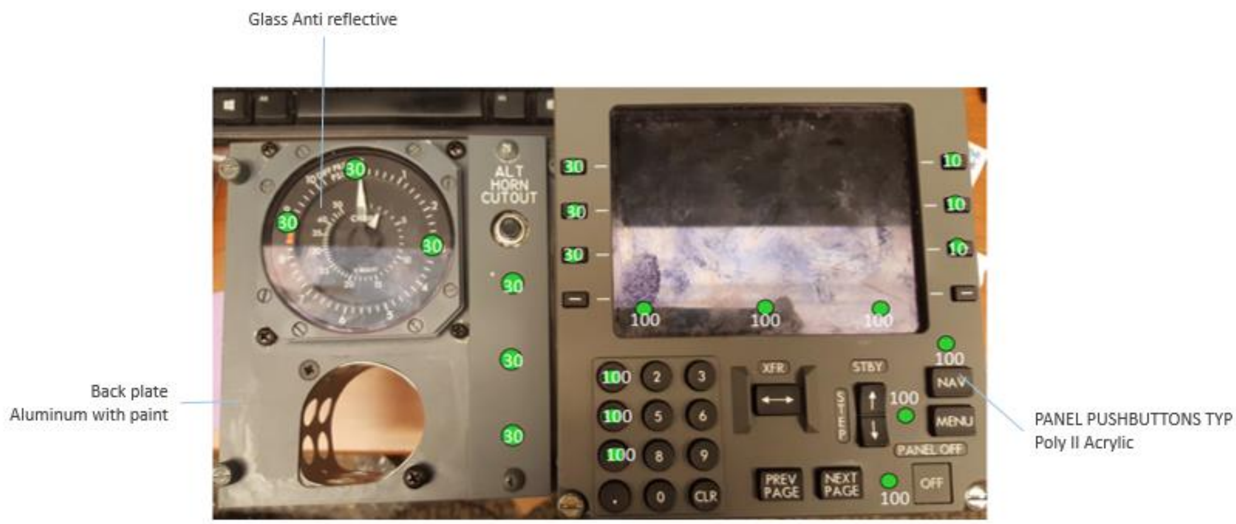

Figure 2: Example of Provided Flight Deck Hardware

Three material types including Painted Aluminum/Acrylic Back Plate, Anti-reflective Glass Indicator Lens, and Poly II Acrylic Pushbutton were selected as being good indicators of efficacy by considering a combination of factors such as availability, thermal conductivity of the materials, touch time during use, material amount, and difficulty to clean. To understand the effects of an expanded temperature and humidity range, an additional round of testing was conducted. This testing was limited to the Poly II Acrylic material (pushbutton) since it is the most touched of all the materials. Results of testing were then provided to Boeing for analysis and application.

Targeted Viral Inactivation Rate

Prior research by the University of Arizona with non-enveloped viruses examined the percentage of viruses transferred from contaminated surfaces to a human finger.[8] Assuming a similar finger transfer rate for SAR-CoV-2, a 3 $\log_{10}$ viral inactivation (99.9%) due to heating is

Copyright © 2021 Boeing. All rights reserved.

sufficient to consider surfaces disinfected. Work is underway to validate this assumption for SARS-CoV-2 which is an enveloped virus.

Lab Efficacy Testing Results

Figure 3 shows how each of the materials responded to the initial lab efficacy testing conducted. Time ranges of 180 minutes, 240 minutes, and 300 minutes for all materials resulted in a viral inactivation rate greater than 3 $\log_{10}$ (99.9% reduction). The results presented for all lab efficacy testing conducted show reductions of the SARS-CoV-2 virus from the contribution of thermal disinfection and natural die off of the virus.

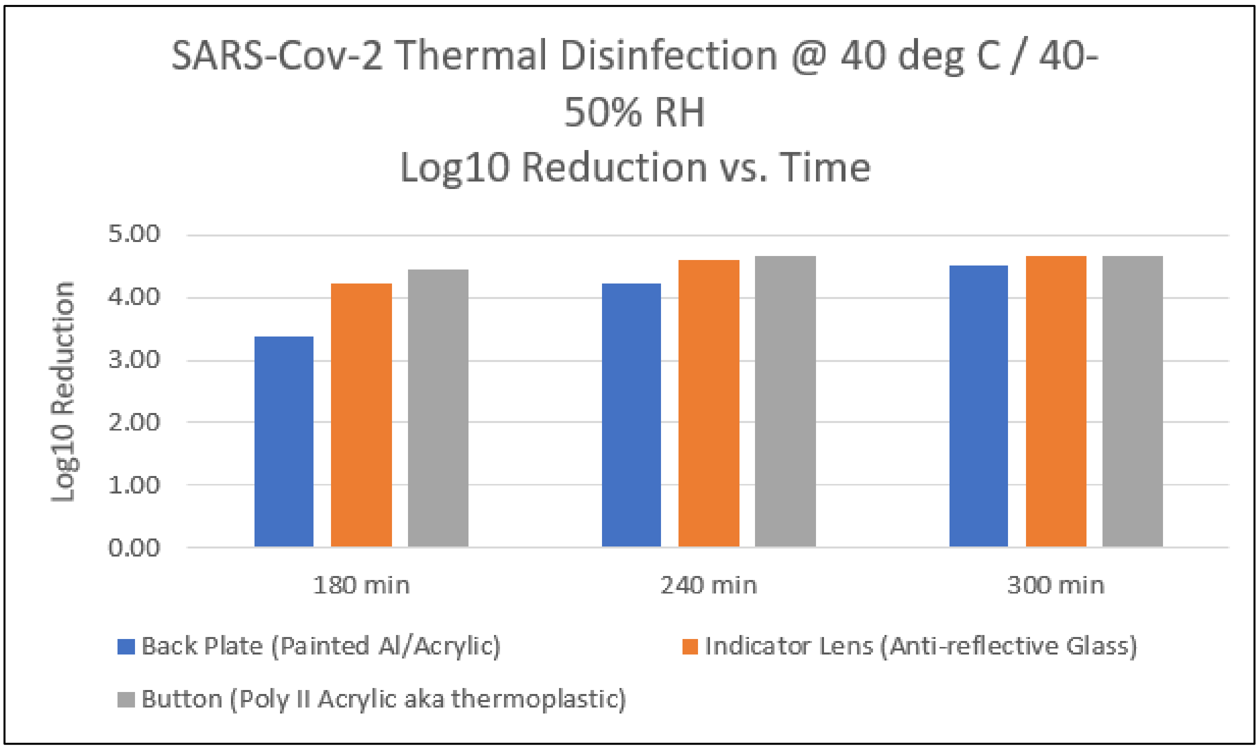

Figure 3: Surface Difference for Thermal Disinfection

The expanded temperature and humidity range testing results are shown in Table 2 for Poly II Acrylic, the common flight deck button material. The button material was selected because it was determined to be the highest touched surface. Phase 1 testing is highlighted in blue. Phase 2 testing is highlighted in green in the table. The overall goal of the Phase 2 lab testing was to determine if lower exposure times (30-120 minutes) at higher temperatures (50-55 ^{o}C), while maintaining the ambient relative humidity (40-50%) and expected airplane cabin relative humidity (<20%), played any appreciable role in an increase in viral inactivation. Overall, Phase 2 testing provided a wider range of reduction levels, as expected, and highlighted the role relative humidity plays. Lower relative humidity levels resulted in a 1-2 $\log_{10}$ reduction in viral inactivation differences for identical time and temperatures. No time frame tested at <20% RH

Copyright © 2021 Boeing. All rights reserved.

resulted in the targeted 3 $\log_{10}$ viral inactivation rate of 99.9%. Lastly, where $\log_{10}$ reductions are reported to be greater than 4.5, the virus was not detected.

Table 2: All Testing Conducted (Blue: Phase 1, Green: Phase 2)

	Average $\log_{10}$ Reduction					
Time (min) ----->	30	60	120	180	240	300
40°C / 40-50% RH				4.44	4.67	4.67
50°C / 40-50% RH	3.00	3.50	3.56	4.61	4.61	4.61
50°C / < 20% RH	1.00	1.44	2.06			
55°C / < 20% RH	1.78	2.11	2.83			

Thermal Disinfection Analysis

In Figure 4, testing was isolated for Poly II Acrylic, the common flight deck button material. The trend lines of the data below show a strong $\log_{10}$ linear relationship between reduction and time until the reductions approach the limit of viral detection (observed as a plateau). The 40°C / 40-50% RH plot was estimated using a log-linear approximation offset from the 50°C / 40-50% RH plot and through the observed data near the limits of detection. The 50°C / <20% RH and 55°C / <20%RH plots were estimated using a log-linear approximation through the observed points. The 40°C / <20% RH plot was derived using a rough log-linear approximation and y-intercept offset to the 40°C / 40-50% plot. These plots, derived from observed data and analysis, yield approximate time intervals to reach 3 log10 (99.9%) reductions.

Figure 4: Relationship of RH and Temperature on Disinfection

Copyright © 2021 Boeing. All rights reserved.

Tables 3 and 4 summarizes the results of the lab efficacy testing performed. The time required to achieve a 99.9% reduction in the viral titer of SARS-CoV-2 (3 $\log_{10}$ inactivation) for specific temperatures and relative humidity was determined for the down selected button material.

Table 3: Predicted Time to Disinfect at 40-50% RH

Steady State Temperature at 40-50%RH	**Efficacy Achieved**	**Approximate Time Required**
40°C (104°F)	99.9%	70 minutes (1.167 hours) **predicted from data*
50°C (122°F)	99.9%	30 minutes (0.5 hours)

Table 4: Predicted Time to Disinfect at <20% RH

Steady State Temperature at <20 %RH	**Efficacy Achieved**	**Approximate Time Required**
40°C (104°F)	99.9%	305 minutes (5 hours) **predicted from data*
50°C (122°F)	99.9%	200 minutes (3.33 hours) **predicted from data*
55°C (131°F)	99.9%	134 minutes (2.23 hours) **predicted from data*

Based on the typical conditions expected when heating the flight deck, <20% humidity is more applicable. For example, ambient conditions at 10°C (50°F) and 100% RH resulted in 10% RH when heated to 50°C (122°F). The impact that humidity has on SARS-CoV-2 shown in the tables above falls in line with empirical data in the scientific literature.[8]

Copyright © 2021 Boeing. All rights reserved.

Background: Airplane Thermal Limitations and Methods

Airplane components (e.g. materials and electronics) are designed to meet "military grade" thermal standards including MIL-STD-810 and DO-160. Boeing internal standards provide further limits on expected thermal resistance based on analysis conducted by Boeing equipment engineers. Most commonly, airplane components are designed to the following maximum temperature limits:

Table 5: Airplane Thermal Limits

	Operating	**Non-Operating (unpowered)**
Up to 60°C (140°F)	Indefinite exposure	Indefinite exposure
60 to 70°C (140-160°F)	No greater than 30 minutes	
70 to 85°C (160-185°F)	N/A	

Airplane Applications for Thermal Disinfection

Airplane flight decks are compact volumes with a variety of sensitive equipment that may not be certified for repeated exposure to traditional chemical spraying. Moreover, the vast quantity of knobs, switches, and topographical interfaces makes hand wiping tedious and presents a potential ergonomic risk. The compact space of airplane flight decks means there are a large number of touch sites that are hard to avoid due to design. The airplane flight deck thus becomes a potential source for coming in contact with contamination for the pilots and crew. The lower bacterial risk compared to other airplane locations along with the limitations of other disinfection methodologies due to the sensitive nature of the equipment makes the flight deck the ideal location for implementation of thermal disinfection.

There are technical challenges in implementing thermal disinfection at other locations such as the cabin, galleys, and lavatories. The amount of energy needed to heat and maintain the cabin at these temperatures along with the potential for dead zones (locations that air does not flow to and would not result in disinfection) make the cabin and galleys unpractical for thermal disinfection. Other means of disinfection that aren't applicable in the flight deck (such as electrostatic spraying) may be more viable and easily incorporated within the airplane cabin.

Within the lavatories and galleys, in many cases, increasing temperatures to the ranges presented here can lead to bacterial growth[9], potentially resulting in a less safe environment for the passengers. A variety of other disinfection methods are effective for a variety of viruses and bacteria with less potentially negative impacts.

Copyright © 2021 Boeing. All rights reserved.

Airplane Thermal Disinfection Methodology Selection

Autoclaves and other common high temperature thermal disinfection devices would damage equipment and materials on the airplane. Various methods of heating flight control surfaces to desired temperatures for disinfection have been evaluated for feasibility and are compared below. Boeing down selected and proceeded with evaluation of the recirculating air heaters with exit temperature control.

Table 6: Evaluations of Thermal Disinfection Methods

Radiant heaters	Cannot achieve uniform surface temperature because of varying absorptivity and conductivity of surfaces.
Heater Blankets	Cannot achieve uniform surface temperature. Provide constant heat flux across surfaces with varying thermal conductivity.
Hot air blower	Handheld blowers are not feasible because of the extended amount of time required for thermal disinfection at temperatures safe for equipment and materials.
Heat with airplane Environmental Control Systems (ECS)	The airplane ECS is theoretically capable of supplying heat at temperatures for thermal disinfection, but the systems are specifically designed to prevent excessive cabin air temperatures for safety reasons.
Heat with external ground cart	Currently available ground carts have insufficient heating power to heat an entire airplane to disinfection temperatures, and no feature currently exists to direct ground air solely to the flight deck. Ground cart concepts also inefficient because hot air is blown *through* the volume being disinfected, meaning that expensively heated air must constantly leak from the airplane at the rate new air is supplied.
Heat with recirculating air heaters with exit temperature control	This is the concept chosen and tested by Boeing. Air is recirculated to avoid blowing heated air out of the disinfection volume. Active controls limit the exit air temperature to match the equipment and material limits of the disinfection volume, preventing any surface from becoming overheated.

Copyright © 2021 Boeing. All rights reserved.

Boeing Recirculating Heater Test Methodology

Based on lab efficacy testing data, recirculating heaters were designed and built by Boeing for ground testing. Four 1.6 kW heaters were used with two >600cfm actively controlled fans. Figure 5 shows the recirculating heater concept. The heaters require active controls to limit exit temperature to 60°C to protect avionics in the flight deck. As such, the heaters were equipped with PID controllers rated to 60°C.

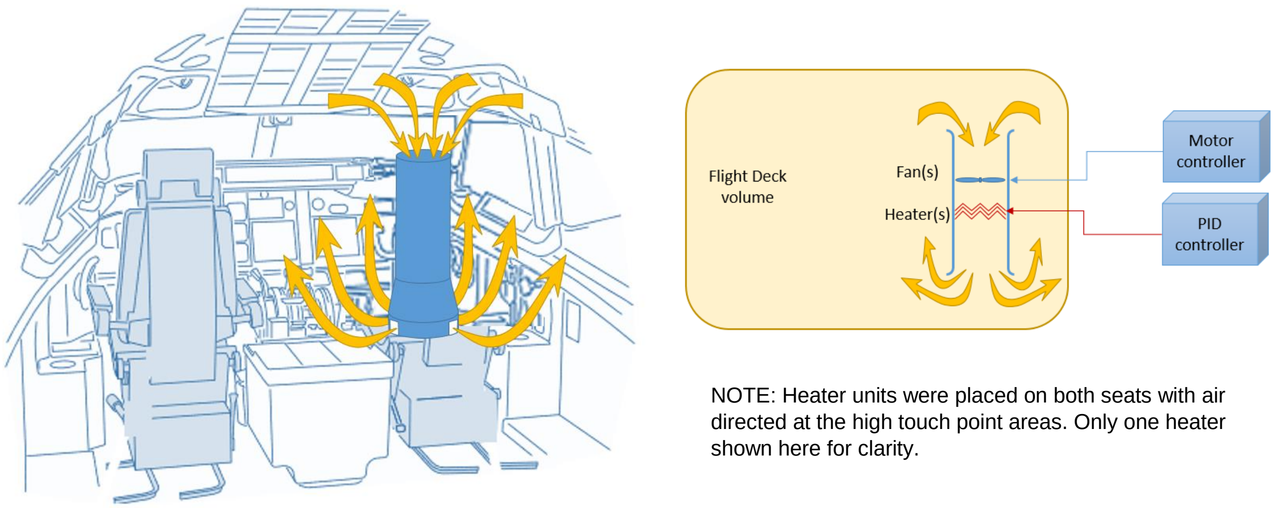

Figure 5: Boeing Recirculating Heater Concept Schematic

These were utilized on a Boeing owned 737-8 to test the practicality of achieving a 40-60°C temperature range in the flight deck. Three rounds of testing were completed with modification to configurations and the heaters themselves after each round. Thermal disinfection temperatures were only achieved and maintained in the last round of test where the airplane was in the power off configuration.

Boeing Recirculating Heater Test Results

Figure 6 shows the relationship between time and air temperature during the Boeing 737-8 testing for the third round of testing with the airplane powered off. With the airplane powered off, the airplane flight deck ramp up time was approximately 90 minutes. The fluctuations in the data can be correlated to external interferences in the flight deck when the door was opened. The control mechanism of the heaters was effective in ramping up to the require temperatures without resulting in overheating. Figure 7 shows thermal imaging across the flight deck during testing.

Copyright © 2021 Boeing. All rights reserved.

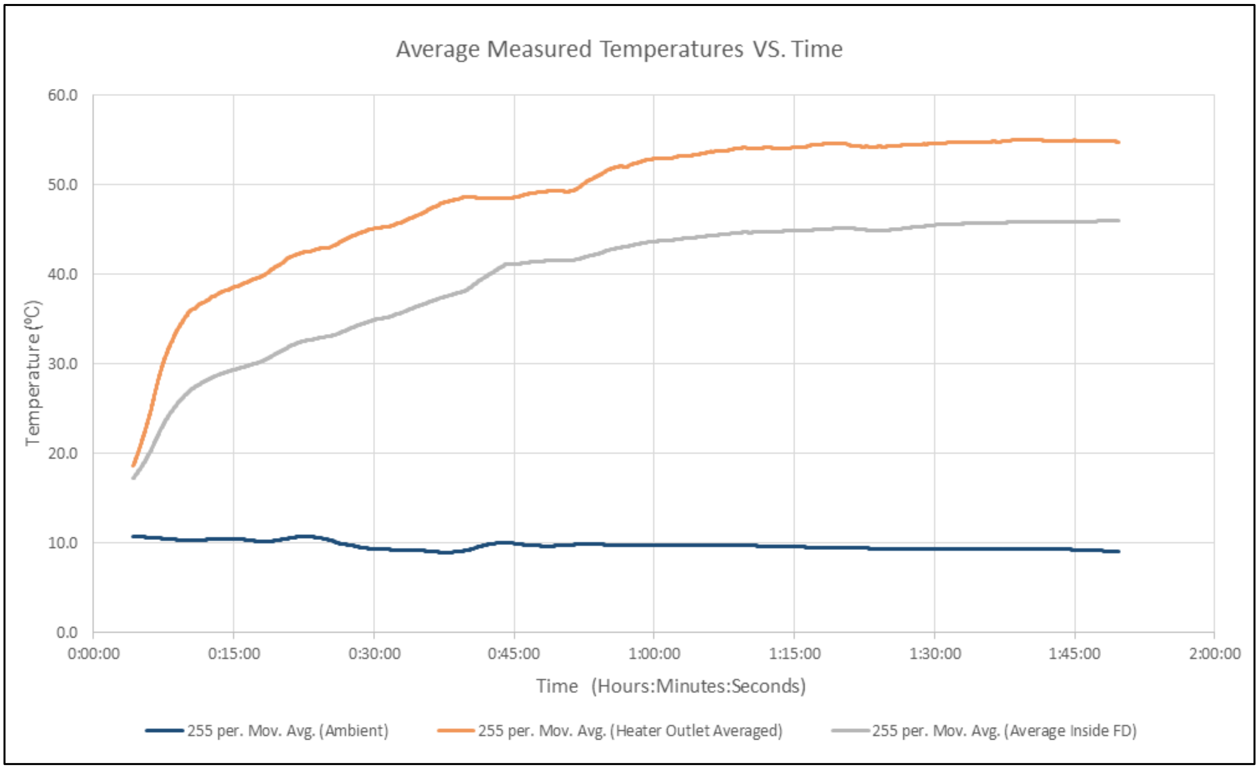

Figure 6: Relationship of Temperature and Time for Applicability Testing in 737-8 Flight Deck

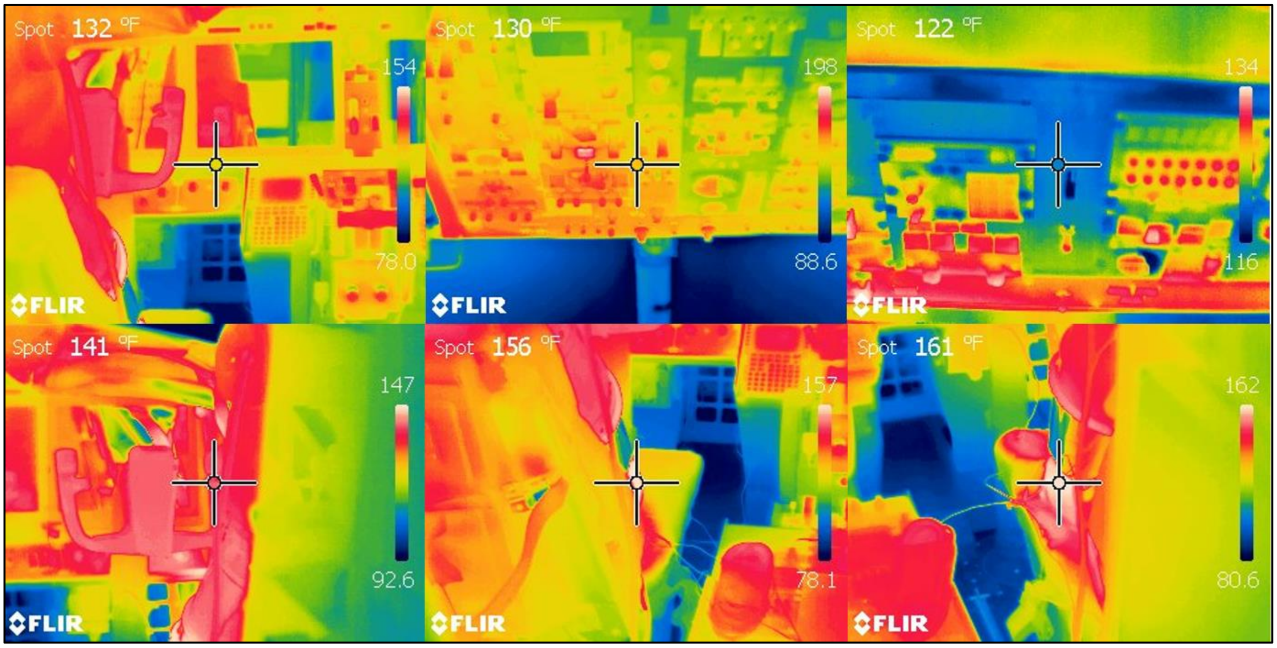

Figure 7: Boeing Recirculating Heater Thermal Images

Copyright © 2021 Boeing. All rights reserved.

All rounds of Boeing testing provided insight. Below are the major findings.

- Flight Deck equipment is protected with active equipment cooling system fans that remove much of the added heat from the flight deck. It was determined that thermally disinfecting a *powered* airplane was not feasible with the equipment available during the test.
- As expected, environmental conditions played a significant role in the amount of time and energy needed to achieve the desired temperature range. Testing that occurred early in the summer resulted in faster temperature ramp up times than testing that occurred in late fall when outside temperatures were cooler.
- Subsequent testing using more advanced heaters on an *unpowered* airplane had better results. Removing power from the airplane disables the equipment cooling system, keeping the heated air within the airplane. Additionally, unpowered equipment is less thermally sensitive because it is not generating its own internal heat.
- The tests determined that it was possible to heat the flight deck to a disinfection temperature of 50°C (122°F) in approximately 90 minutes with an ambient temperature of 10°C (50°F) under cloudy conditions while the airplane was unpowered.
- Through testing, it was identified that the commercial grade heater controllers should be located outside the flight deck volume being disinfected if possible.
- Successful testing required active control of both heater power and fan air flow to ensure flight deck temperatures did not exceed the equipment's thermal limit of 60°C.

Conclusion and Application

The use of thermal disinfection in the flight deck was validated as a potentially viable methodology for inactivating the SAR-CoV-2 virus. As shown above, the flight decks on Boeing airplanes are capable of withstanding repeated exposure to the time and temperature ranges required to inactivate the virus. Benefits of this technology include efficiency and ergonomic considerations. This is another one of the multi-layered solutions for disinfection that Boeing has investigated.

In addition, Boeing has identified the following considerations when using thermal disinfection:

- Operators must maintain 40°C for approximately 395 minutes, 50°C for 290 minutes, or 55°C for 224 minutes to achieve disinfection at expected flight deck humidity conditions (<20% RH). These times do include the time it takes to ramp up to these temperatures (ramp up time) of approximately 90 minutes as shown through Boeing recirculating heating testing.
- In all but the warmest climates, thermal disinfection will require heat in excess of domestic power available at the typical jet way.
- The airplane should be unpowered during thermal disinfection. This reduces the risk of damage to avionics due to overheating and removes the heat loss due to the operation of the equipment cooling system.
- Disinfection with the airplane powered, if possible would require significantly more power and careful control of exit temperatures to protect avionics.

Copyright © 2021 Boeing. All rights reserved.

- Best results were obtained with a mix of variable speed fans and variable power heaters. Commercial grade heater controllers should be located outside the flight deck volume being disinfected.
- Efficacy tests conducted by the University of Arizona on SARS-CoV-2 determined the environmental conditions and times necessary to successfully inactivate 99.9% of the SARS-CoV-2 respiratory viruses.

Copyright © 2021 Boeing. All rights reserved.

References

[1] *K H Chan et al. The effects of temperature and relative humidity on the viability of the 343 SARS coronavirus. Advances in virology* 2011 (2011). DOI: 10.1155/2011/734690

[2] Mahesh Jayaweera, Hasini Perera, Buddhika Gunawardana, Jagath Manatunge. *Transmission of COVID-19 virus by droplets and aerosols: A critical review on the unresolved dichotomy*. Environ Res 2020; DOI: 10.1016/j.envres.2020.109819.

[3] *Alex W H Chin, Julie T S Chu, Mahen R A Perera, et al. "Stability of SARS-CoV-2 in different environmental conditions" - School of Public Health, LKS Faculty of Medicine, The University of Hong Kong, Hong Kong Special Administrative Region, China.* Lancet, Volume 1, Iss 1, 2020/05/01; DOI:https://doi.org/10.1016/S2666-5247(20)30003-3

[4] *Dylan H. Morris, Kwe Claude Yinda, Amandine Gamble, Fernando W. Rossine, Qishen Huang et al. "The effect of temperature and humidity on the stability of SARS-CoV-2 and other enveloped viruses"* Princeton, 2020/10/16; DOI: https://doi.org/10.1101/2020.10.16.341883.

[5] Boris Pastorino, Franck Touret, Magali Gilles, Xavier de Lamballerie, Remi N. Charrel *Evaluation of heating and chemical protocols for inactivating SARS-CoV-2* – Viruses. doi: https://doi.org/10.1101/2020.04.11.036855

[6] David E. Harbourt, Andrew D. Haddow, Ashley E. Piper, Holly Bloomfield, Brian J. Kearney, David Fetterer, Kathleen Gibson, Timothy Minogue. *Modeling the Stability of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) on Skin, Currency, and Clothing* – PLOS Neglected Tropical Diseases. doi: https://doi.org/10.1101/2020.07.01.20144253

[7] Linsey C. Marr, Julian W. Tang, Jennifer Van Mullekom, and Seema S. Lakdawala *"Mechanistic Insights into the Effect of Humidity on Airborne Influenza virus survival, transmission and incidence"* – Journal of the Royal Society Interface, 01/2019; DOI: https://doi.org/10.1098/rsif.2018.0298

[8] *Michael O. Ryan, Charles N. Haas, Patrick L Gurian, et al. "Application of quantitative microbial risk assessment for selection of microbial reduction targets for hard surface disinfectants"* – American Journal of Infection Control, 42, 2014; DOI:https://doi.org/10.1016/j.ajic.2014.07.024

[9] *D A Ratkowsky, J Olley, T A McMeekin, A Ball. "Relationship between temperature and growth rate of bacterial cultures"* – Journal of Bacteriology, 1/1982; DOI:https://jb.asm.org/content/jb/149/1/1.full.pdf

Copyright © 2021 Boeing. All rights reserved.