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Field Evaluation of Whole Airliner Decontamination Technologies – Wide-Body Aircraft With Dual-Use Application for Railcars

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16. Abstract

The outcome of a field evaluation of decontamination of a wide-body aircraft using AeroClave's thermal decontamination system both as a stand-alone technology and as a means of delivering STERIS vaporized hydrogen peroxide (VHP®)* is discussed. The report is submitted in the context of a decontamination technology selection exercise, laboratory work conducted on the efficacy of thermal decontamination, and as a follow-on to a field evaluation performed previously on a McDonnell Douglas DC–9 aircraft. The thermal decontamination system appears to be capable of reproducing temperatures needed for an efficacious antiviral process. However, work will be required to improve the temperature control and humidity levels attainable. The thermal decontamination + VHP add-in combination was found to be sporicidal at numerous locations within the cabin. The impact of issues relating to the failure to deactivate Biological Indicators (BIs) in certain locations with limited peroxide penetration, condensation of peroxide within the cabin, and more generally, issues related to the presence of residual peroxide in the cabin after aeration need to be addressed. Serious weather-related disruptions and a limited budget, coupled with a tight schedule, precluded these concerns being addressed on this occasion. Overall, the field evaluation of both the stand-alone thermal decontamination system and the VHP add-in can be described as successful.

*VHP is a registered trademark of the STERIS Corporation, Mentor, OH.

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The authors also express their thanks to Dr. Vipin Rastogi and Ms. Lalena Wallace, of the U.S. Army Edgewood Chemical Biological Center for visiting the demonstration site and for helpful discussions on the evaluation methodology employed.

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ABBREVIATIONS

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

Abbreviation	Meaning
AERF	Aircraft Environmental Research Facility
APU	Auxiliary power unit
BIs.	Biological indicators
CAMI	Civil Aerospace Medical Institute
ECBC	Edgewood Chemical Biological Center
ECS	Environmental control system
OSHA	Occupational Safety and Health Administration
PCA	Preconditioned air
PEL	Permissible exposure level
RH	Relative humidity
TSI	Transportation Safety Institute
TWA	Time weighted average
VHP	Vaporized hydrogen peroxide

CONTENTS

Field Evaluation Of Whole Airliner Decontamination Technologies – Wide-Body Aircraft With Dual-Use Application for Railcars

INTRODUCTION

This report describes a follow-on from an earlier evaluation of a thermal decontamination system, which was used both as a stand-alone technology and as a means of delivering vaporized hydrogen peroxide (VHP) in a narrow-body aircraft. Whereas the earlier report (Gale, 2007) focused on a field evaluation using a narrow-body, single-aisle, aircraft, the present report considers the application of the same technology to a wide-body, twin-aisle aircraft. This work employed the FAA's Aircraft Environmental Research Facility (AERF), a grounded Boeing 747 aircraft located at the Civil Aeromedical Institute in Oklahoma City, OK. An attempt was also made to apply the same technologies to a two-decker commuter rail car belonging to the Transportation Safety Institute and co-located with the 747.

METHOD

Objectives

747 – Stand-Alone Thermal Decontamination System

The aim was to demonstrate the ability of the system to heat the entire cabin to a temperature of 60ºC, under conditions of controlled relative humidity (RH), without significantly over-shooting this temperature at any location, hold the entire cabin isothermal at 60ºC for an arbitrary time without significant temperature fluctuations, and to cool back to room temperature rapidly, but in a controlled fashion.

747 – VHP Add-in

In this instance, the goal was to demonstrate the feasibility of using the stand-alone thermal decontamination system as a means of delivering VHP in an efficient fashion, without requiring bulky vaporizers or other heavy equipment within the cabin, and that the system is capable of delivering controlled quantities of VHP, such that sporicidal conditions can be achieved throughout the cabin. As such, the VHP tests were not intended to be definitive but to explore initial viability and establish parameters for more detailed tests in the future.

It is to be stressed that, unlike earlier work on a smaller McDonnell Douglas DC-9 aircraft for which there was extensive prior setup, the work on the 747 was relatively exploratory. Furthermore, in the case of the railcar, this was no more than an initial demonstration of capability, not a formally evaluated test of decontamination performance.

Railcar – Thermal and VHP Runs

A single decontamination unit was employed to demonstrate both thermal and VHP decontamination.

Methodology

The thermal decontamination system, as a stand- alone technology, was deployed in its standard configuration. Details of this may be found in the outcomes of the decontamination technology down select (Gale et al., 2006) and in an earlier report on work on narrow-body aircraft (Gale, 2007). In summary, the thermal decontamination system is designed to deliver heated or cooled air, under feed-back control from a self contained unit housed on a semi-trailer. Given the relatively large volume of the 747's interior, two such units were employed, both of which were controlled from a station set up adjacent to the aircraft. The units were connected to the cabin via flexible air delivery and return hoses. Custom door plugs connected to the inlet and outlet hoses were fabricated on-site. In this configuration, the air inlets were at the emergency exit doors above the wing and the air outlets at the front and rear cabin doors. Air supplies and returns were located on both the port and starboard sides of the aircraft.

It is important to note that the 747 aircraft used in the evaluation did not retain the original configuration of the environmental control system (ECS). Hence, only the cabin interior and not the cargo bay or ECS ducts were decontaminated. The AERF is equipped for evacuation research and hence has a smoke elimination system. This was capped off before starting the present work, and so the cabin geometry is reasonably similar to that of an operational 747. The cabin of the AERF was equipped with almost a complete set of seats. Dummy plywood fixtures with a stick-on plastic coating are used by CAMI in place of the lavatories and galleys.

The thermal decontamination system in its original configuration did not include a humidification capability. Hence, on heating, the relative humidity in the cabin dropped quickly. Based on the results of an earlier study (Rudnick et al., 2006), which indicated a need to maintain a RH of ≥ 35% at 60ºC, the equipment manufacturer opted to add a 100 kW steam-based humidification system, which was employed during the evaluation described in this report. The output from the steam generator was fed into the first of the two semi-trailers used to decontaminate the 747.

In the case of the VHP add-in, a detailed description of the setup employed may be found elsewhere (Thomas, 2007), and hence only the key points are discussed here. VHP was injected into the air delivery system from an external bank of two VHP generators located in the second trailer.

It is important to note that the intended function of the thermal decontamination system changes depending on which mode this is employed in.

In the stand-alone configuration, the thermal decontamination system is intended to deliver hot air of controlled humidity to achieve thermal decontamination to eliminate viruses and then cool the aircraft back to a desired temperature and relative humidity so that people may re-enter the cabin. The thermal decontamination system may also have other applications, such as non-chemical disinsection, as was discussed in the technology evaluation (Gale et al., 2006).

The thermal decontamination system, when used in conjunction with the VHP add-in, produces environmental preconditioning prior to the injection of VHP. This involves reducing the RH to below 60% (ideally 50% or lower), delivery of VHP to the cabin, and aeration to extract VHP from the cabin.

Railcar – Thermal and VHP Run

Although the primary focus of the work reported here was on wide-body aircraft, the opportunity was taken to demonstrate decontamination of a two-decker commuter railcar. In this case, a single decontamination unit was employed to demonstrate both thermal and VHP decontamination. The inlet and outlet hoses were placed in the end doors of the railcar, using door plugs manufactured on site.

Protocols

The following protocols were established in advance of the testing. As was noted above, work on the 747 was exploratory and so the aim was simply to approach these conditions as closely as possible, rather than a "pass/fail" scenario for the technology.

747 – Stand-Alone Thermal Decontamination System

The cabin of the 747 would be instrumented with relative humidity sensors (one in the front and one at the rear of the cabin) and 36 thermocouples, and data were logged continuously.

At least three sets of data were to be collected, one of which would be on the day of the Edgewood Chemical Biological Center (ECBC) evaluation and meeting the following criteria. The target cabin surface would be maintained at 60°C for at least two hours. The temperature at the air inlet would not exceed 65°C, and the target relative humidity would be 50%. The cargo area would be excluded from the evaluation.

747 – VHP Add-in

The cabin would be equipped with the same instrumentation used for the stand-alone thermal decontamination system. Additionally, six ATI hydrogen peroxide vapor sensors for measuring the working concentration of the VHP would be included.

Thirty Apex 6 log G. Stearothermophilus biological indicators (BIs) would be placed throughout the cabin. Note: In the field work, chemical indicators (CIs) were co-located with the BIs so as to supplement the peroxide sensors, although this was not specified in the protocol.

Peripheral sensors would be placed around the aircraft, including near the outlet used to flush the VHP, to demonstrate compliance with OSHA PEL and other relevant exposure limits. Handheld sensor(s) with manual data recording would be used in lieu of suitably calibrated automated sensors, not available on-site. VHP concentrations would be monitored on entering the cabin after each run using suitable instrumentation.

A minimum of three runs would be performed, including one on the day of the formal evaluation, with observers from the FAA and ECBC present.

All of the runs would be performed under the following conditions: VHP concentration would be maintained between 125 – 200 ppm for at least two hours at all locations sampled. The VHP concentration would not be allowed to exceed 500 ppm at any location to minimize the risk of condensation.

VHP concentrations would be monitored on entering the cabin after each run to ensure that the reading did not exceed 1 ppm for those runs in which aeration was allowed to run to completion.

In view of time constraints, the run during the ECBC (Rastogi, 2007) and FAA visit would be terminated at 2 – 5 ppm, while ensuring that the duration of exposure for personnel harvesting the BIs was carefully monitored so that no individual's exposure would exceed the OSHA 1 ppm TWA PEL. In the case of all runs, except that carried out on the day of the evaluation, the monitoring described in the previous paragraph would be repeated to detect any VHP out-gassing from porous media within the cabin. Additional aeration would be employed as found necessary, and the measurements would be repeated.

Railcar – Thermal and VHP Run

The monitoring procedures for both the thermal and VHP decontamination runs would be similar to those employed for the 747 but with a reduced number of sensors. This would not be a formal evaluation, as has already been noted, but would be an initial demonstration of capability.

RESULTS

747 – Stand-Alone Thermal Decontamination System

It proved possible to heat the majority of the 747 cabin to close to 60ºC and hold fairly near to this temperature for an extended period with the use of two thermal decontamination units (Figure 1). However, in some cases regions, it was not possible to hold at 60ºC for 2 hours, as stipulated in the protocol (Figure 2). Surface temperatures in other locations (e.g. adjacent to the inlet) were found to exceed 65ºC, with a maximum temperature of 71ºC being observed where the incoming air stream impinged on the cabin (Figure 3). The two thermal decontamination units appeared to be well matched to the thermal mass of the 747, whereas a single unit had a rather larger heating capability than that required for a DC-9.

An effort was made to sample the temperature at locations throughout the cabin, encompassing surfaces comprised of a wide range of materials and thermal masses. All temperatures specified are surface temperatures, not air temperatures. Some run-to-run scatter was apparent for runs conducted with identical control parameters.

Using the 100 kW steam generator, it was not found possible to bring the cabin RH to above 20% (Figures 4 and 5).

747 – VHP Add-In

The combined system appeared to be capable of controlling the VHP concentration in the 747's cabin, based on the output from 8 hydrogen peroxide sensors (Thomas, 2007). It was possible to maintain an average cabin hydrogen peroxide concentration of around 175 ppm under non-condensing conditions, which should be sufficient to produce a sporicidal action (concentrations above ~ 80 ppm are usually considered sporicidal). The hydrogen peroxide concentration measured adjacent to the inlet did not exceed 275 ppm, and hence there does not appear to be a risk of macroscopic condensation of the peroxide (and localized condensation would require pockets of high humidity). However, some condensed peroxide was apparent in the return air cabinet of the thermal decontamination system's air handler and at weather-induced breaches to the temporary wooden door plugs.

In a few cases, the 6 log G. Stearothermophilus biological indicators (BIs) placed throughout the cabin did not achieve complete kill. These BIs were placed in locations where peroxide access proved difficult to achieve (see Gale, 2007 for a note on the limitations of the label claims made by STERIS with respect to occluded spaces). The only cases of extensive kill failures in large portions of the cabin were due to weather-generated equipment failures that caused condensation of the peroxide (Thomas, 2007). Table 1 summarizes the data obtained from the BIs. As in earlier work on the DC-9, some issues were encountered with release of peroxide trapped in seat fabrics, etc. Optimization of the aeration cycle seemed to help significantly in addressing this problem, although this still remains an issue. This work is described in detail in another report (see Thomas, 2007).

Railcar – Thermal and VHP Run

Although not formally evaluated, initial work on the railcar indicated that it is possible to reach the targeted environmental conditions for both thermal and VHP decontamination. The absence of absorbent surfaces within the railcar made the removal of VHP during post-decontamination aeration much less challenging than was the case for the 747. A two-hour exposure at an average 250 ppm VHP concentration deactivated all BIs placed in the rail car. Table 2 shows the kill results from the BIs.

DISCUSSION

747 – Stand-Alone Thermal Decontamination System

As already noted, the primary focus of the work reported was on determining the feasibility of scaling up of decontamination from the earlier work on the DC-9 to the 747, rather than on optimization of the decontamination process itself. Hence, the issues that were not addressed in the DC-9 work remain (Gale, 2007). In the interests of brevity, they will not be repeated here.

Notwithstanding the modifications made to the 747, the work performed on the AERF can be regarded as a reasonable analogue for decontamination of an actual airliner cabin (minus the cargo area and ECS ducts) in that the thermal mass should still be fairly similar to an actual wide-body aircraft, and most of the original materials of construction remained in place.

Most of the cabin was efficiently heated, without resort to an air distribution system within the cabin. However, one location, adjacent to one of the cabin service areas (galleys and lavatories), was found to have insufficient airflow, so an extension trunk was used to deliver air to this location (Thomas, 2007). It is possible that, with further optimization of the air delivery system, the extension trunk could be eliminated.

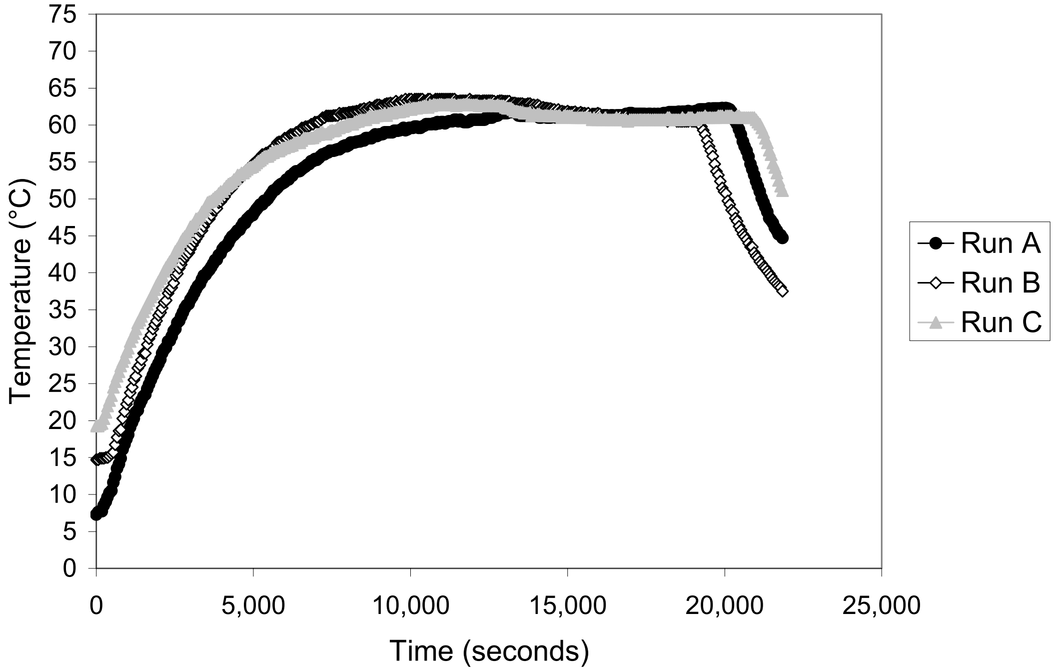

Figure 1. Profile from an armrest towards the rear of the cabin

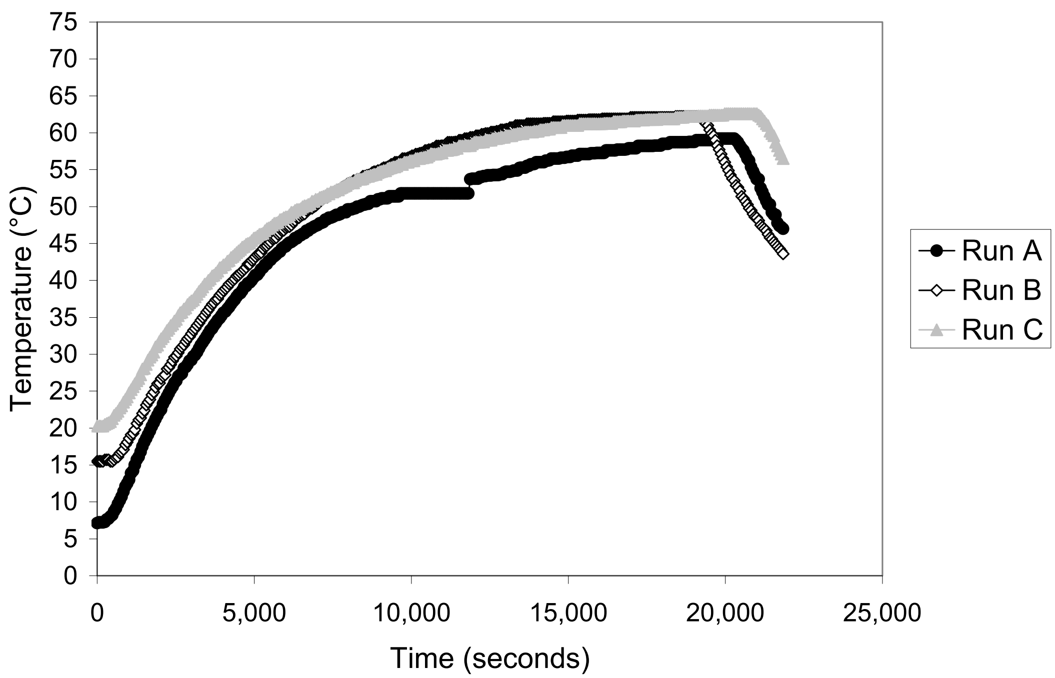

Figure 2. Profile from an armrest towards the front of the cabin

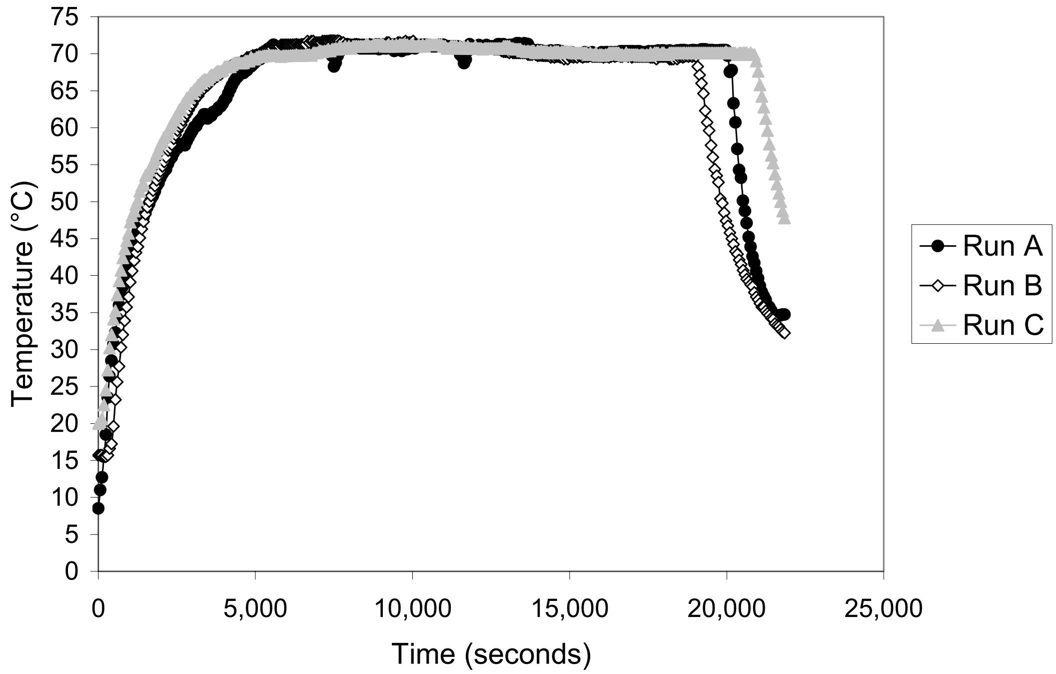

Figure 3. Profile from an overhead area adjacent to inlet

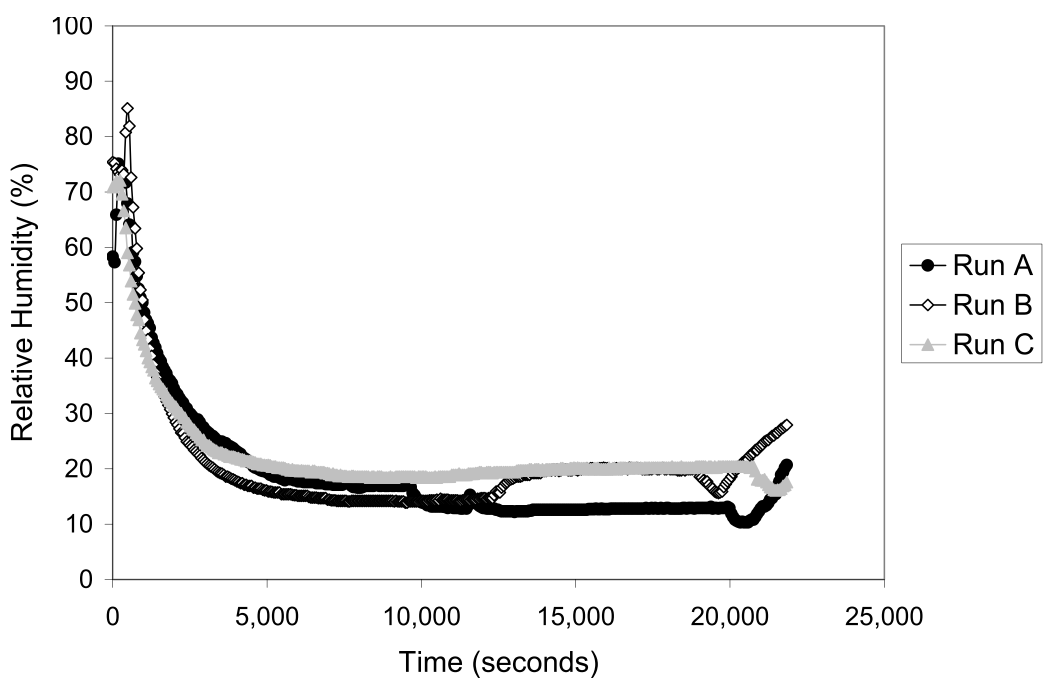

Figure 4. Relative humidity profile from the rear of the cabin

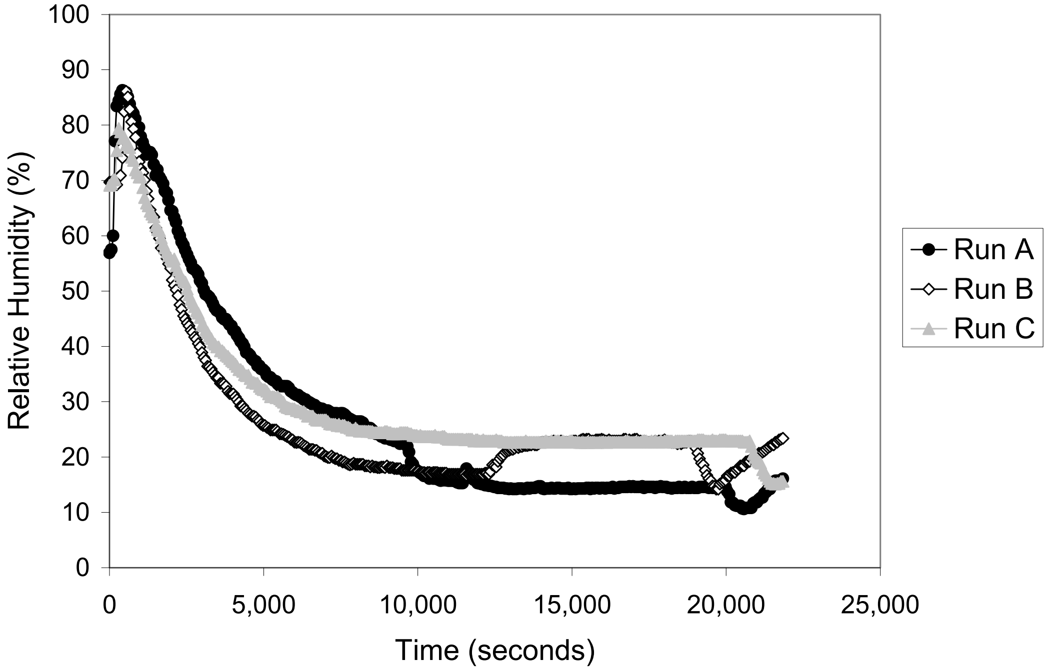

Figure 5. Relative humidity profile from the front of the cabin

Table 1. Biological Indicator Results for 747 (Provided by Jim Thomas, STERIS Corporation)

BI Location	Record Run 1		Record Run 2		Record Run 3	
	48 hr	7 day	48 hr	7 day	48 hr	7 day
1	-	-	-	-	+	+
2	-	-	-	-	-	-
3	-	-	-	-	-	-
4	-	-	-	-	-	-
5	+	+	-	-	-	-
6	-	-	-	-	-	-
7	-	-	-	-	-	-
8	-	-	-	-	-	-
9	-	-	-	-	-	-
10	-	-	-	-	-	+
11	-	-	-	-	+	+
12	+	+	-	-	-	-
13	-	-	-	-	+	+
14	-	-	-	-	-	-
15	-	-	-	-	+	+
16	-	-	-	-	+	+
17	-	-	-	-	+	+
18	-	-	-	-	-	-
19	-	-	-	-	+	+
20	+	+	-	-	+	+
21	-	-	-	-	+	+
22	-	-	-	-	-	-
23	-	-	-	-	-	-
24	-	-	-	-	-	-
25	-	-	-	-	+	+
26	-	-	-	-	-	-
27	-	-	-	-	-	-
28	-	-	-	-	-	-
29	-	-	-	-	-	-
30	-	-	+	+	-	-
+ Control	+	+	+	+	+	+
+ Control	+	+	+	+	+	+
+ Control	+	+	+	+	+	+
+ Control	+	+	+	+	+	+

Table 2. Biological Indicator Results for Rail Car (Provided by Jim Thomas, STERIS Corporation)

BI Location	48 hr	7 day
1	-	-
2	-	-
3	-	-
4	-	-
+ Control	+	+
+ Control	+	+
+ Control	+	+

Cabin temperature on multiple cabin surfaces exceeded the desired 60ºC. This was due to one of the two units having to be operated at 65ºC and the second at 85ºC, due to on-site power limitations. It must be noted that the present trials were conducted on a very tight schedule and budget. It is likely that given a longer lead time, more proving runs, and additional resources, the temperature control issues can be addressed.

Failure to reach a humidity of $\geq$ 30% RH for rapid antiviral efficacy (Rudnick et al., 2006) was disappointing. However, this does not appear to be a fundamental problem with the system but a matter of exceeding the capacity of the existing steam generator to humidify a wide-body aircraft. This is an issue that can be addressed easily in the future.

Apart from the above, no significant issues were apparent that had not already manifested themselves in the DC-9 work. Indeed, the results are generally encouraging with respect to the feasibility of scaling up thermal decontamination to wide-body aircraft.

747 – VHP Add-In

As in the case of thermal decontamination, issues identified in the DC-9 work persisted with the 747. However, progress does seem to have been made with respect to improving the efficiency of aeration (Thomas, 2007). Nonetheless, in our opinion, this is an issue that still needs to be addressed and one with scope for further improvement through optimization of the aeration stage.

It was noted in the ECBC report (Rastogi, 2007) that there was evidence, post test, of the presence of residual peroxide at a significant, but unquantified, concentration. Unfortunately, it has not yet proved possible, after the fact, to identify exactly when and where any peroxide hotspot occurred. During break-down of the system after the experiments, one of the authors did notice some residual peroxide in the supply lines, but it is hard to see how this would have been apparent during the demonstration itself.

The work conducted on the 747 is generally encouraging in that scale-up was achieved. However, issues related to residual peroxide remaining after aeration must be addressed in any future work.

Railcar – Thermal and VHP Run

Although not formally evaluated, no problems were encountered during the railcar decontamination demonstration, and this appears to be a successful initial demonstration of a capability for decontaminating such vehicles.

CONCLUSIONS

As a result of the field evaluation of the stand-alone thermal decontamination system and the VHP add-in, scaled up for application to a wide-body aircraft, the following conclusions have been drawn:

The thermal decontamination system appears to be capable of reproducing in the field the temperatures found in an earlier study to be needed for an efficacious antiviral process (Rudnick et al., 2006). Further work will need to be done to improve the temperature control to eliminate overheating of cabin surfaces. Reaching a relative humidity > 20% was found to be a problem, but this appears to be easily addressable with the addition of either a larger capacity or second steam generator.

The thermal decontamination + VHP add-in combination was found to be sporicidal at numerous locations within the cabin. The impact of issues relating to the failure to deactivate BIs in certain locations with limited peroxide penetration will need to be addressed. Condensation of peroxide within the cabin will also need to be addressed in future work on a wide-body aircraft. More generally, issues related to the presence of residual peroxide in the cabin after aeration need to be more fully addressed.

This evaluation of the 747 was conducted on a very limited budget and a tight schedule. Furthermore, there were weather-related disruptions that severely impeded set up and operation of the equipment. Given more time and resources, it is envisaged that most of the issues of concern can be addressed.

Although this was not a formal evaluation, the initial outcome from the railcar decontamination demonstration appears to be promising.

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