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Literature Search and Review for Sampling, Analysis, and Decontamination of Biological Warfare Agent — Contaminated Maritime Vessels

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LITERATURE SEARCH AND REVIEW FOR SAMPLING, ANALYSIS, AND DECONTAMINATION OF BIOLOGICAL WARFARE AGENT— CONTAMINATED MARITIME VESSELS

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DISCLAIMER

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FOREWORD

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The Center for Environmental Solutions and Emergency Response (CESER) within the Office of Research and Development (ORD) conducts applied, stakeholder-driven research and provides responsive technical support to help solve the Nation’s environmental challenges. The Center’s research focuses on innovative approaches to address environmental challenges associated with the built environment. We develop technologies and decision-support tools to help safeguard public water systems and groundwater, guide sustainable materials management, remediate sites from traditional contamination sources and emerging environmental stressors, and address potential threats from terrorism and natural disasters. CESER collaborates with both public and private sector partners to foster technologies that improve the effectiveness and reduce the cost of compliance, while anticipating emerging problems. We provide technical support to EPA regions and programs, states, tribal nations, and federal partners, and serve as the interagency liaison for EPA in homeland security research and technology. The Center is a leader in providing scientific solutions to protect human health and the environment.

This report summarizes the current scientific literature on remediation-related activities associated with US Coast Guard vessels and other assets. It also provides descriptions of research gaps and needs for consideration by US Coast Guard and other federal agencies to improve on sampling and decontamination of vessels following a biological warfare agent release scenario.

Gregory Sales, Director
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°C	Degree(s) Celsius
°F	Degree(s) Fahrenheit
AHP	Accelerated hydrogen peroxide
APC	Aircraft Performance Coating
BI	Biological indicator
BiSKit	Biological Sampling Kit
BSA	Bovine serum albumin
BSL	Biosafety level
BWA	Biological warfare agent
CARC	Chemical agent resistant coating
CASCAD	Canadian Aqueous System for Chemical/Biological Agent Decontamination
CD	Compact disk
CESER	Center for Environmental Solutions and Emergency Response
CDC	Centers for Disease Control and Prevention
CFU	Colony forming unit(s)
ClO^-	Hypochlorite
ClO_2	Chlorine dioxide
cm^2	Square centimeter(s)
CMAD	Consequence Management Advisory Division
COTS	Commercial off-the-shelf
CPU	Central processing unit
CT	Contact time
CWA	Chemical warfare agent
DHS	U.S. Department of Homeland Security
DTIC	Defense Technical Information Center
DVD	Digital video disk
ECL	Electrochemiluminescence
$eClO_2$	Electrochemically generated chlorine dioxide
ELISA	Enzyme-linked immunosorbent assay
EMS	Emergency Medical Service
EPA	U.S. Environmental Protection Agency
EtO	Ethylene oxide
EtOH	Ethanol
FMDV	Foot-and-mouth disease virus
FOUO	For Official Use Only
EVD	Ebola virus disease
g	Gram(s)
GPU	Graphics processing unit
H_2O_2	Hydrogen peroxide
HDPE	High density polyethylene
HEPA	High efficiency particulate air
HINS-light EDS	High-intensity narrow-spectrum light environmental decontamination system
HOCl	Hypochlorous acid
HSMMD	Homeland Security and Materials Management Division
HVAC	Heating, ventilation, and air conditioning

in^2	Square inch(es)
kGy	Kilogray(s)
L	Liter(s)
LDPE	Low density polyethylene
LOD	Limit of detection
LR	Log reduction
m^3	Cubic meter(s)
MCE	Mixed cellulose ester
MDR	Multidrug resistant
MeBr	Methyl bromide
MeI	Methyl iodide
mg	Milligram(s)
MgF_2	Magnesium fluoride
mL	Milliliter(s)
MRSA	Methicillin-resistant *Staphylococcus aureus*
NaOCl	Sodium hypochlorite
NFB	Non-freezing bleach
NHSRC	National Homeland Security Research Center
NIOSH	National Institute for Occupational Safety and Health
nm	Nanometer(s)
NTC	Navy (ship) top-coat
O_3	Ozone
OCSPP	Office of Chemical Safety and Pollution Prevention (U.S. EPA)
OEM	Office of Emergency Management (U.S. EPA)
OLEM	Office of Land and Emergency Management (U.S. EPA)
OPPT	Office of Pollution Prevention and Toxics (U.S. EPA)
ORD	Office of Research and Development (U.S. EPA)
pAB	pH-adjusted bleach
PC	Personal computer
PCR	Polymerase chain reaction
PDA	Personal digital assistant
PI	Principal Investigator
PPE	Personal protective equipment
ppm	Part(s) per million
ppmv	Part(s) per million by volume
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
PX-UV	Pulsed xenon ultraviolet
RB-M	Response Boat – Medium
RB-S	Response Boat – Small
RH	Relative humidity
RTU	Ready to use
RV-PCR	Rapid Viability PCR
SDF	Surface decontamination foam
USCG	United States Coast Guard
USPS	U. S. Postal Service

UV	Ultraviolet
UV-A	UV light within the “A” band
UV-B	UV light within the “B” band
UV-C	UV light within the “C” band
VHP	Vaporous hydrogen peroxide
VRE	Vancomycin-resistant *Enterococcus*

1. INTRODUCTION

1.1. Background

The U.S. Environmental Protection Agency (EPA) is responsible for preparing for, responding to, and recovering from threats to public health, welfare, or the environment caused by actual or potential hazardous materials incidents. Hazardous materials include chemical, biological, and radiological substances, whether accidentally or intentionally released.

In 2002, Congress passed the Public Health Security and Bioterrorism Preparedness and Response Act (Bioterrorism Act). The Office of the President issued a series of Homeland Security Presidential Directives to specify the responsibilities of federal agencies as related to the Bioterrorism Act. EPA's roles and responsibilities include protecting human health and the environment from bioterrorism. Included within the scope of these responsibilities are the personnel and assets of the U.S. Coast Guard (USCG), the principal federal agency responsible for maritime safety, security, and environmental stewardship in U.S. ports and waterways.

The USCG protects and defends more than 100,000 miles of U.S. coastline and inland waterways. To this end, the USCG may be responsible for countering and responding to incidents involving weapons of mass destruction, including biological warfare agents (BWAs) and chemical warfare agents (CWAs). To carry out their mission, the USCG maintains a fleet of small boats, larger cutters and aircraft, as well as a network of fixed infrastructure. Such assets are likely to be utilized in the event of a USCG response to an incident involving BWAs and/or CWAs and would likely become contaminated as a result.

Following a contamination incident, decontamination is necessary so that assets may be returned to service and USCG capability can be maintained. Efficacious decontamination strategies are thus necessary. Further, effective sampling is necessary to determine the extent and magnitude of contamination, inform responders on selection of decontamination strategies, determine the success of decontamination strategies, and determine the presence/absence of residual contaminants to clear assets for return to service. USCG vessel usage scenarios, operating environments, and materials of construction present unique challenges to BWA and CWA decontamination and sampling that have not been previously addressed.

1.2. Scope and Purpose

The purpose of this project was to: (1) conduct a review of existing BWA and CWA contamination response and management, decontamination, and sampling strategies; (2) assess their applicability to USCG vessels and the associated materials of construction; and (3) identify knowledge/capability gaps associated with decontamination and sampling of USCG vessel materials. The review of existing BWA and CWA contamination response and management, decontamination, and sampling strategies was accomplished through completion of a systematic search of the open literature, focused primarily on representative USCG vessels and contaminant groups (refer to Sections 2.1.1 and 2.1.2, respectively). The results of the literature search and discussion of knowledge/capability gaps related to methodologies, procedures, and technologies for decontamination and sampling of CWA contamination on USCG assets is provided in a separate report.

1.3. Objectives

Specific objectives to support the purpose of this project included the following:

- Conduct a search of the open literature (including existing guidance documentation, information, scientific literature, secondary data, etc.) for BWA and CWA contamination response and management, decontamination, and sampling strategies that are potentially applicable to USCG vessels and associated materials of construction.
- Develop summaries of the guidance documentation, information sources, scientific literature, secondary data sources, etc., that were identified and collected during the search and develop a source compilation document to collate the findings from the literature search according to primary research focus.
- Identify knowledge/capability gaps associated with decontamination and sampling of USCG vessel materials due to their unique vessel usage scenarios, operating environments, and materials of construction.
- Develop reports to summarize and discuss:
    - The approach and resources used to conduct the literature search and the results of the search.
    - The approaches, procedures, and methodologies for BWA and CWA contamination response and management, decontamination, and sampling and analysis that were identified during the search and that may have relevance to USCG vessels and associated materials of construction.
    - The knowledge/capability gaps identified that relate to the unique challenges presented by USCG vessel operations and materials that must be overcome for development of effective decontamination and sampling strategies for BWA- and/or CWA-contaminated USCG vessels that allow for prompt and safe return to service.

Figure 1 provides an overview of the steps taken during the project to accomplish the above project objectives to conduct the literature search, summarize the search results and collate the summaries into the source compilation document, identify knowledge/capability gaps based on the search results, and develop reports to present the search results, information and data collected, and gaps identified.

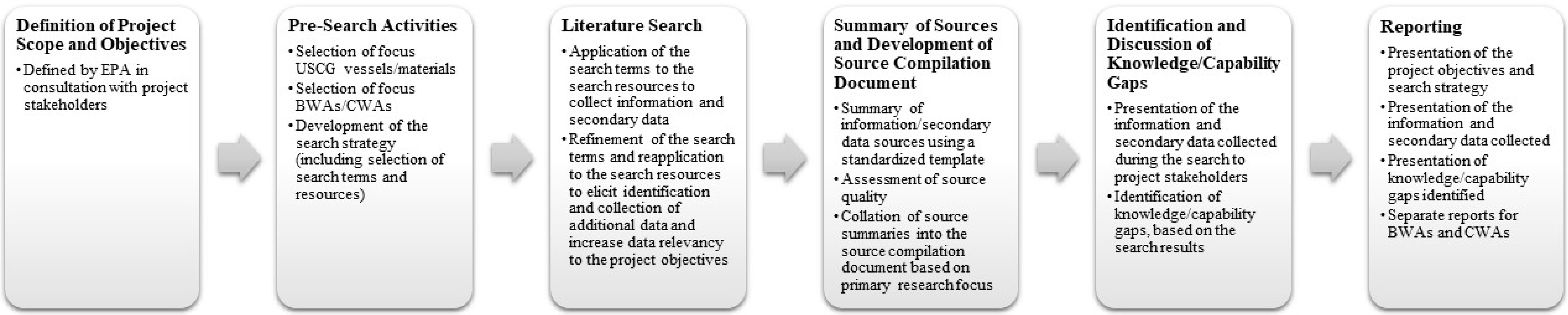

Figure 1. Project Overview and Progression

1.4. Use of Secondary Data

Secondary data are defined as existing data, also termed nondirect measurements, that were not developed originally through the project to which they are being applied [1]. For this project, secondary data that were gathered consisted of information and data related to BWA and CWA contamination response and management, decontamination, and sampling strategies that are potentially applicable to USCG vessels and associated materials of construction. These data were collected from various sources, including government reports and publications in the open literature.

1.5. Organization of Report

This report is organized by section to: (1) describe how the literature search was conducted to review existing BWA contamination response and management, decontamination, and sampling strategies, and how the quality of the secondary data and information that were collected were assessed; (2) present and review the secondary data and information collected; and (3) describe the approach for identification of knowledge/capability gaps associated with decontamination and sampling of USCG vessel materials and present the outcomes of the gap discussions. The three primary sections of the report are outlined and described as follows:

- **Literature Search**

  The approach for conducting the literature search is described (Section 2.1). To focus the literature search efforts, specific USCG vessels and their associated materials of construction and specific BWAs were selected as focus materials/contaminants (Sections 2.1.1 and 2.1.2). Search criteria including lists of strategic keywords (i.e., search terms) and the arrangements of the keywords with Boolean operators to execute the searches were developed (Section 2.3), and the criteria were applied to a variety of repositories/resources (Section 2.2) to identify and collect information and secondary data. Quality of the information and secondary data sources that were collected was assessed qualitatively and quantitatively (Section 2.4). Following completion of the search but prior to development of this report, the articles, reports, guidance documents, and other information and secondary data sources of sufficient quality that were collected during the literature search were summarized using a standardized summary structure, categorized according to content and primary research focus, and the summaries were collated into a source compilation document (Section 2.6).

- **Knowledge Review**

  The information and secondary data collected during the literature search are presented, categorized according to content and primary research focus, and bibliographic citations are provided for the literature sources from which the information and secondary data were collected. The research focus areas include: (1) BWA fate and transport, (2) BWA contamination management and response, (3) BWA decontamination efficacy studies, (4) BWA decontaminant material compatibility studies, and (5) BWA sampling and analysis methodologies (Sections 3.1 through 3.5).

- **Knowledge/Capability Gap Assessment**

  Based on the results of the literature search, gaps in information/secondary data related to methodologies, procedures, and technologies for decontamination and sampling of BWA contamination on USCG assets were identified. Project stakeholders met to discuss the literature search and the identified gaps. The knowledge/capability gaps identified and other information, discussions, and notes from the meeting are presented in Section 4.

As discussed in Section 1.2, the scope of this project included: (1) review of existing contamination response and management, decontamination, and sampling strategies, (2) assessment of the applicability of the strategies to USCG vessels and their associated materials of construction, and (3) identification of knowledge/capability gaps associated with decontamination and sampling of USCG vessel materials for both BWA and CWA contaminants. The approach for conducting the literature search to include both BWAs and CWAs is included in Section 2 of this report, but the results of the literature search and discussions of knowledge/capability gaps provided in Sections 3 and 4, respectively, are focused only on BWAs in this report. Literature search results and discussion of knowledge/capability gaps related to methodologies, procedures, and technologies for decontamination and sampling of CWA contamination on USCG assets are provided in a separate report.

2. LITERATURE SEARCH

2.1. Literature Search Approach

The literature search was conducted using the resources described in Section 2.2 and the search criteria and strategy described in Section 2.3. The secondary data gathered during this effort include information on BWA and CWA contamination response and management, decontamination, and sampling strategies that are potentially applicable to USCG vessels and associated materials of construction. For the purpose of this search, BWA and CWA contamination response and management, decontamination, and sampling were defined as:

- Contamination response and management – Initial action(s) taken in response to an incident involving creation or spread of contamination by BWA, CWA, or similar agents, as well as ongoing actions taken to assess the initial response and to direct and modify subsequent response steps. Such actions may include: initial steps to stop the spread of contamination and contain existing contamination (in the case of USCG vessels, such actions may include storing/staging of contaminated vessels that cannot be decontaminated immediately); procedures and guidance for development of response plans and for continuous assessment and modification of plans, as necessary; guidance and considerations regarding response safety and personal protective equipment (PPE) requirements; and information, considerations, and guidance related to disposition and disposal of contaminated and decontaminated wastes.
- Decontamination – General guidance and procedures for decontamination/neutralization of contamination by BWA, CWA, or similar agents. Information and secondary data related to use and efficacy of specific methodologies and technologies for decontamination of BWA, CWA, or similar agents.
- Sampling and analysis - General guidance and procedures for qualitative and/or quantitative detection of BWA and/or CWA (or similar agent) contamination, either prior to or following decontamination. Information and secondary data related to use, resolution, precision, and accuracy of specific methodologies and technologies for decontamination of BWA, CWA, or similar contamination.

To focus search efforts, information and data related to specific USCG vessels and associated materials of construction and specific BWAs were sought primarily.

2.1.1. *USCG Vessels*

2.1.1.1. *Vessels and Vessel Missions*

Four (4) USCG vessels were selected as focus assets for directing the literature search efforts. The vessels and their primary missions are provided and summarized below:

- Response Boat – Medium (RB-M) – The RB-M is a 45-foot multimission capable, all-aluminum utility boat. The RB-M includes wireless crew communication systems and is powered by twin diesel engines and water jet propulsion. RB-M missions include search and rescue, living marine resources, recreational boating safety, enforcement of laws and treaties, and port, waterway, and coastal security [2].

- Response Boat – Small (RB-S) – The RB-S (also referred to as the Defender-class boat) is a 25-foot boat introduced by the USCG in 2003 to replace shore-based nonstandard boats. RB-S assets serve a variety of law enforcement, security, and vessel safety missions [2].
- RB-S II – The RB-S II, a 29-foot boat designed as an upgrade and replacement to the 25-foot RB-S, is a high-speed deployable asset designed to operate year-round in shallow waters along coastal borders. The RB-S II supports search and rescue, recreational boating safety, law and treaty enforcement, marine environmental protection, defense, and port, waterways, and coastal security missions [2].
- Marine Protector-class Patrol Boat – The 87-foot Marine Protector-class patrol boat is a multimission vessel capable of supporting search and rescue, law enforcement, fishery patrol, drug interdiction, illegal immigrant interdiction, and homeland security missions up to 200 miles offshore. The vessel includes improved seakeeping abilities and enhanced habitability compared to other vessels, capability to interface with surface search radars used by U.S. warships, and is designed to maintain compliance with current and projected environmental protection laws [3].

2.1.1.2. *Vessel Materials of Construction*

Specific materials used in construction of the vessels described in Section 2.1.1.1 were selected as focus materials for the purpose of further directing search efforts. The focus materials selected, categorized by vessel, are provided in Table 1.

Table 1. Focus Materials

	Vessel Type			
Vessel Component	**45-foot RB-M**	**25-foot RB-S**	**29-foot RB-S II**	**87-foot Patrol Boat**
Hull material	• Aluminum	• Aluminum	• Aluminum	• Coated steel
Decking material on hull material	• Nonskid coatings	• Nonskid coatings	• Nonskid coatings	• Nonskid coatings
Sensitive equipment/ components	• Propulsion (air and seawater intakes) • Other electronic systems	• Propulsion (air and seawater intakes) • Other electronic systems	• Propulsion (air and seawater intakes) • Other electronic systems	• Ventilation • Propulsion (air and seawater intakes) • Other electronic and internal systems
Additional relevant materials	• Foam • Glass • Glazing materials • Insulation and other bulkhead coverings	• Foam • Glass • Glazing materials • Insulation and other bulkhead coverings	• Foam • Glass • Glazing materials • Insulation and other bulkhead coverings	• Glass • Glazing materials • Insulation and other bulkhead coverings

2.1.2. *Target BWAs*

Two (2) BWAs were selected in consultation with stakeholders as the focus contaminants for the purpose of directing the literature search efforts. The two BWAs include:

- *Bacillus anthracis* Ames – Virulent strain of gram-positive spore-forming bacterium that is the causative agent of anthrax disease [4].
- Ebola virus – Refers to one of six known viral species within the genus *Ebolavirus*. It is the single member of the species *Zaire ebolavirus*, which is the type species for the genus *Ebolavirus*, family *Filoviridae*, order *Mononegavirales*. Causes Ebola virus disease (EVD), a severe and often fatal hemorrhagic fever [5].

In addition, *Bacillus anthracis* Δ Sterne was included in the literature search as a simulant. *Bacillus anthracis* Δ Sterne is an avirulent *Bacillus anthracis* strain. This strain is attenuated through loss of the pXO1 (toxin synthesis) and pXO2 (capsule synthesis) plasmids [6].

2.2. Literature Search Resources

The following resources were utilized to identify information and secondary data related to BWA and CWA contamination response and management, decontamination, and sampling strategies that are potentially applicable to USCG vessels and associated materials of construction:

- **SciTech Premium (also or formerly known as ProQuest Science & Technology)**
  Multidisciplinary content collection of scholarly material in the natural sciences, technology, engineering and related disciplines. Includes numerous databases, including a military database that indexes over 700 scholarly journal articles, trade and industry journals, magazines, technical reports, conference proceedings, government publications, etc. Included as part of the military database is the National Technical Information Service, which provides summaries of U.S. government research, development, and engineering, plus analyses prepared by federal agencies or their contractors.
- **Scopus**
  An abstract and citation database of peer-reviewed literature, with bibliometric tools to track, analyze and visualize research. Scopus contains over 22,000 titles from more than 5,000 publishers around the world, covering the fields of science, technology, medicine, social sciences, and others. Scopus has 55 million records dating back to 1823, and 84% of these contain references dating from 1996.
- **Battelle Library**
  The Battelle library holds over 20,000 volumes and subscribes to over 10,000 print and e-journal titles in a range of scientific and technical disciplines, both foreign and domestic. In addition, the library manages access to more than 150 foreign and domestic databases, including eBrary™, Hoovers®, Applied Science & Technology, EBSCOhost®, and National Technical Reports Library.

- **Internet**
  Internet searches (e.g., – EPA website, Google, Google Scholar™, etc.) were used to identify available information on studies conducted using BWAs and CWAs focused on vessel response, decontamination, and sampling.

2.3. Literature Search Criteria and Strategy

Prior to initiation of the literature search, the criteria used to perform the search were developed. The criteria included lists of strategic keywords anticipated to elicit identification of relevant secondary data and information, and the arrangement of the keywords with Boolean operators to execute the searches. Following each iteration of the search and subsequent review of the results, the arrangement of keywords and Boolean operators was revised to further focus the search and attempt to identify additional relevant secondary data and information.

To ensure identification of a wide breadth of response and management, decontamination, and sampling strategies potentially applicable to BWA- and CWA- contamination on USCG vessels, initial search criteria were comprehensive, including provisions for identification of procedures, methodologies, techniques, and technologies for contamination response and management, decontamination, and sampling for any type of contaminant (toxic chemicals, biological contaminants, radionuclides, etc., beyond the focus BWAs discussed in Section 2.1.2) from any maritime vessel or environment-related material (beyond the focus materials provided in Table 1 in Section 2.1.1.2). Information regarding fate and transport of persistent BWAs and CWAs on and across various materials was sought as well. Furthermore, the search criteria were developed to elicit collection of information related to all relevant aspects of BWA and CWA contamination on USCG vessel materials and impacts of use of the contamination response and management, decontamination, and sampling strategies identified.

Boolean searches were performed using strategically selected keywords with the operators AND and OR. After each search run (with a run defined as application of a particular arrangement of the keywords with the operators to the sources provided in Section 2.2), the resulting identified literature was reviewed to determine the effectiveness of the search and the relevancy of the results. Based on the search run results, the Boolean search strategy was revised, and another run was performed. Three runs were performed in this manner using the keywords and operators in different arrangements to refine and focus the searches to maximize the potential of identifying meaningful and relevant results. Figures 2, 3, and 4, below, provide the search strategies used. All search runs were conducted simultaneously for CWA and BWA, and the results from the third search run were used to compile the literature/references for this review.

Related to response and management		Related to decontamination		Related to sampling		Related to contaminants		Related to materials, systems, and environments
Respon*		Decontaminat*		Surface		Chemical agent		Marine
OR Manag*		OR Detoxif*		OR Sampl*		OR Chemical warfare agent		OR Maritime
OR Mitigat*		OR Disinfect*		OR Analy*		OR CWA		OR Vessel
OR Hazard*		OR Clean*		OR Wip*		OR Distilled Mustard		OR Boat
OR Incident*		OR Remov*		OR Headspace		OR HD		OR Seawater
OR Remediat*		OR Attenuat*		OR Vapor		OR Sarin		OR Foul*
	AND	OR Steriliz*	AND	OR Qualitative		OR GB		OR Hull
		OR Neutraliz*		OR Quantitative		OR VX		OR Bulkhead
		OR Oxidiz*		OR Detect*		OR Biological agent		OR Sensitive equipment
		OR Hydroly*		OR Inhibit*		OR Biological warfare agent		OR Propulsion
		OR Degrad*		OR Interfer*		OR BWA	AND	OR Electronic
		OR Efficac*		OR Sorbent		OR Bacillus anthracis		OR Ventilation
		OR Damag*		OR Fate		OR Anthrax		OR Intake
		OR Compatib*		OR Transport	AND	OR Ebola		OR Deck*
						OR Radiological agent		OR Aluminum
						OR Radionuclide		OR Non-skid
						OR Radioactive		OR Glazing
						OR Radioisotope		OR Steel
						OR Cesium*		OR Insulation
						OR Cs-137		OR Foam
						OR Radiological dispersal device		OR Glass
						OR Improvised nuclear device		
						OR Fallout		
						OR Nuclear		
						OR Chlorinated biphenyl		
						OR PCB		
						OR Contamina*		

Figure 2. 1st Search Run

Related to response and management		Related to decontamination		Related to sampling		Related to contaminants		Related to materials, systems, and environments
Mitigat*		Decontaminat*		Surface		Chemical agent		Marine
OR Hazard*		OR Detoxif*		OR Sampl*		OR Chemical warfare agent		OR Maritime
OR Incident*		OR Disinfect*		OR Analy*		OR CWA		OR Vessel
OR Remediat*		OR Clean*		OR Wip*		OR Distilled Mustard		OR Boat
		OR Remov*		OR Headspace		OR HD		OR Seawater
		OR Attenuat*		OR Vapor		OR Sarin		OR Foul*
		OR Steriliz*	AND	OR Qualitative	AND	OR GB		OR Hull
	AND	OR Neutraliz*		OR Quantitative		OR VX		OR Bulkhead
		OR Oxidiz*		OR Detect*		OR Biological agent		OR Sensitive equipment
		OR Hydroly*		OR Inhibit*		OR Biological warfare agent		OR Propulsion
		OR Degrad*		OR Interfer*		OR BWA	AND	OR Electronic
		OR Efficac*		OR Sorbent		OR Bacillus anthracis		OR Ventilation
		OR Damag*		OR Fate		OR Anthrax		OR Intake
		OR Compatib*		OR Transport		OR Ebola		OR Deck*
		OR Inactivat*						OR Aluminum
								OR Non-skid
								OR Glazing
								OR Steel
								OR Insulation
								OR Foam
								OR Glass

Figure 3. 2nd Search Run

	Related to response and management			Related to decontamination			Related to sampling			Related to contaminants			Related to materials, systems, and environments
	Mitigat*			Decontaminat*			Sampl*			Chemical warfare agent			Marine
OR	Hazard*		OR	Detoxif*		OR	Analy*		OR	Distilled Mustard		OR	Maritime
OR	Incident*		OR	Disinfect*		OR	Wip*		OR	HD		OR	Boat
OR	Remediat*		OR	Remov*		OR	Headspace		OR	Sarin		OR	Seawater
OR	Emergency	AND	OR	Steriliz*	AND	OR	Vapor		OR	GB		OR	Foul*
OR	Attack		OR	Neutraliz*		OR	Detect*		OR	VX		OR	Hull
OR	Rescue		OR	Oxidiz*		OR	Interfer*	AND	OR	Biological warfare agent		OR	Bulkhead
OR	Contain*		OR	Hydroly*		OR	Sorbent		OR	BWA		OR	Sensitive equipment
OR	Risk		OR	Degrad*		OR	Fate		OR	Bacillus anthracis		OR	Ventilation
OR	Cleanup		OR	Inactivat*		OR	Transport		OR	Anthrax	AND	OR	Deck*
									OR	Ebola		OR	Aluminum
									OR	Vesicant		OR	Non-skid
									OR	Nerve agent		OR	Steel
												OR	Foam
												OR	Glass
												OR	Sea
												OR	Military
												OR	Coast Guard (coast + guard)

Figure 4. 3rd Search Run

2.4. Literature Source Quality Assessment

2.4.1. *Qualitative Quality Assessment*

During the literature search, information and secondary data sources were qualitatively assessed according to the source document type. Table 2 provides the source document type list used during the literature search (not all source document types were accumulated during the search). Knowledge of the document type provided an indication of trustworthiness of the information/secondary data contained therein, based on general professional judgment of each document type.

Table 2. Source Document Types

Designation	Description
A	Technical Report, U.S. Government
B	Technical Report, Contractor for U.S. Government
C	Translated Foreign-Language Document
D	Translated Foreign-Language Abstract
E	Untranslated Foreign-Language Document
F	Untranslated Foreign-Language Abstract
G	Peer-Reviewed English Language Literature, post-1975
H	Peer-Reviewed English Language Literature, 1925-1975
I	Peer-Reviewed English Language Literature, pre-1925
J	Government Website, with citations
K	Government Website, without citations
L	Non-Government Website, with citations
M	Non-Government Website, without citations
N	Book Chapter or Book, with peer-review and/or editorial oversight
O	Book Chapter or Book, no peer-review nor editorial oversight
P	Book Chapter or Book, peer review and editorial oversight unknown
Q	Patent (United States)
R	Patent (International)
S	Thesis/Dissertation
T	News Article
U	Manufacturer-Supplied Literature
V	Other
W	Analysis Pending

Most of the sources collected were of type A (Technical Report, U.S. Government), type B (Technical Report, Contractor for U.S. Government), or type G (Peer-Reviewed English Language Literature, post-1975).

2.4.2. *Quantitative Quality Assessment*

Each source of information and/or secondary data was evaluated according to the following categories: focus, verity, integrity, rigor, utility, clarity, soundness, uncertainty and variability, and evaluation and review. A description of each attribute is provided in the Literature Assessment Factor Rating (Attachment A). Information sources were evaluated against the Literature Assessment Factor Rating and assigned an overall rating to accomplish a semiquantitative assessment of the quality of the source. For the quality of a source to be deemed adequate, the source was required to receive an overall Literature Assessment Factor Rating score of 15 or greater.

Source quality evaluations (document type designations and Literature Assessment Factor Rating scores) for all sources of sufficient quality that were collected during the literature search, included in the source compilation document (refer to Section 2.6), and discussed in Section 3 are included as Attachment B.

2.5. Literature Search Results

During the literature search, 83 sources of information and secondary data related to BWA contamination response and management, decontamination, and sampling strategies that are potentially applicable to USCG vessels and the associated materials of construction (the focus materials provided in Table 1 in Section 2.1.1.2) were collected. All articles, reports, guidance documents, and other pertinent information sources of adequate quality that were collected during the literature search were summarized using a standardized summary structure and categorized according to content and primary research focus. Table 3 provides a list of the research focus areas and the number of information/secondary data sources collected for each category during the literature search.

Table 3. Research Focus Areas and Sources Collected

Research Focus Area	Number of Sources Collected
BWA Fate and Transport	3
BWA Contamination Management and Response	8
BWA Decontamination Efficacy Studies	49
BWA Decontaminant Material Compatibility Studies	12
BWA Sampling and Analysis Methodologies	11
Total	**83**

2.6. Source Compilation Document

Following the literature search and summary of the information/secondary data sources that were collected, the summaries were collated into a source compilation document according to the primary research foci listed in Table 3. The source compilation document also provided descriptions of the literature search approach, strategy, criteria, and resources (as described in Sections 2.1, 2.2, and 2.3) and provisions for assessment of the quality of information/secondary data sources that were collected during the search (as described in Section 2.4).

3. KNOWLEDGE REVIEW

3.1. BWA Fate and Transport

The information and secondary data related to BWA fate and transport described below were collected during the search and should be assessed, as applicable, alongside the information and data on decontamination strategies (described in Section 3.3) and sampling strategies (described in Section 3.5) that were collected when decisions are made and strategies are developed for response to incidents that involve BWA contamination of USCG vessels. Fate and transport of BWA contamination on USCG vessel construction materials will impact not only the efficacy of decontamination and sampling methodologies but also the required extent of decontamination and sampling efforts/operations and thus will drive contamination response and management decisions.

Prime examples of the transportability of BWAs are the anthrax attacks that occurred over the course of several weeks in 2001 (also known as "Amerithrax"), during which letters containing anthrax spores were mailed to news media and federal government offices. Widespread contamination of the affected U. S. Postal Service (USPS) facilities and exposure of multiple personnel to *Bacillus anthracis* spores resulted from the letters being routed through normal mail processing procedures [7]. Aerosolized bacterial spores, including those of *B. anthracis*, can remain aloft for hours and are capable of wide dispersion [8]. *B. anthracis* spores are also very resistant to inactivation by biocides and may survive on surfaces for centuries if not remediated [8]. "Amerithrax" remediation efforts were of an unprecedented scale, with costs reaching approximately $320 million [8]. Following the attacks, several studies (including the following) were conducted to evaluate and characterize the threat presented by spore-contaminated letters, potential mitigation strategies, and the propensity for spread of spores by normal handling and processing of contaminated letters:

- A study of potential mitigation procedures intended to deal with letters contaminated with *B. anthracis* spores using a *B. anthracis* simulant spore release scenario within an actual office building was conducted [9]. Spore aerosols were created by opening letters containing 0.1 gram (g) of dry powdered *Bacillus atrophaeus* spores. The movement of *B. atrophaeus* spores throughout an office building was evaluated based on various mitigation strategies including moving away from the letter opening area, closing doors, turning off heating, ventilation, and air conditioning (HVAC) systems, water spray mitigation, and letter opener clothing removal and showering. Potential total inhalational hazard for the letter opener ranged from 4.1×10^5 to 1.6×10^6 colony forming units (CFU) compared to 3.9×10^5 CFU for controls. Surface contamination of the letter opener was highest on the right hip (4.8×10^4 to 1.0×10^5 CFU/square centimeter [cm^2]) and lowest on the right or left side of the head (2.2×10^2 to 3.7×10^3 CFU/cm^2). Mitigation procedures tested in this study generally did not reduce aerosol hazard or surface contamination.

- Letters contaminated with fluorescent tracer powder were opened using various techniques in an office setting [10]. Spread of contamination was qualitatively assessed using an ultraviolet (UV) light source. Results clearly demonstrated that when letters containing powdery contaminants are opened, the contaminant can be dispersed both on the immediate and surrounding areas, on the person, on objects nearby, and into the HVAC system. Potentially contaminated persons are not limited to those in direct contact with the envelope and/or its contents.

The information and secondary data presented in these studies highlight the high potential and high risk for spread of BWA contamination. Given the operational setting of USCG vessels, spread of BWA contamination into water/marine environments must also be considered, in addition to the spread of contamination throughout an affected vessel itself. The fate of viruses and mechanisms controlling virus inactivation in coastal waters have been evaluated and discussed [11]. Inactivation rates in estuarine and marine waters in laboratory studies range from 1 to 43 days when expressed as the time required for a tenfold reduction in concentration.

3.2. BWA Contamination Management and Response

USCG vessel materials and operational settings present unique challenges to the development of effective, efficient, and safe strategies for management of and response to BWA contamination incidents. Despite these challenges, the objectives of USCG-vessel BWA contamination incident management, response, and remediation operations must remain unchanged from the objectives of any other BWA contamination incident: (1) Personnel safety must be ensured; (2) BWA contamination must be identified, contained, and adequately decontaminated; and (3) deleterious environmental, equipment/infrastructure, and financial impacts must be avoided or minimized to the greatest extent possible.

BWAs are highly pathogenic, and exposure (as a direct result of a BWA attack, during incident response and remediation actions, after an incident due to residual contact hazard, etc.) can often be lethal. Numerous studies, literature assessments, and data analyses are available [12,13,14,15,16,17,18] that collate available information and summarize and describe: (1) BWA types/classes, (2) pathogenic characteristics and mechanisms of pathogenesis, (3) delivery/exposure routes, (4) exposure symptoms and medical diagnosis guidance, and (4) prevention and prophylaxis, treatment options, and intervention, etc. These data and considerations highlight the lethality of BWAs and the need for effective, comprehensive, and rapidly mobilized contamination management, response, and remediation strategies following incidents involving USCG vessels/assets and BWA.

Fitch, Raber, and Imbro discuss considerations related to response to a biological terrorist attack and identify and discuss numerous technologies for detection, sampling, and decontamination of BWAs [19]. The primary focus of the review is on field systems, and emerging laboratory technologies and a general strategy for characterization of and response to a BWA contamination incident are provided and discussed. The overall response to an incident involving BWAs is broken down into four main phases: (1) monitoring and notification (i.e., contamination detection), (2) first response, (3) characterization (i.e., sampling to discern contamination extent and severity), and (4) restoration (i.e., decontamination). Several technologies for BWA sampling and decontamination are identified and discussed, including liquid and vaporous technologies (multiple liquid-applied decontamination technologies as well as chlorine dioxide [ClO_2] gas and vaporized hydrogen peroxide [H_2O_2, VHP] are highlighted).

Existing plans governing operations and procedures for sampling and detection of BWAs, contamination management, and equipment and infrastructure for other organizations, sites, facilities, installations, etc., can be used as templates for development of effective similar plans and guidance documents tailored to specific USCG sites, vessels, and/or assets. Existing plans may often also provide insight into strategies for selection of adequate PPE and development of emergency response and exposure control/response plans. Similarly, assessment of the effectiveness of response and management strategies used during previous BWA outbreak and contamination incidents (whether accidental or terrorism-related), the associated outcomes, and the successes and failures that were experienced can provide invaluable insight during post-incident refinement and improvement of procedures and development of new and/or modified procedures and/or capabilities based on any knowledge/capability gaps that were exposed. Examples from the literature include the following:

- Specialized training for ambulance staff, decontamination logistics considerations, procedures for infection control (PPE and engineering and administrative controls), and ambulances with special technical features (e.g., controlled ventilation, high efficiency particulate air [HEPA] filtration, intercom systems, separation of drivers from patients, etc.) for Emergency Medical Service (EMS) transport of patients with confirmed or suspected EVD are discussed [20].
- Procedures and equipment for containment and treatment of EVD patients are discussed [21]. Use of Trexler isolator tents is discussed as a means of providing critical care to EVD patients while minimizing risk to care providers.
- Following the anthrax attacks that occurred in October 2001, the USPS developed plans to install HEPA filtration systems at mail processing facilities to capture and prevent/minimize airborne/aerosolized spores (most notably aerosolized *B. anthracis* spores) in the event of a release. A report from the U.S. General Accounting Office describes the results of government review of the proposed designs of the HEPA filtration system [22]. Results include consideration of necessary air sampling and detection equipment to monitor/confirm effectiveness of the filtration systems and ensuring existing infrastructure can accommodate the needs of the system (e.g., logistics, power, etc.).
- Describes dispatch and operation of a mobile Biosafety Level (BSL)-3 laboratory and well-trained diagnostic team to Sierra Leone to assist in EVD diagnosis when the largest

outbreak of EVD to date emerged in West Africa in 2014 [23]. The setup allowed for the diagnosis of suspected EVD cases in less than four (4) hours following receipt of samples. The mobile laboratory was composed of three (3) container vehicles and was equipped with an advanced ventilation system, communication system, and electricity and gas supply systems.

While, as discussed, review, assessment, and consideration of the approaches, procedures, and technologies used by other organizations for BWA contamination management and response operations, as well as review of past incidents and the associated response actions utilized (both successful and unsuccessful), can be valuable for directing the development of new and improvement of existing strategies for management and response during USCG vessel-related BWA incidents, as mentioned previously. The environmental settings in which the USCG operates and the assets requiring decontamination are likely to be very different from those involved during incidents in civilian/urban/etc., settings. Nonetheless, various basic principles for contamination management and response strategies may still be translatable.

Quantitative risk analysis systems, computer simulations, and mathematical models have also been developed as valuable tools used to inform decision makers and assist with BWA contamination management and response operation planning, such as in the following examples.

- A mathematical model was utilized to simulate a release of anthrax in lower Manhattan to compare a HEPA air cleaner/vacuum cleaner remediation plan with vaccinations to a ClO_2 fumigation remediation plan [24]. Cost, recovery time, and number of inhalation anthrax cases among reoccupants were the metrics of interest. The study suggested that a HEPA/vaccine approach is viable for most buildings after a large-scale anthrax attack.
- Available information on five BWAs (including *B. anthracis*, *Yersinia pestis*, *Francisella tularensis*, *Variola major*, and Lassa fever) was collected (including fate and transport and sampling data) and assessed to develop quantitative guidelines for the relationship between environmental pathogen concentrations and human health risk in an indoor environment [25]. An integrated model of environmental BWA transport and exposure was constructed that: (1) included effects of environmental attenuation, (2) considered different pathogens instead of just *B. anthracis*, (3) considered contact exposure (e.g., ingestion or dermal risk) as well as inhalational exposure, and (4) included an uncertainty analysis and identified key input uncertainties (which may inform the direction of future research). Findings provide a framework for developing the standards required for making risk-informed response decisions.
- An integrated mathematical model was developed that included environmental transport, exposure, and health risk following a release of *B. anthracis* spores [26]. The model linked environmental concentrations of *B. anthracis* to health risk so that once a target level of health risk was specified, environmental concentration standards corresponding to the

risk level could be computed. Intended use of the model was to support prospective risk analysis (i.e., determining future risk, which can/will inform remediation activities).

3.3. BWA Decontamination Efficacy

Remediation of BWA contamination can be accomplished using a wide variety of strategies, approaches, and technologies including use of volumetric decontaminants (i.e., vaporous or gaseous technologies, fumigants, fogs, etc.), liquid-applied technologies (via spray, foam, or simply through use of a mop or sponge), photodegradative/photolytic approaches and ionizing radiation, cold atmospheric plasma, physical removal approaches (e.g., washing, vacuuming, etc.), thermal decontamination approaches (e.g., hot air, autoclaving, etc.), and others [8]. Furthermore, the activities of reactive BWA decontaminants are based on a variety of chemistries including hypochlorous acid (HOCl)/hypochlorite (ClO^-), H_2O_2, peracetic acid, ClO_2, aldehydes, and others [8].

As discussed by Wood and Adrion [8], the specific material contaminated by BWA can often be a critical factor affecting the efficacy of decontamination approaches/technologies. Nonporous, hard, and inorganic materials (e.g., glass and stainless steel) are typically more easily decontaminated than porous, permeable, or organic materials (e.g., wood, concrete, soil, etc.). Soil and other/similar organic materials may impart a deleterious effect on the efficacy of decontaminants that rely on oxidative degradation/inactivation of contaminants. Spores may orient within microlocations throughout porous materials and be shielded from contact with decontaminants. Regarding the target USCG vessel-related materials provided in Table 1 in Section 2.1.1.2, high/sufficient decontamination efficacy may be easier to achieve from hard nonporous materials such as aluminum and glass but more difficult to achieve from porous materials such as foam and insulation. Efficacy of decontaminants on coated steel and nonskid coatings will likely be dependent on the nature/characteristics of the coating (e.g., permeability).

3.3.1. *BWA Decontamination State of the Science*

Numerous sources are available that provide reviews of the open literature to summarize the state of the science with respect to BWA decontamination. Such sources collected during the literature search performed for this effort include the following:

- Wood and Adrion provide an extensive review of a wide variety of approaches and technologies for decontamination of *B. anthracis* spores [8]. Reviewed/discussed decontamination methodologies are primarily categorized as liquid-based sporicides (including HOCl and ClO^-, peroxide, and aldehyde-based technologies), gaseous decontaminants (including ClO_2 gas, VHP, methyl bromide [MeBr], methyl iodide [MeI], metam sodium, formaldehyde gas, and ozone [O_3]), and physical-based decontaminants (including thermal decontamination approaches and UV radiation). Focus was placed primarily on technologies that inactivate spores (i.e., technologies that simply remove spore contamination are not considered), that are commercially available, and that are potentially applicable to use during large-scale BWA decontamination efforts.

- A comprehensive report commissioned by the EPA National Homeland Security Research Center (NHSRC) summarized data and information related to multiple characteristics of a wide variety of decontamination technologies, including general decontaminant applicability and principles of operation, available decontamination efficacy and material compatibility data, technical maturity, possible user concerns, and cost considerations [27]. Decontaminants were broadly categorized as: (1) liquid-based, (2) foams and gels, and (3) gas and vapor decontaminants, and included specific technologies such as hypochlorite (bleach, dilute bleach, pH-adjusted bleach [pAB]), aqueous ClO_2, aqueous H_2O_2, TechXtract®, Sandia Foam, Decon Green™, Canadian Aqueous System for Chemical/Biological Agent Decontamination (CASCAD™) surface decontamination foam (SDF), L-Gel, ClO_2 gas, H_2O_2 vapor, paraformaldehyde, and MeBr.
- An EPA technical brief discussed several BWA decontamination methodologies that could be considered for use during outdoor and/or wide-area *B. anthracis* contamination remediation operations [28]. Methodologies included liquids, foams, fumigants, gels, and wipes based on a variety of active species that have demonstrated efficacy against *B. anthracis* spores on contaminated surfaces. Application procedures/conditions, available efficacy data, and other considerations were provided in tabular form for EPA-registered liquid *B. anthracis* decontaminants, liquid H_2O_2/peracetic acid decontaminants, H_2O_2 foams, HOCl liquids and foams, liquids and fumigants for soil decontamination, and commercial off-the-shelf (COTS) sodium hypochlorite (NaOCl) wipes. Effective surface decontamination options according to surface type were provided, with multiple decontaminant options provided for nonporous materials, porous materials, and soil. Considerations related to use of decontamination approaches in outdoor settings were discussed, with the primary consideration being the potential presence of grime on surfaces to be decontaminated (liquid sporicides are generally less effective on heavily grimed surfaces). Sodium persulfate may be the best liquid sporicidal option for decontamination of soil. MeBr has decontaminated *B. anthracis* on outdoor building materials while ClO_2 may be effective in decontaminating soil and surfaces covered with dirt or grime. Metam sodium is the most widely used soil fumigant in the United States. Metam sodium achieved a ≥ 6 log reduction (LR) of *B. anthracis* on topsoil. In the same study, MeBr [180 milligrams per liter (mg/L) for a 36-hour exposure] also achieved ≥ 6 LR of *B. anthracis* on topsoil at 25 degrees Celsius [°C].

3.3.2. *Vaporous/Volumetric Decontamination Technologies*

Vaporous/volumetric technologies provide decontamination approaches that can be used on accessible surfaces, across larger/wide areas, and in confined or "hard to reach" areas. Hazardous residues left following application and use of volumetric decontaminants and fumigants may still need to be mitigated/remediated, as applicable, and compatibility of the decontaminated items/surfaces/structures with fumigants must also be considered (e.g., corrosion and/or condensation in electronic equipment). Secondary information and data from studies collected during the literature search that are focused on evaluation of vaporous/volumetric decontamination methodologies include the following:

- Gaseous O_3 at 3 mg/L (1,500 parts per million [ppm]) produced approximately a 3 LR of *Bacillus subtilis* spores (a simulant for *B. anthracis*) within 4 hours of exposure at 90% relative humidity (RH) on glass surfaces [29]. Inactivation rates on vinyl floor tile and office paper were nearly the same as on glass. Slower inactivation was measured from carpet (approximately 2 LR after roughly 4 hours) and hardwood (approximately 1.5 to 2 LR after approximately 4 hours).
- Treatment with MeI for a duration of 12 hours at generally ambient laboratory condition yielded a 6 LR in *B. anthracis* spores on stainless steel strips [30]. Efficacies greater than 6 LR reduction were achieved at 55°C after an hour.
- Complete inactivation of biological indicators (BIs) was achieved using H_2O_2 (22%)/peracetic acid (4.5%) fog, and the decontaminant also reduced aerosol-deposited *B. anthracis* spores to less than 1 log CFU (with numerous samples having no detectable spores) [31]. A 4 LR of viable spores was achieved on wood and stainless steel. Results for concrete were generally not significantly different from zero.
- Carpet, Mylar® coating, aluminum, rubber, upholstery, fiberglass siding, air filter materials, and unpainted concrete were inoculated with *B. anthracis* Ames or *B. atrophaeus* (approximately 1×10^8 CFU per coupon). Peracetic acid and H_2O_2 decontaminant fogs achieved ≥ 6 LR of *B. anthracis* Ames from rubber, upholstery, aluminum, and Mylar [32]. Efficacy on unpainted concrete was generally lower.
- *Geobacillus stearothermophilus* biological indicators (BIs) and stainless steel and cotton carriers containing greater than 4 $\log_{10}$ viable multidrug-resistant (MDR) methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin-resistant *Enterococcus* (VRE), or MDR *Acinetobacter baumannii* were treated with H_2O_2 vapor [33]. *G. stearothermophilus* spore BIs were inactivated (representing > 6 LR) and no MRSA, VRE, or MDR *A. baumannii* were recovered from the steel and cotton carriers.
- Exposure to 35% H_2O_2 vapor for a period of 40 minutes achieved full inactivation of foot-and-mouth disease virus (FMDV) on BIs on a repeated basis [34]. The results demonstrate a higher decontamination efficacy for 35% H_2O_2 vapor compared to formaldehyde (considered to be the primary decontamination agent for FMDV), which requires 10 hours of contact time.
- The efficacy of H_2O_2 vapor (concentration in excess of 100 ppm) and aerosolized H_2O_2 (less than 50 ppm) was evaluated against 4- and 6-log *G. stearothermophilus* BIs and test disks containing approximately 10^6 spores of MRSA, *Clostridium difficile* or *A. baumannii* [35]. H_2O_2 vapor generally achieved a 6 LR, whereas aerosolized H_2O_2 generally achieved less than a 4 LR.

- Carpet, pine wood, painted concrete, glass, Formica laminate, galvanized metal, and painted drywall were inoculated with $1x10^8$ spores of *B. anthracis* Ames, *B. subtilis*, or *G. stearothermophilus*. Contaminated coupons were exposed to ≥ 1,000 ppm H_2O_2 gas for 20 minutes. Mean LR values of *B. anthracis* Ames spores ranged from 3.0 (carpet) to 7.9 (glass and laminate). *B. subtilis* LR values ranged from 1.6 to 7.7. *G. stearothermophilus* LR values ranged from 0.81 to 6.0. All mean LRs were statistically significantly different from zero, except *G. stearothermophilus* reduction on carpet [36].
- Stainless steel coupons contaminated with *Bacillus* spores and BIs preloaded with greater than 10^6 spores of *B. atrophaeus* or *G. stearothermophilus* were exposed to H_2O_2 vapor at 500 ppm to 750 ppm for 20 minutes to 60 minutes at 35°C or to ClO_2 gas at 396 ppm for 60 minutes at 25°C [37]. H_2O_2 vapor achieved a 6 LR of *B. atrophaeus* within 6 minutes, a 5 LR of *G. stearothermophilus* within 20 minutes, and a 6 LR of *Bacillus thuringiensis* within 20 minutes. ClO_2 gas achieved a 5 LR of *G. stearothermophilus* in 60 minutes, a 5 LR of *B. atrophaeus* after 60 minutes, and *B. thuringiensis* was not significantly reduced after 60 minutes of treatment with ClO_2 gas.
- H_2O_2 vapor at 250 and 50 ppm by volume (ppmv) was used to decontaminate *B. subtilis* on galvanized metal and fiberglass HVAC duct liner (using both coupons and actual lined HVAC ducts) [38]. Decontaminant contact durations of 90 or 240 minutes were used. The lined duct exhibited significant H_2O_2 vapor desorption during the post-decontamination aeration phase, contributing approximately 75% of the total H_2O_2 exposure. High efficacy (≥ 7.3 LR) was achieved using 250 ppmv for both the 90-minute and 240-minute decontaminant contact durations. Fumigation at 50 ppmv resulted in lower efficacy (4.7 LR during fumigation for 90 minutes and no measurable reduction during the desorption phase).
- A condensing H_2O_2 vapor system, in which H_2O_2 is injected into the air until saturation and H_2O_2 begins to condense on surfaces, was tested against five viruses inoculated on stainless steel disks [39]. H_2O_2 exposure periods of 2 to 3 hours were utilized. Viruses were inactivated completely after H_2O_2 vapor exposure in 25-milliliter (mL), 27-mL, and 33-mL cycles.
- EPA testing has demonstrated *B. anthracis* reductions by H_2O_2 vapor of 6.9 LR or better from nonporous surfaces and 3.0 LR or better from porous surfaces. Other studies have shown that 500 ppm H_2O_2 vapor with 30 ppm ammonia can achieve a 6 LR of *B. anthracis* spores within 5 minutes on operationally relevant materials. Decontamination with 300 ppm H_2O_2 vapor for 2.5 hours decontaminated *G. stearothermophilus* BIs [40].
- Carpet, ceiling tile, unpainted cinder block, painted steel, painted wallboard, and unpainted wood were inoculated with 10^6, 10^7, or 10^8 spores of *B. anthracis* NNR1Δ1. Coupons were fumigated with either ClO_2 gas or H_2O_2 vapor. In general, mean spore

recovery from the different material surfaces ranged between 24% and 78% of the inoculated spores. LR was observed to be a strong function of material type [41].

- An EPA technical brief presented the results of multiple studies evaluating the efficacy of volumetric decontamination technologies against BWAs on subway-related materials [42]:
  - The efficacies of sporicidal liquid fogs (specifically peracetic acid and H_2O_2 fogs) against *B. anthracis* were evaluated on carpet, aluminum, upholstery, rubber, Mylar®, fiberglass siding, air filters, and unpainted concrete. Efficacy of ≥ 6 LR was achieved on every material except unpainted concrete and carpet. Lower efficacy was measured at lower temperature (10°C). Similar results were achieved using 35% H_2O_2 and peracetic acid fogs. Comparatively lower efficacy was measured using a 22% H_2O_2 fog.
  - MeBr fumigation was performed on coupons contaminated with *B. anthracis* surrogate spores. MeBr at a concentration of 212 mg/L (with no chloropicrin) and conditions of 24°C and RH greater than 75% was applied for a 36-hour exposure to contaminated coupons of carpet, fiberglass, aluminum, rubber, Mylar®, and vinyl. No viable spores were recovered from fiberglass and aluminum coupons. Viable spores were detected on only a limited number of carpet, rubber, Mylar®, and vinyl coupons.
  - ClO_2 fumigation of grimed subway materials (concrete, painted steel, and ceramic tile) was evaluated. A 6 LR in viable spores was achieved at 24°C and ≥ 75% RH using 230 ppmv ClO_2 for a 12-hour exposure duration or 3500 ppmv ClO_2 for a 4-hour duration. The impact of dirt and grime on decontamination efficacy was less noticeable than the impact of temperature and was dependent on the material.
  - MeBr fumigation of ceramic tile, painted steel, concrete, and granite was assessed. Materials were tested with and without simulated subway grime. Fumigation with MeBr was evaluated at a concentration of 212 mg/L at conditions of 4.5°C or 10°C and 50% or 75% RH and using exposure times ranging from 2 to 9 days. Fumigant conditions were found to affect the efficacy of MeBr. Grime increased the time required to achieve a 6 LR.
  - A mock subway system was contaminated with a *B. anthracis* surrogate. Decontamination via either bleach fogging or spray-application of pAB was performed. Eleven (11) of 132 post-decontamination samples were positive following bleach fogging. Five (5) of 138 post-decontamination samples were positive following pAB spraying.
- An EPA technical brief summarized the results of multiple studies and discusses the effectiveness of various volumetric decontamination technologies as a function of the operational conditions under which they are applied [43]:

- MeBr is efficacious against *B. anthracis* Ames spores at concentrations ranging from 212 to 300 mg/mL, RH of 75%, temperatures ranging from 22°C to 32°C, and exposure durations ranging from 18 to 36 hours.
- ClO_2 fumigation at high concentrations (e.g., 1,000 to 3,000 ppm) has demonstrated efficacy against *B. anthracis* Ames spores, but such high concentrations are likely to create issues related to material compatibility and/or generation capacity. Additional testing has thus been performed to evaluate the efficacy of lower concentration ClO_2 fumigation (e.g., 100 to 300 ppm) for longer exposure durations (e.g., 3 to 12+ hours).
- Formaldehyde fumigation for 10 hours at a concentration of 1,100 ppm at conditions of 16°C to 32°C and 50% to 90% RH can effectively inactivate *B. anthracis* Ames spores on several surfaces, including industrial carpet, bare pine wood, painted concrete, glass, decorative laminate, and galvanized metal ductwork.
- EPA has tested VHP generators and identified the H_2O_2 concentration of 400 ppm with minimum exposure duration of 6 hours (cumulative exposure of 2,400 ppm-hours at a temperature of 18°C or higher) to be efficacious against *B. anthracis* Ames spores.
- Ethylene oxide (EtO) has been found to be an effective decontaminant against *B. anthracis* Ames under optimal conditions of concentration, contact time, temperature, and RH. On glass and carbon steel, efficacious EtO application conditions range from ≥ 600 mg/L EtO, 50% RH, 50°C, and a contact duration ≥ 180 minutes, to ≥ 300 mg/L EtO, 75% RH, 37°C, and at least a 90-minute contact duration.
- EPA has measured the value of 6 LR for *B. anthracis* Ames from glass, ceiling tile, carpet, painted wallboard paper, wood, and unpainted concrete using 200 mg/L MeI at conditions of 25°C and greater than 70% RH for a 12-hour contact duration.
- Effective peracetic acid fogging against *B. anthracis* requires at least 10 mL of 4.5% peracetic acid per 1 cubic meter (m^3) volume with a contact duration of three (3) or more hours at 75% to 80% RH and a temperature of 21 to 27°C.
- Efficacious O_3 parameters against *B. anthracis* Ames spores on building materials were identified as a concentration of 12,000 ppm, a 9- to 12-hour exposure time, 85% RH, and temperature of 21 to 27°C.

- Vaporous decontaminants including ClO_2 vapor, formaldehyde vapor, and H_2O_2 vapor are discussed [44]. Benefits, drawbacks, and the intended-use BWAs are identified and discussed for each.

- Adequate formaldehyde efficacy requires RH to be maintained at or above 70%. Formaldehyde is toxic, an irritant, and is classified as a human carcinogen.
- Gaseous ClO_2 is not stable and cannot be stored, thus it must be generated on site. ClO_2 decontamination during the 2001 anthrax attacks involved treatment with ClO_2 at 750 ppm for 12 hours while maintaining temperature above 75 degrees Fahrenheit (°F) and RH above 75%. These ClO_2 conditions have achieved a 6 LR of *B. anthracis* spores and are consistent with laboratory data. ClO_2 gas can penetrate some materials (e.g., porous materials, plastic, rubber). However, large volumes of liquid waste are generated, and ClO_2 concentrations above 10% pose a risk for explosion.
- H_2O_2 vapor is typically produced by heating a 30 to 35% solution of H_2O_2 in water, and numerous commercial H_2O_2 vapor generators are available. Scalability of VHP treatment up to 5,660 m^3 has been demonstrated.

- Decontamination using VHP can lead to absorption of H_2O_2 into treated porous or permeable materials (e.g., polymethyl methacrylate [Plexiglas®]). Subsequent outgassing can then allow H_2O_2 vapor concentrations to reaccumulate to levels capable of inactivating *B. anthracis* spores [45].
- Automated H_2O_2 vapor room disinfection was found to reduce the incidence of *C. difficile* infection in a hospital setting [46].

3.3.3. *Liquid-Based/Applied Decontamination Technologies*

Several secondary information and data sources were collected during the literature search from studies focused on evaluation of decontaminants based on a variety of active species applied as liquids, including hypochlorite-based decontaminants (e.g., NaOCl [household bleach], dilute bleach, CASCAD™ SDF, pAB, etc.), H_2O_2 and peracetic acid-based decontaminants (including Peridox® Ready to Use [RTU], Spor-Klenz® RTU, etc.), and other decontamination technologies. BWA decontamination efficacy data collected on liquid-applied technologies include the following:

- CASCAD™ SDF achieved *B. atrophaeus* spore LR values of 9.1, 9.2, and 9.0 from steel, brick, and lumber, respectively, outperforming Peridox® RTU which achieved LR values of 4.7, 9.3, and 8.0, respectively, and pAB (4.8, 8.6, and 4.9, respectively) [47].
- Aqueous ClO_2 achieved an 8 LR of viable *B. anthracis* Sterne spores in suspension in only three (3) minutes. Spraying or spreading liquid ClO_2 onto surfaces (type 304 stainless steel and polystyrene) resulted in only a 1 LR because ClO_2 gas was rapidly vaporized from the solutions [48]. Full potency of the sprayed aqueous ClO_2 solution was restored by preparing the ClO_2 solution in 5% bleach (0.3% NaOCl).
- *B. anthracis* spores, *Burkholderia thailandensis*, *Vibrio cholerae*, *Salmonella enterica*, aflatoxin, and brevetoxin were decontaminated from seven (7) types of pipe materials

including high density polyethylene (HDPE), polyvinyl chloride (PVC), aged black iron pipe, and epoxy-coated steel pipe using NaOCl, Pipe-Klean®, and Simple Green® [49]. NaOCl was the most effective for reducing the adherence of bacteria and levels of *B. anthracis* spores but not as effective against aflatoxin as the other treatments.

- *Burkholderia pseudomallei* was more easily decontaminated from nonporous materials (e.g., glass and aluminum) than porous materials (e.g., wood, concrete, and carpet) using pAB, citric acid (1%), ethanol (EtOH; 70%), quaternary ammonium, and PineSol® [50]. Citric acid demonstrated poor efficacy. pAB, 70% EtOH, quaternary ammonium, and PineSol® demonstrated > 6 LR on glass and aluminum at both 20°C and 12°C, but achieved varying results for decontamination from wood, carpet, and concrete.
- Coupons of aluminum, wood, glass, concrete, and carpet were inoculated with approximately 1×10^8 CFU per coupon of one of *Y. pestis, F. tularensis, Burkholderia mallei,* or *V. cholerae*, then decontaminated with pAB (pH approximately 6.8, approximately 6,200 ppm chlorine), 1% citric acid, quaternary ammonia, 70% ethanol, or Pine-Sol® [51]. Decontaminants were applied via spray and utilized 15-minute (nonporous materials) or 30-minute (porous materials) decontaminant contact periods. Complete inactivation was achieved more often with Pine-Sol® and pAB than with other decontaminants (particularly from nonporous materials). Roughly 7 to 8 LR was achieved for both Pine-Sol® and pAB for all four organisms from aluminum and glass. Citric acid (1%) demonstrated the lowest efficacy for all four organisms on all materials.
- Bleach (5,250 ppm NaOCl), SDF, and Virkon (2%) were used to decontaminate spores (*G. stearothermophilus*, 4.6×10^6 CFU) on stainless steel carrier disks with and without light or heavy organic load at -20°C, 4°C, 10°C, or 23°C for predefined time periods up to 24 hours [52]. At -20°C, less than 2.0 LR was achieved. With light organic load after two (2) hours at 4°C and 10°C, bleach achieved 4.4 and 4.7 spore LR values, respectively. After 24 hours with light organic load at 4°C and 10°C, both bleach and SDF LR were more than 5.0. Virkon was less efficacious at all temperatures with light organic load. With heavy organic load, all three decontaminants produced less than 2 LR within two (2) hours at either 4°C or 10°C. Efficacy of SDF was 4.5 LR at both temperatures after 24 hours. With both organic loads at 23°C, SDF and Virkon achieved 5.5 LR in 24 hours. Bleach was comparable with the light organic load but not with the heavy organic load.
- Bleach at 2%, 5%, and 10% (by volume in water, without adjusting pH), Virkon (5%), Spor-Klenz® RTU, Rescue Sporicidal Liquid (4.5% H_2O_2, accelerated hydrogen peroxide [AHP]) and Allen Vanguard SDF were used to decontaminate 10^6 CFU of *B. anthracis* Sterne spores on stainless steel [53]. Bleach (10%) consistently achieved ≥ 6 LR of spores after 5 minutes at room temperature, whereas it took ≥ 10 minutes of contact time for AHP and at least 20 minutes for 5% bleach and Spor-Klenz®.

- Bleach, Spor-Klenz® RTU (peracetic acid and H_2O_2), and Metricide 14-Day (2.6% glutaraldehyde) were used to decontaminate *B. subtilis* on glass [54]. Three efficacy levels per decontaminant were evaluated, and LR values increased with increasing efficacy level.
- Bleach (5,000 ppm available chlorine), 70,000 ppm accelerated H_2O_2, 1,000 ppm ClO_2, and 3,000 ppm peracetic acid were used to decontaminate various species of *Bacillus* spores on stainless steel disks [55]. ClO_2 achieved a LR of ≥ 6 of *B. anthracis* Sterne spores at all the contact times tested. *B. licheniformis* exhibited the highest resistance to inactivation by ClO_2. Peracetic acid showed a faster level of sporicidal activity (higher levels of spore kill at 5 minutes than the other three decontamination formulations tested). Peracetic acid activities at 10 and 20 minutes were roughly comparable to diluted bleach and accelerated H_2O_2.
- Tyvek, butyl rubber, stainless steel, and polycarbonate were inoculated with *B. anthracis* Δ Sterne or ricin protein toxin and disinfected with pAB or dilute Peridox® RTU [56]. No viable *Bacillus* spores were recovered from any surface after 15 minutes of treatment with pAB or dilute Peridox® RTU (representative of > 6 LR). Ricin protein toxin was not detected on any surface after 15 minutes of treatment with pAB. Ricin toxin was detected on all surfaces after 30 minutes of treatment with dilute Peridox® RTU.
- Ebola virus surrogates (bacteriophages MS2, M13, Phi6, and PR772) were inoculated onto stainless steel disks and decontaminated using 0.1% and 0.5% dilute bleach [57]. Contact periods for inactivation ranged from 1 to 10 minutes. Dilute bleach (0.5%) achieved 3.4 and 3.5 LR values against MS2 and M13, respectively, after a 10-minute treatment time. PR772 achieved a 4.8 LR using 0.5% dilute bleach after only 1 minute. Phi6 achieved a 4.1 LR using 0.5% dilute bleach after 5 minutes and was not detected after 10 minutes.
- An EPA technical brief discussed the test procedures and results of studies performed to evaluate strategies and technologies for decontamination of BWAs in outdoor environments and challenging settings [58]:
    - Evaluation of *B. atrophaeus* (*B. anthracis* surrogate) and bacteriophage MS2 decontamination efficacy of pAB, Spor-Klenz® RTU, and citric acid (2%) applied using a handheld sprayer, backpack sprayer, and chemical sprayer on concrete and treated plywood was performed. pAB was more effective than Spor-Klenz® RTU against spores on concrete (7.3 LR using the backpack sprayer). Spor-Klenz® RTU was more effective than pAB against spores on plywood (7.4 LR using backpack sprayer).
    - Eight (8) nonfreezing bleach (NFB)-based formulations were evaluated for efficacy against *B. atrophaeus* on concrete and glass when applied at temperatures ranging from -25°C to 25°C. pAB was included during tests conducted above

freezing temperatures (> 0°C) as a reference decontaminant. None of the NFB formulations were as effective as pAB, and as test temperatures were lowered, decontamination efficacies also tended to decrease.

- *B. anthracis* Δ Sterne and *B. anthracis* Ames spores were inoculated onto stainless steel coupons and decontaminated using electrochemically generated ClO_2 ($eClO_2$) [59]. The $eClO_2$ decontaminant achieved a 7.0 ± 0.5 LR of spores following a contact period of 1 minute.
- Coupons of aircraft performance coating (APC)-painted aluminum, stainless steel, Navy ship top-coat (NTC)-coated stainless steel, chemical agent resistant coating (CARC)-W-coated stainless steel, magnesium fluoride (MgF_2)-coated glass, low density polyethylene (LDPE), and Lexan® were inoculated with ≥ 7 logs of spores of *B. anthracis* Ames, *B. anthracis* Δ Sterne or *B. thuringiensis* Al Hakam. Contaminated coupons were decontaminated using PES-Solid at room temperature using a 15-minute decontaminant contact period. Either no spore survival or less than 1 log of viable spores was recovered from 56 of 63 possible test combinations (strain, decontaminant formulation, and test material surface) after treatment with PES-Solid. Less than 2.7 log CFU survived in the remaining test combinations [60].

3.3.4. *UV Irradiation and Photodegradative Decontamination Technologies*

Secondary information and data collected during the literature search from studies focused on evaluation of UV irradiation and other photodegradative decontamination technologies include the following:

- UV irradiation within the "C" band (UV-C; specifically, 253.7 nanometers [nm] in this study) was evaluated for inactivation of eight varieties of *Bacillus* spores (including *B. subtilis*, *B. anthracis* Sterne, and others) [61]. Percent kill on agar plates increased from an average of 21% for a 30-second exposure to an average of 71% for a 120-second exposure (a high value of 81% was achieved at 120 seconds for a strain of *B. subtilis*).
- Pulsed xenon UV (PX-UV) disinfection demonstrated a > 4 LR for canine parvovirus (an Ebola virus surrogate) on glass carriers, face shield material, and gown material initially inoculated at 5.98 log per carrier [62].
- The effect of simulated sunlight (UV irradiation in the A [380 to 320 nm] and B [320 to 290 nm] ranges, i.e., UV-A and UV-B) on the inactivation kinetics of virulent *B. anthracis* Ames spores and *B. subtilis* spores was investigated [63]. *Bacillus* spores were dried on porous (including wood, unpainted concrete, and topsoil) and nonporous materials (glass) at $1x10^8$ CFU per coupon. Contaminated coupons were exposed to both UV-A and UV-B radiation using elapsed times of 2, 14, 28, and 56 days. Data showed that viable spore recovery is diminished when contaminated coupons are exposed to simulated sunlight on all materials except topsoil. UV-A/B exposure resulted in roughly 1

to 2 LR on glass, wood, and concrete. As high as 6 LR on glass at 56 days was observed. Without exposure to UV, only approximately 1 LR on glass, concrete, and wood was observed for both *Bacillus* species. Minimal reduction in/on topsoil was observed regardless of spore species/UV exposure condition.

- Suspensions of *Candida albicans*, *Aspergillus niger*, *B. subtilis*, *Clostridium perfringens*, and *Mycobacterium fortuitum* were exposed to a UV light source at a distance of eight feet for a duration of 30 minutes [64]. An LR value of 4 was achieved for *Bacillus subtilis* and *C. perfringens*. An LR of 3 was achieved for *C. albicans* and *M. fortuitum*. LR for *A. niger* was less than 3.
- A ceiling-mounted 405-nm high-intensity narrow-spectrum light environmental decontamination system (HINS-light EDS) achieved a decrease between 22% and 86% in the mean number of surface bacteria (hospital room-related surfaces) [65]. When use of the HINS-light EDS was discontinued, surface bacteria increased by 78% to 309%.

3.3.5. *Physical Removal-Based Decontamination Approaches*

As discussed earlier, physical removal approaches include methods such as washing, vacuuming, wipe-removal of contaminants, etc. Such approaches decontaminate surfaces by removing BWAs, but do not always inactivate spores/viruses/etc. Thus, rinsate, vacuuming waste, and used wipes must be further decontaminated using other reactive approaches/technologies prior to disposal. Addition of reactive components to wipe technologies (e.g., saturation of wipes with reactive liquid decontaminants) can impart BWA inactivating/degradative qualities. Secondary information and data collected during the literature search from studies focused on evaluation of sporicidal and disinfecting wipe technologies include the following:

- Four (4) hypochlorite-based sporicidal decontamination wipes (Clorox® Healthcare™ Bleach Germicidal Wipe, Sani-Cloth® Bleach Germicidal Disposable Wipe, Dispatch® Hospital Cleaner Disinfectant Towel with Bleach, and Hype-Wipe® Disinfecting Towel with Bleach), a H_2O_2/peracetic acid-based sporicidal wipe (Steriplex® SD Wipe), two commercially available disinfecting wipes (Lysol® Disinfecting Wipe and Clorox® Disinfecting Wipe), and a pAB-wetted wipe were evaluated for efficacy in inactivation of *B. atrophaeus* spores (*B. anthracis* surrogate) on glass Petri dishes, stainless steel, composite epoxy, LDPE, and painted drywall [66]. All four hypochlorite-based sporicidal wipes achieved a LR of at least 7 of *Bacillus* spores, with the exception of the Dispatch® wipe on painted drywall (5.71 LR).
- Four sporicidal wipes (Clorox® Healthcare™ Bleach Germicidal Wipe, Sani-Cloth® Bleach Germicidal Disposable Wipe, Dispatch® Hospital Cleaner Disinfectant Towel with Bleach, and Hype-Wipe® Disinfecting Towel with Bleach) and three disinfecting wipes (Steriplex® SD Wipe, Lysol® Disinfecting Wipe, and Clorox® Disinfecting Wipe) were used to inactivate *B. atrophaeus* on 12-inch by 12-inch coupons of stainless steel, glass, composite epoxy, painted drywall, and LDPE [67]. The sporicidal wipes

achieved ≥ 6.1 LR on all materials with only a single exception (the Dispatch® wipe on painted drywall, which achieved a 5.7 LR). Two sporicidal wipes were then used to inactivate *B. atrophaeus* on larger glass and painted drywall surfaces with dimensions of 42-inches by 42-inches. The highest efficacy obtained when spores were evenly distributed across the surfaces was 4.5 LR from glass by the Hype-Wipe®.

3.3.6. *Thermal Decontamination*

Thermal decontamination can provide an efficacious and, depending on the surface, material-compatible BWA inactivation approach. Secondary information and data collected during the literature search from studies focused on evaluation of thermal decontamination include the following:

- Thermal decontamination (using hot, humid air) was capable of complete decontamination of *B. anthracis* Δ Sterne or *B. thuringiensis* Al Hakam spores (> 7 $\log_{10}$) from aluminum, anti-skid material, and wiring insulation but not nylon webbing [68]. Nineteen (19) combinations of temperature (55°C, 65°C, and 75°C), RH (70%, 80%, and 90%), and duration (1, 2, or 3 days) were evaluated for efficacy. Porous materials and organic debris delay decontamination kinetics for hot, humid air.
- APC-coated aluminum, anti-skid-coated aluminum, InsulFab insulation, wiring insulation, nylon webbing, and polypropylene coupons were inoculated with ≥ 7 $\log_{10}$ of *B. anthracis* Δ Sterne and *B. thuringiensis* Al Hakam spores. Hot humid air decontamination (upper limit of temperature and RH of 77°C and 90%) was less effective at inactivating spores on nylon. For wet spore controls and spores dried onto wiring insulation, most of the test runs showed complete spore inactivation [69].

3.3.7. *Additional Approaches, Information, and Data*

Plasma is an emerging technology that shows potential as a simultaneously efficacious and material-compatible surface decontamination approach. A prototype nonequilibrium corona plasma surface decontamination technology achieved *B. subtilis* destruction efficiencies of 98% on plastic, 99.9% on aluminum, and 99.4% on cotton surfaces with a 60-second treatment duration [70]. Treatments of 5 minutes resulted in > 3 LR without harm to material surfaces. Plastic and CARC-painted aluminum inoculated with 2.5 x 10^6 spores of *B. anthracis* were treated, with up to 99.7% of spores destroyed with a 60-second exposure.

Secondary information and data from other studies collected during the literature search that are focused on decontamination of BWAs by a variety of technologies using multiple application approaches include the following:

- Acoustic ceiling tile, carpet, fabric, painted wallboard, concrete, and CARC-painted metal were contaminated with spores of *Bacillus globigii* (*B. anthracis* simulant) via aerosol spray (10^7 to 10^8 CFU per 4 square inches [in^2]). University of Michigan Nanotech (novel, broad-spectrum antimicrobial nanoemulsion), SNL aqueous foam, and

L-Gel performed better than gaseous O_3, activated hypochlorite, GD-5 (mixture of aminoalcholates and surfactant), and metal oxide nanoparticles at inactivating spore contamination [71].

- Tile, fabric, wood, activated carbon-based PPE, glass, paper, plastic, and metal coupons were contaminated with *B. atrophaeus* spores. NaOCl (5%, 0.5%, and 0.05%) at pH 7 and pH 12 (30 min contact time) resulted in no bacterial growth on any sample, except for paper (0.5% and 0.05% NaOCl at pH 12 as well as 0.05% NaOCl at pH 7) and both tile and metal (0.05% NaOCl at pH 12). Spores were detected on tile after sterilization with EtO, but no spores were detected after autoclaving, 2% glutaraldehyde sterilization for 30 minutes, boiling water treatment for 30 minutes, or treatment with 3% H_2O_2. UV irradiation (24 h) completely removed contamination from fabric, wood, PPE, and paper. Free chlorine solutions (1,000 mg/L and 10,000 mg/L) provided full disinfection of all materials [72].
- UV light-based systems have been shown to achieve up to a 4 LR of vegetative bacteria on carriers in (up to) 20 minutes, and up to a 4 LR of *C. difficile* in (up to) 100 minutes. H_2O_2 systems have been demonstrated to achieve complete inactivation (> 6 LR) of *G. stearothermophilus* spores and all surface contamination of MRSA, VRE, *M. tuberculosis*, and other various spores, viruses, and multidrug-resistant gram-negative bacilli [73].
- Data from the open literature on UV light and H_2O_2 room decontamination systems were reviewed [74]. Efficacy of UV light and H_2O_2 systems against microbes experimentally plated on carrier materials as well as MDR pathogens in hospital settings has previously been demonstrated. Data presented for UV irradiation demonstrate MDR organism LR values as high as 4.71 on carriers. H_2O_2 systems (aerosolized H_2O_2 and VHP) have demonstrated MDR organism percent reduction values between 86% and 100% in contaminated hospital rooms.

Decontamination approaches selected for remediation of BWA contamination on USCG vessels must be simultaneously efficacious and material-compatible to ensure BWA surface hazards and the potential for, e.g., spore re-aerosolization are sufficiently remediated/mitigated while not compromising the integrity and function of vessel materials, construction, and mechanical and electrical systems, allowing for unlimited return of vessels to service. Other characteristics of decontamination technologies may also be particularly relevant to consideration of their use during USCG vessel-related decontamination operations. Examples of other potentially relevant technology characteristics given the operational settings of USCG vessels (beyond decontamination efficacy and material compatibility) include: (1) any logistical burden related to application and/or use of technologies (i.e., high utility requirements, bulky equipment, high raw material or reagent needs, etc.), (2) production of large amounts of wastes and/or hazardous wastes, (3) demonstration of the technology/approach at full-scale, (4) cost and availability, (5) potential health and environmental impacts, and others [8].

3.4. BWA Decontaminant Material Compatibility

Reactive decontaminants that have either demonstrated efficacy against BWAs or have been evaluated for efficacy against BWAs are based on a variety of chemistries (e.g., hypochlorite-based and oxidative technologies). However, not all BWA decontamination technologies are appropriate for use in certain circumstances given the corrosive nature of some reaction chemistries toward the surface(s) to be decontaminated, especially critical for sensitive equipment and related surface materials, as such equipment and materials are often associated with high procurement costs and long lead times for procurement. Sensitive equipment and surfaces are incorporated extensively into the construction of USCG vessels. Consideration of the compatibility of decontamination systems with the materials incorporated into the construction of USCG vessels, including sensitive equipment and related materials, is critical to ensuring a prompt and unlimited return to service of the assets following decontamination.

Secondary information and data collected during the literature search from studies focused on evaluation of the compatibility of decontamination technologies with a variety of materials (including sensitive equipment and sensitive equipment-related materials) include the following:

- The compatibilities of unpainted concrete cinder block, standard stud lumber (fir), latex-painted gypsum wallboard, ceiling suspension tile, painted structural steel, carpet, and electrical circuit breakers with VHP (application conditions of $< 30\%$ RH and $> 30°C$) were evaluated [75]. Materials were exposed to either 250 ppm VHP for four (4) hours for a total contact time (CT) of 1000 ppm-hours, or 125 ppm VHP for eight (8) hours also for a total CT of 1000 ppm-hours. Generally, VHP-exposed building materials showed no change in appearance or integrity compared to nonexposed samples.
- The effects of MeBr fumigation and its interactions with 24 different test materials, including HVAC duct and liner and painted metal, were evaluated [76]. Materials were exposed to MeBr at 1,000 ppm for 16 hours. Generally, MeBr did not ad/absorb appreciably onto/into the materials tested, though some diffusion into porous materials occurred.
- Compatibilities of MeBr (300 mg/L with 2% chloropicrin for nine (9) hours at 37°C and 75% RH), ClO_2 gas (CTs ranging from 900 ppmv-hours to 9,000 ppmv-hours), VHP, and EtO gas with sensitive equipment (including functioning personal computers [PCs]) were evaluated [77]. ClO_2 treatment caused material degradation, but PCs remained functional. No changes in visual appearance or functionality due to exposure to VHP were observed. Corrosion was observed on low carbon steel and steel outlet/switch boxes following MeBr fumigation (no other materials were affected). Power supplies in all MeBr-fumigated PCs failed (but this was attributed to the chloropicrin component of the MeBr fumigant). Little to no impact to any of the materials following fumigation with EtO was recorded.

- Fumigation technologies that have been used to decontaminate sensitive equipment materials were reviewed [78]. Fumigation with EtO generally demonstrates the greatest degree of material compatibility. However, EtO is highly toxic and flammable, so ex-situ decontamination (off-site or at a separate location on-site) is recommended. VHP treatment is effective and material-compatible, but the application process must be closely monitored and controlled to prevent damage (due to condensation). MeBr demonstrates material compatibility but is toxic to humans. ClO_2 gas is generally a more efficacious decontaminant than VHP but demonstrates decreased material compatibility in comparison to VHP.

- Compatibility of ClO_2 fumigation with sensitive electronic components and materials was evaluated using multiple conditions including: (1) 3,000 ppmv ClO_2 with 75% RH, (2) 75 ppmv ClO_2 with 75% RH, (3) 75 ppmv ClO_2 with 40% RH, and (4) 3,000 ppmv ClO_2 with 90% RH [79]. No visual or functional changes for stainless steel, laser-printed paper, or gaskets were observed. Circuit breaker screws and inkjet-printed paper were affected under every condition (including tests using only high RH [i.e., no ClO_2]). RH at 75% severely affected low carbon steel, copper, photographs, and drywall nails and screws. ClO_2 fumigation at high temperature and RH led to intermittent light switch failures. No impacts to personal digital assistant (PDA) devices under any fumigation condition were observed. Mild discoloration and fading of cell phone screens were noted under certain conditions. ClO_2 and condensing humidity caused severe corrosion of fax machine printer bars, compact disks (CDs), and digital video disks (DVDs). At lower RH, these impacts were not observed. Power state of PCs had an effect on material/decontaminant compatibility. ClO_2 and RH at least 75% resulted in corrosion of computer components. CD/DVD drives were damaged by 3,000 ppmv ClO_2 and RH greater than 75%.

- Compatibility of sensitive electronic components and materials with MeBr was evaluated at a MeBr concentration of 300 mg/L (with 2% chloropicrin), 75% RH, and 37°C for nine (9) hours [80]. Compatibility with ClO_2 was also evaluated at 3,000 ppmv ClO_2, 75% RH, and 24°C for 3 hours (CT 9,000 ppmv-hours). MeBr fumigation with chloropicrin caused some surface corrosion of low carbon steel and rusting around the edges of steel outlet/switch boxes, but otherwise no effects were observed. CDs, DVDs, cell phones, PDAs, and a fax machine all retained visual and functional integrity. PC parts affected by the MeBr (with chloropicrin) and ClO_2 fumigants included external and internal stamped metal grids, external metal slot covers, and internal cut metal edges. All PCs exposed to MeBr fumigation exhibited power supply failures, but the failures were traced to the chloropicrin component of the MeBr fumigant. PC central processing units (CPUs) and CPU and graphics processing unit (GPU) heat sinks were not impacted by either fumigant.

- Unpainted concrete cinder block, standard stud lumber (2-inch by 4-inch fir), latex-painted 0.5-inch gypsum wallboard, ceiling suspension tile, painted structural steel, carpet, and electrical (circuit) breakers were exposed to ClO_2 vapor [81]. Fumigation conditions were 2,000 ppm ClO_2 for six (6) hours for a total CT of 12,000 ppm-hours, or 1,000 ppm ClO_2 for twelve (12) hours also for a total CT of 12,000 ppm-hours. RH target was 75%, and temperature target was 75 °F. No visual differences were observed for any of the materials following ClO_2 exposure. Tensile strength of standard stud lumber furring strips was reduced by exposure to high concentrations of ClO_2 for short durations. Under a 30-amp load, ClO_2-exposed circuit breakers tripped more slowly than the control units. Otherwise, no functional impacts were observed.

- MeBr (without chloropicrin) and MeI fumigation were performed under conditions of 26 to 30°C and 75 to 85% RH for 48 hours at target MeBr or MeI concentrations of 200 to 250 mg/L [82]. Desktop computers were used as surrogates for high-value sensitive/electronic equipment. Coupons of metals used frequently in electronics (copper, aluminum, tin) were included to evaluate corrosion. Only copper coupons showed a noticeable difference in appearance after fumigation (green and brown discoloration). The most substantial effect observed on PC functionality was damage to displays fumigated with MeI, particularly those that were powered on during fumigation (demonstrated reduced brightness and a bluish tint).
- Compatibility of gamma irradiation at 30 and 50 kilograys (kGy) with historical oil paintings, archival documents, books, photographs, historical pastel paintings, wood/furniture, porcelain/bisque, fabrics, metal and alloys, and leather was evaluated [83]. All materials showed some visual changes.
- The material demand (mass flux) of selected materials for ClO_2 under select fumigation conditions (specifically, ClO_2 concentrations of 1,000 ppmv or 2,000 ppmv to achieve a total CT of 12,000 ppmv-hours) was determined [84]. The materials included concrete, painted steel, wood, gypsum wallboard, ceiling tile, and carpet. Required feed concentration and the time required to reach the target ClO_2 fumigant concentration were found to be functions of building material. Rank of ClO_2 demand for the building materials over the 0 to 12,000 CT range was (from highest demand to lowest) ceiling tile > wood ≥ gypsum wallboard > carpet > concrete = steel = baseline for the 1,000 ppmv tests, and ceiling tile > gypsum wallboard > carpet > wood > concrete = steel = baseline for the 2,000 ppmv tests.
- Compatibility of H_2O_2 (3% liquid), bleach (0.58% hypochlorite), and Oxone® (1%) was evaluated on metals (copper, brass, silver, tin, titanium, iron, and gold), inks, cellulose from new and aged paper and cotton fabrics, collagen, keratin, and fibroin (silk) [85]. Results demonstrated that the decontaminants damaged the materials, but the degree of damage varied with the specific decontaminant and the material. Damage can be minimized with the appropriate choice of decontaminant. H_2O_2 was generally the least aggressive on metals. Oxone® was the most aggressive on organic materials. Bleach decontamination affected a higher percentage of inks.

- The material demands of unpainted concrete cinder block, standard stud lumber, latex painted gypsum wallboard, acoustical ceiling suspension tile, primer-painted structural steel, and carpet for VHP was evaluated [86]. The concrete cinder block coupon had the greatest impact on maintaining the VHP concentration, while carpet and steel had a low impact on the VHP concentration.

3.5. BWA Sampling and Analysis

To identify specific BWA contaminants, accurately and precisely determine the extent of BWA contamination, and assess the effectiveness of BWA decontamination efforts, effective sampling procedures, methodologies, and technologies for qualitative and/or quantitative measurement of BWA concentrations/amounts in a variety of environmental matrices are necessary (including measurement of surface concentration levels, concentrations in liquid matrices, and aerosol/aerosolized concentrations). As with approaches for decontamination, the unique operational settings and construction materials associated with USCG vessels can create challenging sampling scenarios. Effective surface sampling can be challenged by the materials themselves (which, at times, incorporate complex coating systems) and/or by various contaminants and foulants introduced by USCG vessel operational settings (e.g., seawater, grime, etc.).

Silvestri et al. summarized and discussed key challenges faced in collecting, analyzing, and interpreting microbial field data from a contaminated site (consideration is given primarily to *B. anthracis* contamination) [87]. The implications and limitations of using field data for determining environmental BWA concentrations both before and after decontamination were explored. Considerations, challenges, and limitations associated with collection of field samples for BWA contamination characterization and/or assessing remediation effectiveness as well as estimation of environmental concentrations from interpretation of the data were also presented and discussed.

In addition to the efficacy of BWA sampling methods for recovery of target contaminants from intended matrices, other method characteristics must also be considered when decisions are made regarding which methods to use during BWA contamination response and remediation operations. One such important consideration is the potential for cross-contamination from application of the sampling method. Fluorescing tracer powder was used to evaluate cross-contamination potential during sample collection and packaging operations [88]. *B. atrophaeus* was used as a surrogate for *B. anthracis*. Sampling was performed according to Centers for Disease Control (CDC), National Institute for Occupational Safety and Health (NIOSH) and EPA methods using 3M Sponge-Sticks, and recommendations were provided (based on the results) to minimize/eliminate the observed transfer of contamination that occurred during application of the sampling approaches.

Once appropriate/effective BWA sampling methods have been selected and implemented, collected samples must be analyzed to qualitatively/quantitatively determine BWAs. BWA analysis and detection technologies include culture-based assays, polymerase chain reaction (PCR)-based technologies (including real-time PCR and Rapid Viability PCR [RV-PCR]) biosensors, microarrays, immunoassays, electrochemiluminescence (ECL), enzyme-linked immunosorbent assay (ELISA), and others. A literature review by Herzog et al. (2009) includes discussion of studies on detection of BWAs in soil and air, detection on fomites, and detection in water [89]. Methods for surface sampling include collection of BWA samples from stainless steel, plastic, wood, glass, painted wallboard, carpet, and concrete using swabs, wipes, vacuum socks, and a biological sampling kit [BiSKit; designed to sample surfaces for viruses, bacteria, and toxins]). The data collected suggest that pre-moistened swabs perform better than dry swabs, although the BiSKit outperforms swab sampling. The predominant methods used for detection of BWAs are cultivation/culture-based assays and PCR-based methods (including RV-PCR). Considering the median instrument limit of detection, real time PCR and PCR are the most sensitive methods, with median instrument limits of detection (LODs) of 430 and 440 cells/mL, respectively.

Common BWA surface sampling approaches include vacuum-based methods and wipe/sponge-based methods. Secondary information and data collected during the literature search from studies focused on evaluation of vacuum-based BWA sampling methodologies, including the following.

- Recovery of (aerosol-deposited) *B. atrophaeus* spores from pleated HVAC filters by an extraction method (phosphate-buffered saline) and two vacuum methods (vacuum sock and cassette filter) were compared [90]. The HVAC filters were tested both with and without dust loading to approximately 50% of their holding capacity. Recovery of spores from the filters via extraction was higher than recovery by either of the vacuum methods. Vacuum recovery was approximately 30% of the recovery achieved by the extraction method. Recoveries between the two vacuum methods that were evaluated were not significantly different. Although the extraction methods provided higher recovery, the vacuum methods may provide a more rapid and inexpensive approach for confirming BWA contamination. Dust loading did not affect recovery by the vacuum methods.
- Commercially-available autonomous (robotic) floor cleaners were evaluated for efficacy in sampling *B. atrophaeus* spores (*B. anthracis* surrogate) from the surface of various indoor flooring materials (both porous [e.g., carpet] and nonporous [e.g., laminate and tile]) and from concrete surfaces [91,92]. Three vacuum-based robots, one wet vacuum-based robot, and one wipe-based robot were evaluated (on appropriate surface types, i.e., the wet-vacuum and wipe technologies were not evaluated on carpet). Recoveries by the robot technologies were compared to sponge wipe and vacuum sock methods to calculate a comparative recovery value for each robot. Generally, the wipe and wet-vacuum-based robots performed better than the dry vacuum robots on hard nonporous material surfaces. The dry vacuum-based robots performed as well as or better than a vacuum sock method

for spore recovery from carpet. A small but detectable amount of spore reaerosolization due to operation of the robots was detected.

- Vacuum socks, mixed cellulose ester (MCE) filter cassettes, polytetrafluoroethylene (PTFE) filter cassettes, and 3M™ forensic filters were comparatively evaluated for efficacy in recovery of *B. atrophaeus* (*B. anthracis* surrogate) spores from the surface of concrete, carpet, and upholstery [93]. Stainless steel surfaces were also inoculated with spores and sampled using pre-moistened wipes to act as a control. The MCE filter cassettes exhibited higher recoveries than the other vacuum-based sampling methods when sampling spores from concrete and upholstery. Vacuum socks demonstrated the highest relative recoveries of spores from carpet, but no statistically significant difference between the methods was determined.

Secondary information and data collected during the literature search from studies focused on evaluation of wipe and/or sponge-based BWA sampling methodologies (including composite sampling methodologies) include the following.

- Stainless steel, vinyl tile, and drywall were contaminated with *B. atrophaeus* spores. Cellulose sponges were used to collect wipe samples using one of three composite sampling approaches. A multiple medium/multiple pass composite sampling method resulted in the highest recovery of *Bacillus* spores [94].

- Two composite-based collection approaches using cellulose sponge samplers were evaluated for efficacy in recovery of *B. atrophaeus* (*B. anthracis* surrogate) spores from the surface of stainless steel (a CDC-defined method and a modified method) [95]. Results indicated that the composite sampling methods evaluated during the study can increase the number of surface area samples without increasing laboratory processing time, labor, or consumable materials. The results also suggest that the CDC method can be used with fewer passes over a single sampling location without compromising the efficiency of the method.

- Recovery of bovine serum albumin (BSA; used as a BWA surrogate) deposited via aerosol onto various materials (including glass, foliage, and sand) by wipe sampling (glass) or extraction (foliage and sand) was evaluated [96]. Results indicated that, for retrospective verification of BWA following a contamination incident, cleaner matrices and horizontal orientation of sampling surfaces provide optimal recoveries.

- As part of an effort to develop and evaluate a fluorescent viability assay (developed as an alternative to plate count methods to determine BWA), a swab and syringe/filter assay sampling approach was developed [97]. *B. globigii* spores were recovered via the swab/syringe/filter approach from glass with efficiencies between 80% and 90%.

3.6. Comprehensive Summary Tables

Table 4 provides a summary of techniques, technologies, and methodologies for decontamination and sampling of BWAs (including the target BWAs [or simulants of the target BWAs] indicated in Section 2.1.2) from the USCG vessel-relevant materials listed in Table 1 in Section 2.1.1.2, based on the information and secondary data collected during the literature search.

Table 4. BWA Decontamination and Sampling Summary (USCG Materials)

Vessels	Material	Information/ Data Area	*Bacillus anthracis* Ames	Ebola virus	Other BWAs [A]
25-foot RB-S, 29-foot RB-S II, 45-foot RB-M, 87-foot Patrol Boat	**Aluminum (hull)**	**Decontamination**	• MeBr fumigation [42] • Peracetic acid fog [32,42] • VHP [32,42] • Thermal decontamination [68,69] • Plasma [70]	NA	• pAB [50] • Citric acid [50] • Sanihol ST [50] • CONFLIKT [50] • PineSol [50] • Thermal decontamination [68,69] • Plasma [70]
		Sampling	NA	NA	
	Coated steel (hull)	**Decontamination**	• MeBr fumigation [42] • Gaseous ClO_2 [42] • Bleach, diluted bleach [49] • Peracetic acid, PES-Solid [60] • Simple Green [49] • Pipe-Klean [49]	NA	• VHP [41] • Gaseous ClO_2 [41] • Bleach, diluted bleach [49] • Simple Green [49] • Pipe-Klean [49] • Peracetic acid, PES-Solid [60]
		Sampling	NA	NA	NA
	Foam	**Decontamination**	NA	NA	NA
		Sampling	NA	NA	NA
	Non-skid coatings (decking)	**Decontamination**	• Thermal decontamination [68,69]	NA	• Thermal decontamination [68,69]
		Sampling	NA	NA	NA
	Glass	**Decontamination**	• Bleach, diluted bleach [72,54,58] • pAB [58] • VHP [36] • MeI fumigation [43] • Peracetic acid, PES-Solid [60] • Liquid ClO_2 [59] • Liquid H_2O_2 [72] • Ozone [29] • Wipes [66,67] • Dichloroisocyanurate [72] • Autoclave [72] • EtO [72] • UV [72] • Boiling water [72] • Spor-Klenz RTU [54] • Aldehydes [72,54] • Liquid ClO_2 [59] • Ozone [29] • Wipes [66,67]	• UV [62]	• Peracetic acid, PES-Solid [60] • pAB [50] • Citric acid [50] • Sanihol ST [50] • CONFLIKT [50] • PineSol [50]
		Sampling	• Sponge/swab [89,97] • Wipe sampling [96,89] • Vacuum [89] • BiSKit [89]	NA	NA
	Insulation, other bulkhead coverings	**Decontamination**	• Thermal decontamination [68,69]	NA	• Thermal decontamination [68,69]

Vessels	Material	Information/ Data Area	*Bacillus anthracis* Ames	Ebola virus	Other BWAs [A]
	Insulation, other bulkhead coverings Glazing materials	**Sampling**	NA	NA	NA
		Decontamination	NA	NA	NA
	Glazing materials Sensitive equipment and components	**Sampling**	NA	NA	NA
		Decontamination	• Thermal decontamination [68,69]	NA	• Thermal decontamination [68,69]
	Sensitive equipment and components	Sampling	NA	NA	NA
		Sampling	NA	NA	NA

NA – Not applicable; no related information or secondary data were collected during the literature search
[A] Non-target BWAs (according to Section 2.1.2), e.g., *Burkholderia pseudomallei*. Refer to reference provided.

Table 5 provides a summary of techniques, technologies, and methodologies identified during the search for decontamination and sampling of BWAs (including the target BWAs [or simulants of the target BWAs] indicated in Section 2.1.2) from various other materials (apart from the USCG vessel-relevant materials identified in Table 1 of Section 2.1.1.2).

Table 5. BWA Decontamination and Sampling Summary (Additional Materials)

Material	Decontamination			Sampling
Noncoated metals (excl. aluminum; e.g., stainless steel, galvanized metal, etc.)	• MeI fumigation [30] • Peracetic acid fog [31] • VHP [33,45,35,36,37,39] • Bleach, diluted bleach [72,48,49,52,55,57] • Peracetic acid, PES-Solid [55,60] • pAB [47,56] • Gaseous ClO_2 [37] • Aldehydes [72]	• Liquid ClO_2 [48,55] • Liquid H_2O_2 [72,53,55] • Wipes [66,67] • Peridox [47,56] • CASCAD SDF [47,52,53] • Dichloroisocyanurate [72] • Autoclave [72]	• EtO [72] • UV [72] • Boiling water [72] • Simple Green [49] • Pipe-Klean [49] • Virkon [52,53] • Spor-Klenz RTU [53]	• Sponge/swab [94,89,95] • Wipe sampling [89,93] • Vacuum [90,89] • Extraction [90] • BiSKit [89]
Tile (e.g., glazed ceramic, vinyl, acoustic ceiling, etc.)	• MeI fumigation [43] • MeBr fumigation [42] • VHP [41] • Bleach, diluted bleach [72] • Gaseous ClO_2 [41,42] • Liquid H_2O_2 [72] • Aldehydes [72]	• Reactive nanoparticles [71] • L-Gel [71] • UM Nanotech [71] • Sandia foam [71] • $Ca(ClO)_2$ with surfactant [71] • GD-5 [71]	• Ozone [71,29] • Dichloroisocyanurate [72] • Autoclave [72] • EtO [72] • UV [72] • Boiling water [72]	• Sponge/swab [94] • Robots [91,92]
Plastics (e.g., LDPE, HDPE, acrylic, laminate, etc.)	• MeBr fumigation [42] • Peracetic acid fog [32,42] • VHP [36] • Bleach, diluted bleach [72,48,49] • Peracetic acid, PES-Solid [60] • pAB [56] • Liquid ClO_2 [48]	• Thermal decontamination [68,69] • Liquid H_2O_2 [72] • Wipes [66,67] • Peridox [56] • Dichloroisocyanurate [72] • Autoclave [72] • Aldehydes [72]	• EtO [72] • UV [72] • Boiling water [72] • Simple Green [49] • Pipe-Klean [49] • Plasma [70]	• Sponge/swab [89] • Wipe sampling [89] • Vacuum [89] • Robots [91] • BiSKit [89]
Coated porous materials (e.g., drywall, concrete, wood, etc.)	• MeI fumigation [43] • Peracetic acid fog [31] • VHP [36,41] • Gaseous ClO_2 [41]	• Reactive nanoparticles [71] • L-Gel [71] • UM Nanotech [71] • Sandia foam [71]	• $Ca(ClO)_2$ with surfactant [71] • GD-5 [71] • Ozone [71] • Wipes [66,67]	• Sponge/swab [94]
Coated nonporous (e.g., coated metals excl. steel, CARC-coated aluminum, etc.)	• Peracetic acid, PES-Solid [60]	• Plasma [70]		NA

Material	Decontamination			Sampling
Noncoated porous materials (e.g., drywall, concrete, wood, etc.)	• MeI fumigation [43] • MeBr fumigation [42] • Peracetic acid fog [31,32] • VHP [36,41] • Bleach, diluted bleach [72,58] • pAB [47,50,58] • Gaseous ClO_2 [41,42] • Liquid H_2O_2 [72] • Reactive nanoparticles [71]	• L-Gel [71] • UM Nanotech [71] • Sandia foam [71] • $Ca(ClO)_2$ with surfactant [71] • GD-5 [71] • Ozone [71,29] • Peridox [47] • CASCAD SDF [47] • Dichloroisocyanurate [72]	• Autoclave [72] • EtO [72] • UV [72] • Boiling water [72] • Citric acid [50] • Sanihol ST [50] • CONFLIKT [50] • PineSol [50] • Spor-Klenz RTU [58]	• Sponge/swab [89] • Wipe sampling [89] • Vacuum [89,93] • Extraction [90] • Robots [92] • BiSKit [89]
Fabric	• Peracetic acid fog [32,42] • VHP [33] • Bleach, diluted bleach [72] • Liquid H_2O_2 [72] • Reactive Nanoparticles [71] • L-Gel 71	• UM Nanotech [71] • Sandia foam [71] • $Ca(ClO)_2$ with surfactant [71] • GD-5 [71] • Ozone [71] • Dichloroisocyanurate [72]	• Autoclave [72] • EtO [72] • UV [72] • Boiling water [72] • Plasma [70]	NA
Rubber	• MeBr fumigation [42]	• Peracetic acid fog [32,42]		NA
Carpet	• MeI fumigation [43] • MeBr fumigation [42] • Peracetic acid fog [31,32,42] • VHP [36,41] • pAB [50] • Gaseous ClO_2 [41]	• Reactive nanoparticles [71] • L-Gel [71] • UM Nanotech [71] • Sandia foam [71] • $Ca(ClO)_2$ with surfactant [71] • GD-5 [71]	• Ozone [71,29] • Citric acid [50] • Sanihol ST [50] • CONFLIKT [50] • PineSol [50]	• Robots [91] • Vacuum [93]
Developmental, reactor studies, data review, or similar	• MeI [8] • MeBr [8,43] • Peracetic acid fog [43] • VHP [74,73,38,46,8,43] • Bleach, diluted bleach [8]	• pAB [43] • Gaseous ClO_2 [8,43] • Liquid ClO_2 [8] • Thermal decontamination [8] • Liquid H_2O_2 [8]	• Ozone [8,43] • EtO [43] • UV [74,73,8] • Aldehydes [8,43]	NA
PPE materials	• Bleach, diluted bleach [72] • pAB [56] • Liquid H_2O_2 [72]	• Peridox [56] • Dichloroisocyanurate [72] • Autoclave [72]	• EtO [72] • UV [72,62] • Boiling water [72]	NA
Soil	• Sodium persulfate [28] • UV [63]	• MeBr [28]	• Metam Sodium [28]	• Extraction [89]
Sand, foliage, or similar	NA			• Wipe sampling [96]
Paper	• Bleach, diluted bleach [72] • Liquid H_2O_2 [72] • Ozone [29]	• Dichloroisocyanurate [72] • Autoclave [72] • EtO [72]	• UV [72] • Boiling water [72]	NA
Coatings	• MeBr fumigation [42] • VHP [42]	• Peracetic acid fog [32,42]	• Wipes [66,67]	NA
Biological indicators, agar plates	• VHP [34,35,40]	• UV [61,64,65]		NA

NA – Not applicable; no related information or secondary data were collected during the literature search

4. KNOWLEDGE/CAPABILITY GAP ASSESSMENT AND RESULTS

As described in Section 2.6, information/secondary data source summaries were collated into the source compilation document according to the content and primary research focus of the sources. This arrangement of the literature summaries in the source compilation document served to illustrate the distribution of the information and secondary data that were collected during the search across the research focus areas and support identification of gaps in information/secondary data related to methodologies, procedures, and technologies for decontamination and sampling of BWA contamination on USCG assets.

On 27 April 2020, project stakeholders from the USCG and the U.S. Department of Homeland Security (DHS) joined with the EPA and Battelle in a meeting to review and discuss the information and secondary data collected during the literature search and to identify data/information/capability gaps related to decontamination and sampling capabilities for BWA contamination on USCG assets. Prior to the discussion, EPA and Battelle provided expected attendees with the complete results of the literature search for review (specifically, the source compilation document was provided, which, as described in Section 2.6, included summaries of all secondary data and information sources collected during the literature search categorized by research focus). Meeting discussions focused on identification of knowledge/capability gaps related to the unique challenges imposed on BWA contamination response and management, decontamination, and sampling and analysis strategies due to USCG vessel operations and operational environments and/or vessel construction materials (based on the information/secondary data collected during the literature search).

The knowledge/capability gaps that were identified and discussed, as well as additional discussion topics, are provided in Sections 4. 1 and 4.2, respectively.

4.1. Knowledge/Capability Gaps

- Although outside the scope of the current work, data on efficacy of decontamination and sampling technologies and methodologies in/on other matrices (not just the select material surfaces) would be valuable.
    - This knowledge may be especially true for air and liquid matrices (i.e., seawater, bilge water, oil, lubricants, fluids, other vessel areas that may require liquid sampling, HVAC, and exhaust systems, etc.).
    - Liquid matrices can become contaminated during decontamination and/or sampling efforts, spread contamination or recontaminate surfaces, and/or cause further penetration into other contaminated materials, areas, and/or surfaces.
- While some data were collected, collection of additional data (and thorough evaluation of collected data) related to sampling porous materials would be valuable.
- The generally smaller amount of data related to decontamination and sampling of BWAs on coated steel that were collected is notable.

    - Some coated-steel-related BWA decontamination and material compatibility data source summaries were presented, but none were focused on evaluation/efficacy of sampling technologies or methodologies.
    - Likely more data have been generated, but such data may be For Official Use Only [FOUO] and/or unpublished.
- No data that appear to be related to BWA decontamination on bumper foam were collected.
    - The term "bumper foam" may have been too restrictive. A use of "elastomeric foam" or "thermoplastic polyurethane coating" may have been a better approach for the literature search.
    - Decontamination and/or sampling data related to bumper foam may have been collected, though the report/article/data source/etc. does not refer to the material as "bumper foam".
    - Need to consider what the bumper foam material is comprised of to determine if data related to BWA/CWA decontamination and/or sampling from the specific composition material(s) have already been collected.
        - Determined that the bumper foam material is comprised of a polyurethane fabric wrapped around a (rounded) interior foam.
    - Data related to decontamination and/or sampling of BWAs on other types of plastic and/or rubber may be applicable/translatable to bumper foam.
- Additional data on and consideration of the impacts to decontamination and/or sampling by fouling of/on a surface (i.e., salt/seawater, grime, etc.) would be valuable.
    - Need data related to realistic surfaces (most of the collected studies used clean [i.e., unused, pristine] materials/surfaces).
    - A few search terms were included to attempt to collect some data related to fouling/foulants, and some data related to BWA decontamination and sampling in the presence of heavy/light organic load were collected [52], but more emphasis should be placed on this topic/focus.
    - Sea/saltwater was discussed as an "interferent" and/or "foulant" impacting decontamination and sampling efficacy. Other specific foulants of interest should be identified.
- Additional data on and consideration of the impacts to decontamination and/or sampling of environmental conditions (temperature, relative humidity) would be valuable
    - Outdoor weather conditions cannot be controlled and may impact decontamination processes.
- In addition to vessels, an area of focus to consider would be areas/locations within USCG bases or stations (and the specific/associated construction materials) that are more susceptible to frequent contamination and/or recontamination/cross-contamination.

- Analogous to subway trains/stations.
    - Surfaces/items that are frequently touched/interacted with.
- Additional data/information related to compatibility of hot/humid air decontamination with the materials of interest would be valuable.
    - Reports/articles on studies performed by other government agencies on efficacy of hot/humid air decontamination of CWAs may also include data/information on compatibility of the tested materials with the decontamination process.
    - It was discussed that studies have been conducted/data have been generated related to the operability of C130 aircraft after hot/humid air decontamination.
- Other characteristics of BWA decontamination and sampling technologies and approaches must be considered also, beyond just efficacy of the technologies/approaches. Such considerations include "scale-up" requirements (for larger areas and/or multiple assets/vessels, etc.), supply-chain, availability limitations, surge capacities, etc.
- With regard to sampling, clearly defined direction and/or a guiding framework for utilization of sampling results is necessary (e.g., sampling results inform and drive decisions for phase-based contamination response, management, and decontamination strategies). Alongside this is the need for tools, strategies, and/or guidance for the development of sampling and analysis plans based on the circumstances, characteristics, and demands specific to an incident (e.g., location, setting, politics, response phase, unknowns, etc.).
- Although outside of scope for this effort, data related to decontamination and sampling of BWAs on soil and vegetation (foliage, grass, etc.) would be valuable.

4.2. Additional Information, Discussion, and Notes

- Scientific articles, reports, guidance documents, etc. that are publicly available from/through the Defense Technical Information Center (DTIC) were collected and summarized during the literature search and included in the source compilation document. Anything not publicly available from/through DTIC (i.e., classified, controlled, limited distribution, etc.) was not collected or included.
- Quality of the scientific articles, reports, guidance documents, etc. collected during the literature search was assessed both qualitatively through use of source document type designations (refer to Section 2.4.1) and quantitatively through use of the Literature Assessment Factor Rating (refer to Section 2.4.2).
- The absence of data in the open literature related to decontamination and/or sampling of a specific contaminant on the surface of a particular material does not necessarily indicate that such knowledge/data/capabilities do not exist. Similarly, the presence/existence of data related to decontamination and sampling of specific contaminants on specific materials in the literature does not indicate that the decontamination and/or sampling technologies/methodologies are efficacious.

- Although there do appear to be gaps in the data/information that were collected and/or that exist related to decontamination and sampling of BWAs on the specified USCG materials, sampling plans and future research can be directed at filling these gaps.
- In addition to specific technologies for decontamination and sampling of BWAs, the methods/procedures for use/application of technologies must be considered (i.e., decontamination and sampling tactics/strategies in addition to technologies).

4.3. Gap Table

The knowledge/capability gaps described in Section 4.1 and the additional information, discussion topics, and notes described in Section 4.2 are summarized in Table 6.

Table 6. Gap Table

	Knowledge/Capability Gaps	Additional Information, Discussion, Notes
Decontamination	• Data on efficacy of decontamination approaches in/on other matrices (besides the target USCG vessel-related materials). • Limited data were collected related to decontamination of BWAs on coated steel. • No data were collected related to decontamination of BWAs on bumper foam. • Additional data on the impacts of foulants and (outdoor) environmental conditions on the efficacy of decontamination technologies/approaches would be valuable. • In addition to vessels, consider areas/locations within USCG bases or stations that are susceptible to contamination. • Additional data on the efficacy of hot, humid air decontamination would be valuable. • Consider other characteristics of BWA decontamination technologies/approaches (e.g., "scale-up" requirements, supply-chain, availability, surge capacities, etc.). • Data related to decontamination of BWAs on soil and/or vegetation would be valuable.	• Literature and data publicly available through DTIC were collected. Anything not publicly available through DTIC was not collected. • Literature and data source quality was assessed both qualitatively and quantitatively (refer to Section 2.4). • The absence of data in the open literature related to decontamination of BWA on a particular material does not necessarily indicate that such knowledge/capability does not exist. Similarly, the presence/existence of such data does not indicate that the described decontamination technology/method is efficacious. • Future research can be directed at filling the knowledge/capability gaps identified during this effort. • In addition to specific technologies for decontamination of BWA, methods/procedures for use/application of decontaminants must be considered.

	Knowledge/Capability Gaps	Additional Information, Discussion, Notes
Sampling	• Data on efficacy of sampling approaches in/on other matrices (besides the target USCG vessel-related materials). • Need additional data related to sampling from porous materials. • Limited data were collected related to sampling of BWAs on coated steel. • No data were collected related to sampling of BWAs on bumper foam. • Additional data on the impacts of foulants on the efficacy of sampling technologies/approaches would be valuable. • In addition to vessels, consider areas/locations within USCG bases or stations that are susceptible to contamination. • Consider other characteristics of BWA sampling technologies/approaches (e.g., "scale-up" requirements, supply-chain, availability, surge capacities, etc.). • Clearly defined direction and/or a guiding framework for utilization of sampling results is necessary. • Data related to sampling of BWAs on soil and/or vegetation would be valuable.	• Literature and data publicly available through DTIC were collected. Anything not publicly available through DTIC was not collected. • Literature and data source quality was assessed both qualitatively and quantitatively (refer to Section 2.4). • The absence of data in the open literature related to sampling of BWA on a particular material does not necessarily indicate that such knowledge/capability does not exist. Similarly, the presence/existence of such data does not indicate that the described sampling technology/method is efficacious. • Future research can be directed at filling the knowledge/capability gaps identified during this effort. • In addition to specific technologies for BWA sampling, methods/procedures for use/application of sampling technologies must be considered.

5. REFERENCES

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