Chemical Disinfectant Evaluation and Approval for the Aerospace Industry

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Executive Summary

The selection and approval of chemical disinfectants to be used on aircraft components is not trivial. The selection process must ensure that the product used is effective against the target pathogen as well as ensuring the product used on aircraft components does not compromise safety of flight. For a chemical disinfectant to be selected for use on a commercial transport aircraft, it must not impact flammability properties, part or component performance, or aesthetics of the aircraft even with the repeated use of the selected disinfectant. This paper will discuss what constitutes an effective chemical disinfectant and detail the process Boeing employed in selecting and authorizing chemical disinfectants to be used both within their manufacturing facilities and on aircraft by airline operators.

1. Introduction

Surface or equipment decontamination is often needed inside the completed airplane or on the factory floor. However, unlike cleaning processes used to remove light soiling from day-to-day usage, disinfection is not a regular occurrence. Disinfection is performed to address incidental contamination and, in extreme cases, pandemic events or acts of terrorism.

In light of the COVID-19 pandemic, multiple efforts[1] have been taken to reduce the risk of SARS-CoV-2 transmission when flying. The aviation industry has been severely impacted and fast deployment of decontamination procedures is needed to protect passengers, crews, and personnel involved in operation of in-service airplanes and the manufacture of aircraft.

While various options are available for microbial decontamination, chemical disinfectants are the most widely used and have the most accessible procedure. One advantage of chemical disinfectants is the wide range of products available. However, the chemistry of disinfectants can vary, which can have an impact on their performance that is manifested in a disinfectant's effectiveness against a target pathogen and also in chemical reaction on the material substrate that the disinfectant contacts. Factors impacting the variation in effectiveness include: the chemistry of the biocidal active, the chemical formulation of the final product, the application manner of the, and the time of contact. Health and regulatory agencies reliably vet the effectiveness of disinfectants against various pathogens and provide lists of approved products to the public[2].

The intent of this document is to share the disinfectant selection and approval process Boeing and its partners employ. The paper starts with an overview of the various levels of decontamination that can be achieved with chemicals and how the chemistries of the disinfectants relate to the inactivation of pathogens. The paper then dives into material compatibility. It focuses on the different types of material degradations on aerospace components that can occur with chemical exposure and the standard test methods performed to ensure that safety of flight is not compromised and that components are not damaged by the disinfectant's use. Lastly, the relevance of material compatibility testing to the intended application process is demonstrated.

2. Understanding Levels of Decontamination

For the purpose of this paper, the Occupational Safety and Health Administration (OSHA) definition of decontamination will be used. According to OSHA, *decontamination* is the process of removing or neutralizing contaminants that have accumulated on personnel and equipment [3]. Below are various levels of inactivation aligned to the definitions set by the United States Center for Disease Control (US CDC)[4] and as used within this paper.

2.1 Cleaning

Cleaning is removal of visible soil (e.g., organic and inorganic material) from objects and surfaces and normally is accomplished manually or mechanically using water with detergents or enzymatic products. This process does not necessarily kill pathogens, but by removing them, it lowers their numbers and the risk of spreading infection.

2.2 Disinfection

Disinfection eliminates many or all pathogenic microorganisms on inanimate objects. This process does not necessarily clean dirty surfaces or remove pathogens, but by killing them on a surface after cleaning, it can further lower the risk of spreading infection.

2.3 Sanitization

Sanitization lowers the number of pathogens on surfaces or objects to a safe level, as judged by public health standards or requirements. This process works by either cleaning or disinfecting surfaces or objects to lower the risk of spreading infection.

2.4 Sterilization

Sterilization involves a higher level of disinfection. It inactivates all microbial contamination including endospores. Although common sterilization procedures involve physical processes, some disinfectants are effective enough to be

considered sterilants.

3. Efficacy

3.1 Biocides

When the need to disinfect an area arises, an important consideration is the efficacy of a given disinfectant. The efficacy of a disinfectant is largely dependent on the chemistry and concentration of the biocide, also called the active ingredient. The most common active ingredients are grouped by chemical families and classified as alcohols, carbolic acids, reducers, oxidizers, and quaternary ammonium compounds (QAC)[5]. They are formulated to contain additives such as surfactants or stabilizing agents that help to optimize the cleaning and disinfecting power of the final product. The chemistry of these additives needs to be taken into account when selecting a disinfectant because they may impact its compatibility with the substrate material.

3.2 Mechanisms of Action

The selection of a specific biocide to target a specific microbe is facilitated by knowing what types of structures can be attacked to render the microorganism inactive. The relative resistance of microorganisms against biocides, in order from least resistant to most resistant, is as shown below[6]:

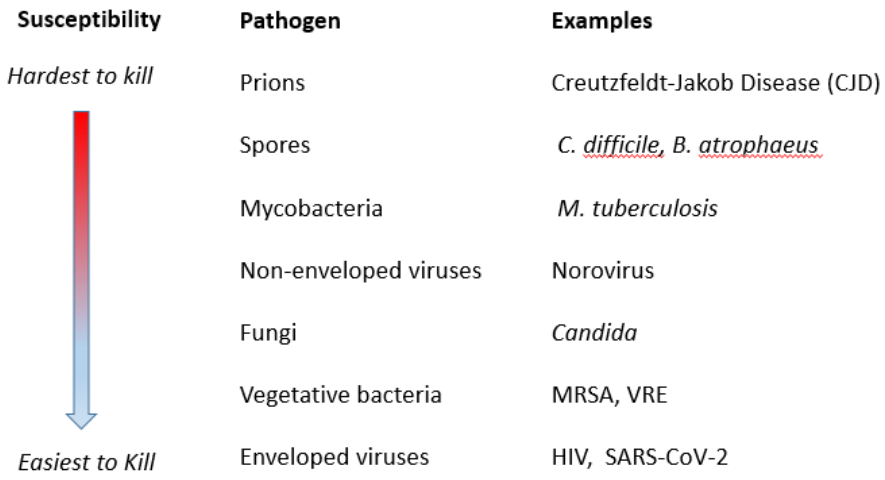

Fig. 1. Order of susceptibility of microorganisms to disinfectants/sterilants

In this scheme, enveloped viruses such as the SARS-CoV-2 would be easier to inactivate compared to a bacterial spore such as anthrax. When selecting a disinfectant from an efficacy standpoint, one should consider the contact time needed to get the desired decontamination level against the target pathogen. This information is needed in determining whether a particular product and application can be used within the operation requirements of an airline or schedule of a manufacturing process.

Biocides, depending on the chemistry and the specific microorganism, are effective in rendering microorganisms inactive. The mechanisms used to inactivate microorganisms are categorized into four common groups[7]:

1. Oxidants - Involved in radical-mediated reactions to oxidize organic material.
   Example: hydrogen peroxide
2. Electrophiles - Covalently react with cellular nucleophiles to inactivate enzymes and initiate the formation of intracellular free radicals which have lethal effects on microorganism.
   Examples: silver, copper, formaldehyde, izothiazolones
3. Membrane-active- Denature cell membranes leading to lysis
   Examples: chlorhexidine, quaternary ammonium compounds, phenols, and alcohols
4. Protonophores - Interfere with the ability of the cell membrane to maintain a proper pH balance, resulting in acidification of the cell interior and widespread disruption of metabolism.
   Examples: parabens, weak acids such as benzoic acids, and pyrithione

The inactivation mechanisms are tied to the chemistry of both the disinfectants and the target pathogen. The same chemical reactions can occur with the material substrates and can have an effect on the physical, chemical, and mechanical properties of treated aircraft components.

4. Selection of Disinfectants and Approval

The availability of effective disinfectants are subject to the regulatory requirements in the countries where they are sold or manufactured. As such, this can limit the global sourcing and availability of disinfectants. In the European Union, disinfectants are subject to the EU Biocidal Product Registration Rule[8] and in the United States the Environmental Protection Agency (EPA) Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). Through FIFRA, the EPA has released List N: Disinfectants for Use against SARS-CoV-2 (COVID-19)[2] which is an extensive list of disinfectants effective against the SARS-CoV-2 virus. Canada also has a list published by Health Canada[9] of approved products for disinfection against the SARS-CoV-2 virus. Of those numerous disinfectants, most are designed for at-home or medical use, but all may not be compatible for use on an airplane.

List N includes disinfectants such as bleach and alcohol (i.e., isopropanol and ethanol) that are well known and used by the general public. Common bleach or ethanol based pre-moistened wipes or gel hand sanitizers are used by many on a daily basis and may be considered a quick and easy option for disinfecting high-touch surfaces. Although these chemicals are readily available, such products should only be used on and in aircraft on a very limited basis. The chlorides from bleach can cause corrosion in metals and cracks in plastics,bleach as a whole can cause discoloration in fabrics, and ethanol based products can severely damage plastics after only one use. The selection and approval of disinfectants based on their chemical reaction with aircraft components will be discussed in more detail below.

In addition to the disinfectants' reactivity with materials, the other factors that need to be considered when selecting chemicals for aircraft use include: the availability of Boeing-approved disinfectants in the relevant geographic area of the world; applicability of the product to be used on both hard/nonporous or soft surfaces; and method of application (e.g., manual or electrostatic spray). These factors will in turn dictate the number of disinfectants the airlines will have to keep in stock to ensure that they have enough product available to support their operation.

5. Material Compatibility

5.1 Material Properties and Performance

Compatibility or incompatibility between materials and disinfectants can have broad meanings. For the purpose of this paper, incompatibility between materials and disinfectants is defined as any type of material degradation – whether it be performance, mechanical, or visual – as a result of repeated, frequent exposure of the material to a disinfectant. Additionally, repeated, frequent exposure to disinfectants is defined here as a minimum of one application of disinfectant per day each day for a minimum of three consecutive weeks. The more frequent the disinfectant is applied, the sooner material degradation will occur if the material is incompatible with the disinfectant.

The single most important consideration when selecting a disinfectant is to ensure that the disinfectant does not compromise flight safety and the most critical area of the airplane to be exposed to disinfectants is the flight deck. In order to verify compatibility, testing is necessary to ensure that disinfectant products do not affect the function of the flight deck control systems – such as control knobs and switches, and visual information or control displays. Additionally, disinfectants must not deteriorate the flight deck window materials, which could include increasing glare or decreasing visibility by any means. The safe operation of the airplane is of utmost importance, and thus the safe disinfection of the flight deck was made a top priority by Boeing.

Verifying the compatibility of materials, parts, and components to chemical disinfectants does not end in the flight deck. It extends to the passenger cabin and the cargo area and the requirements are consistent with the US Federal Aviation Administration (FAA) Special Airworthiness Information Bulletin on Aircraft Interior Disinfection[10]. The requirements for materials present within the passenger cabin and cargo compartment are extensive because these materials provide not only a safe, but also a comfortable flight experience. To ensure the safety and longevity of components and equipment that will be exposed to frequent applications of disinfectant, the most critical performance requirements were chosen for each category of material to be tested.

In the passenger cabin and cargo hold, the primary concern is the potential effects of disinfectants on passenger safety. For example, in order for the airplane to remain airworthy and maintain flammability requirement compliance, the use of disinfectants must not increase how likely a material, part, or component will burn if there is a fire. Understanding disinfectants' effect on a material's flammability performance allows Boeing to provide appropriate guidance on which disinfectants to use or at what interval disinfectant residue build-up must be removed. Disinfectants are also evaluated to ensure they do not cause corrosion of seat legs, seat attachments and seat tracks; cause degradation to seat belt webbing strength; or impact environmental control systems and oxygen systems.

After equipment function and flammability, the next most important performance criteria to be considered is wear and impact. Repeated exposure to disinfectants should reduce a part's resistance to normal wear or an increase in the likelihood of the part's failure due to breaking, cracking, or by some other means. As with flammability performance, an understanding of how repeated disinfectant application impacts a component's wear performance must be established to ensure proper selection and approval of chemical disinfectants.

The final performance criteria is the visual appearance of the parts, components, and materials exposed to disinfectant application. A single application of a disinfectant often will not result in a color change or staining, but multiple applications – especially in relatively frequent succession – may result in unsightly staining or discoloration of a material or part. While this type of performance will not impact any safety aspect, this is an important aspect for all airline operators because matching aesthetics throughout an airplane is a reflection of their brand.

5.2 Modes of Degradation

Disinfectant formulations contain various chemicals that can be reactive with material substrates. With extended contact or repeated application, such reactions can result in material degradation. There are various chemical reactions possible, but the most common modes of degradation that occur with the use of disinfectants include oxidation, acid-base reaction, solvolysis/hydrolysis, and solvation/dissolution.

Oxidation is a common cause of material degradation not only for metals but for organic materials as well. In metals, oxidation results in corrosion including rust formation. Plastics, fabrics, and coatings are also susceptible to oxidation typically manifested as discoloration. This reaction occurs in the presence of chemicals like hydrogen peroxide and chlorine dioxide.

Acid-base reactions, tied with reduction-oxidation, have been implicated in metal corrosion. When polymers, such as polyamide are attacked by acids, the reaction can lead to the material's cracking. In coatings, acids or bases can facilitate hydrolysis and can result in the degradation of coating binders. In cases where solvents such as ethanol are the agent that caused the attack to the substrate, the process is called solvolysis.

There are instances when the mode of action does not necessarily alter the substrate at the molecular level. This can occur during solvation or dissolution. During solvation, disinfectant molecules can form molecular bonds with the substrate and this can lead to material damage such as swelling, blistering, and softening. Conversely, the chemical disinfectant can dissolve some of the components of the substrate which can then leach out. There are chemicals that can dissolve the plasticizer out of polymers and elastomers and this results in the substrate having poor mechanical properties.

Many substrates are designed to resist the degradation mechanisms described above. However, there are phenomena such as galvanic action and environmental stress cracking that can induce damage that may not be observed when the exposure is limited to a single substrate using a flat test panel. Galvanic action or corrosion can occur when dissimilar metals are in the same environment that has the disinfectant acting as the electrolytic solution. A plastic material may prove to be resistant to a chemical, but can crack if bent and set in a stress condition.

In addition to performance-impacting degradation, there is also degradation of a primarily aesthetic nature. The look, feel, and overall experience within the passenger cabin is important. This experience helps define the branding of an airline. Non-uniform coloring through the passenger cabin, the appearance of stained or dingy tray tables, or peeling coatings on latches can give the impression of a dirty and potentially unsafe environment even if that the area has been fully disinfected. Therefore, color change or staining that results from repeated exposure to disinfectants must be considered as a part of the overall compatibility of a disinfectant with materials, parts, and components present in the interior of an airplane regardless of whether or not the performance of the material is degraded.

5.3 Material Compatibility Tests

Before the COVID-19 pandemic, SAE International had released Aerospace Material Specifications – or AMS – industry standards that define testing of disinfectants used in cargo compartments, disinfectants used as general purpose, and water based cleaners for use on hard surfaces in an aircraft interior. Those specification are AMS1451[11], AMS1452[12], and AMS1550[13], respectively. Additionally, Boeing had a historical internal standard to define testing of cleaners to meet its requirements for compatibility. After review of all of the above mentioned standards, Boeing determined additional testing guidance was required to support the more frequent applications of disinfectants as a result of the current pandemic; and thus created a new standard for testing of frequent repeated applications of disinfectants. Table 1 below provides a breakdown of the differences in required testing between industry standards and Boeing standards.

When developing testing methods to determine whether or not a disinfectant is compatible with the materials, parts, or components on which it is applied, considerations should include any safety critical functions, non-safety related performance impacts, and any visual or tactile changes that could negatively affect the experience of those operating or travelling on the airplane. Additionally, the frequency of disinfectant application is considered to determine what happens to materials with frequent and repeated exposure to a disinfectant.

When choosing test methods to verify compatibility between disinfectant products and the aircraft surfaces, the first step is to breakdown the airplane into three categories: Flight Deck, Passenger Cabin, and Cargo Compartment. While there is overlap in compatibility requirements across all three areas, each area does have its own particular area of focus for compatibility. All three areas have similar requirements that flammability performance cannot be degraded with repeated disinfection. Only the flight deck has stringent requirements related to fluid ingress, while only the cargo compartment has requirements related to hydrogen embrittlement of metals. Thus, of the three categories, the passenger cabin has the most options for disinfectant usage.

During the course of testing to the new Boeing standard, the Boeing Research & Technology (BR&T) team occasionally found that additional guidance in the use of a disinfectant was necessary to mitigate potential risks. For instance, one disinfectant was found to build-up residue with each use such that some materials could no longer pass flammability testing. With further testing, the BR&T team determined that a simple cleaning process after every 10 applications of the disinfectant easily resolved the issue. This additional analysis and information provide wider variety of products for airlines while ensuring that the airplane's interior still meets the flammability safety requirements.

This detailed level of testing was carried out for the passenger cabin, cargo compartment, and for the flight deck. As mentioned previous, the flight deck was the most critical aspect of testing conducted; and therefore was subjected to even more stringent compatibility evaluations than were conducted for either the passenger cabin or cargo compartment. The following examinations were conducted on flight deck equipment for every disinfectant candidate tested:

- Visual examination for legibility of markings, crazing or powdering of coatings, and other visible deterioration of equipment exteriors;
- Optical examination by performing pre- and post- exposure glare measurements and color comparisons against reference standards;
- Functional evaluations: Flight test simulations validated performance of equipment after exposure;
- Determination of number of disinfectant applications prior to detectable performance change in equipment. Failure assessment conducted to determine fluid ingress routes and component features impacted by fluid.

In addition to the equipment present in the flight deck, the flight deck windows – which are a structural component of the airplane – were also evaluated after repeated exposure to each disinfectant candidate. To ensure utmost safety, the following properties of the flight deck windows were evaluated:

- Visual deterioration of the window material to determine whether mechanical properties may be compromised;
- Light transmission and haze measurements after fifty disinfection cycles to ensure adequate visibility for flight operation

The final safety precaution Boeing undertook for flight deck testing was to test a select subset of flight deck equipment to failure in an effort to better understand disinfectant liquid ingress and its impact on the safety of flight equipment operation.

Table 1 Comparison of Compatibility Tests

Compatibility Test Methods		Boeing Testing		AMS1451: DISINFECTANT, AIRCRAFT, FOR USE IN CARGO COMPARTMENTS*	AMS1452: DISINFECTANT, AIRCRAFT, GENERAL PURPOSE*	AMS1550: CLEANER, WATER BASE, AIRCRAFT INTERIOR, HARD SURFACE MATERIALS*
		Cleaning - Single application	Disinfection -Repeated applications			
FLAMMABILITY		O	√	X	X	X
METAL	CYCLING CORROSION	X	√	X	X	X
	HYDROGEN EMBRITTLEMENT	X	√	X	X	X
	SANDWICH CORROSION	√	X	O	O	O
	IMMERSION CORROSION	√	√	X	X	X
RIGID CARGO LINER		X	√	X	X	X
FLEXIBLE CARGO LINER		X	√	X	X	X
RUBBER TEST		√	√	X	O	X
SEALANT TEST	ADHESION	√	√	X	X	X
	HARDNESS	X	√	X	X	X
PAINTED SURFACES TEST		√	√	O	O	O
TEDLAR SURFACE TEST		√	√	X	√	X
VINYL SURFACE TEST		√	X	X	√	X
FABRIC AND CARPET TEST		√	√	X	X	X
LEATHER AND NAUGAHYDE TEST		√	√	X	X	X
FLASHPOINT TEST		√	X	√	√	√
POLYCARBONATE CRAZING TESTING		√	√	O	O	O
TEMPERATURE STABILITY		X	X	O	√	X
SHORT TERM STORAGE STABILITY		X	X	√	X	X

LONG TERM STORAGE STABILITY	X	X	√	√	√
QUALITY (VISUAL)	X	X	√	√	√
PERFORMANCE (SOIL REMOVAL)	X	X	X	X	√
RESIDUE	X	X	√	X	X
UNPAINTED INTERIOR SURFACES	X	X	X	X	√

Key:
√: Exact Match
O: Partial Match
X: Does Not Match/Missing
*AMS standards are all single application testing

Table 1 provides a side-by-side comparison of Boeing and AMS industry standards related to disinfectant approval. With the exception of the Boeing specification for repeated applications, the standards in Table 1 were established prior to the onset of the COVID-19 pandemic. The simplest definition of the difference between Boeing specifications and AMS standards is that AMS standards are intended to be applicable across every variety of airplane regardless of the manufacturer, while the Boeing standards are intended to be applicable specifically to Boeing aircraft as Boeing is able to test to the exact materials they know will be disinfected. With this more detailed information and data, Boeing is able to provide more detailed disinfection guidance to its airline customers while acknowledging regulatory requirements for safe airplanes with the need to keep those planes free of a virus that has so negatively impacted public health and safety.

6. Application of Disinfections

6.1 Manual Application

Disinfectants can be applied to surfaces by a variety of methods. The most common are directly spraying the product onto the contaminated surface or onto a wipe that is subsequently used to disinfect a surface. This process is very effective in targeting localized contamination areas and allows easier monitoring to ensure the appropriate contact time is achieved. The use of wipes also helps enhance decontamination by physically removing surface soiling. This method is quick, easy, and does not require expensive or sophisticated equipment. Likewise, many disinfectants can be purchased in mechanical spray bottles pre-diluted making them very easy to use. Additionally, some disinfectants are even available as a pre-moistened wipe. Disadvantages observed by BR&T related to manual spray application included difficulty in obtaining uniform fluid coverage and a tendency to apply excess fluid. Excess fluid can lead to ingress and consequently failures of equipment in the flight deck. As such, the disinfectant application process is included in Boeing's internal standard test methodology.

6.2 Fogging and Electrostatic Spray

For a more comprehensive application of disinfectant in a large area, fogging and

electrostatic spraying can be employed. These processes offer the advantage of disinfecting a larger area in a shorter amount of time. If properly controlled, the process can provide the needed disinfection level using a smaller amount of the disinfectant and providing for good surface coverage. Electrostatic spraying has been proven to be an effective means of applying disinfectant in the passenger cabin and will be documented in another paper.

7. Summary

The use of chemical disinfectants in the aerospace industry requires careful selection mainly due to the aggressiveness of chemical disinfectants and the sensitivity of materials that they contact. Therefore, airline operators should determine the efficacy of the product they are intending to use and also insure that its use is approved on various aircraft components. Boeing has set up a standard set of test methodologies to determine material compatibility of chemicals and to evaluate test results to ensure that their use meets material requirements prior to approving a disinfectant.

8. Acknowledgments

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