Review of Thermal Destruction Technologies for Chemical and Biological Agents Bound on Materials
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U.S. Environmental Protection Agency (EPA)
Office of Research and Development (ORD)
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DISCLAIMER

The United States Environmental Protection Agency through its Office of Research and Development managed the research described here under Contract No. EP-C-11-038, Task Order Number 0020 to Battelle. It has been subjected to the Agency’s review and has been approved for publication. Note that approval does not signify that the contents necessarily reflect the views of the Agency. Mention of trade names, products, or services does not convey official EPA approval, endorsement, or recommendation.
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<thead>
<tr>
<th>ACF</th>
<th>activated carbon fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANOVA</td>
<td>analysis of variance</td>
</tr>
<tr>
<td>APD</td>
<td>atmospheric plasma decontamination</td>
</tr>
<tr>
<td>APPJ</td>
<td>Atmospheric Pressure Plasma Jet</td>
</tr>
<tr>
<td>Ba</td>
<td><em>Bacillus anthracis</em></td>
</tr>
<tr>
<td>BDR</td>
<td>building decontamination residue</td>
</tr>
<tr>
<td>Bg</td>
<td><em>Bacillus globigii</em></td>
</tr>
<tr>
<td>BI</td>
<td>biological indicator</td>
</tr>
<tr>
<td>bp</td>
<td>boiling point</td>
</tr>
<tr>
<td>BWA</td>
<td>biological warfare agent</td>
</tr>
<tr>
<td>BW</td>
<td>biological weapon</td>
</tr>
<tr>
<td>CAA</td>
<td>Clean Air Act</td>
</tr>
<tr>
<td>CARC</td>
<td>chemical agent resistant coating</td>
</tr>
<tr>
<td>CAM</td>
<td>chemical agent monitor</td>
</tr>
<tr>
<td>CB</td>
<td>chemical or biological</td>
</tr>
<tr>
<td>CP</td>
<td>chlorobenzene</td>
</tr>
<tr>
<td>CBR</td>
<td>chemical, biological or radiological</td>
</tr>
<tr>
<td>CBRNIAC</td>
<td>Chemical, Biological, Radiological and Nuclear Information Analysis Center</td>
</tr>
<tr>
<td>CFD</td>
<td>computational fluid dynamics</td>
</tr>
<tr>
<td>CFS</td>
<td>configured fireside simulator</td>
</tr>
<tr>
<td>CFU</td>
<td>colony forming unit(s)</td>
</tr>
<tr>
<td>CI</td>
<td>confidence interval</td>
</tr>
<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>COM</td>
<td>commercial hazardous waste burning rotary kiln</td>
</tr>
<tr>
<td>CP</td>
<td>chlorophenol</td>
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<tr>
<td>CWA</td>
<td>chemical warfare agent</td>
</tr>
<tr>
<td>CWC</td>
<td>Chemical Weapons Convention</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>D/F</td>
<td>dioxin/furan</td>
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<tr>
<td>DES</td>
<td>diethyl sulfide</td>
</tr>
<tr>
<td>DFP</td>
<td>diisopropyl fluorophosphate</td>
</tr>
<tr>
<td>DFS</td>
<td>deactivation furnace system</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>DIMP</td>
<td>diisopropyl methylphosphonate</td>
</tr>
<tr>
<td>DMMP</td>
<td>dimethyl methylphosphonate</td>
</tr>
<tr>
<td>DMOR</td>
<td>Disaster Mortuary Operational Response (Team)</td>
</tr>
<tr>
<td>DNA</td>
<td>deoxyribonucleic acid</td>
</tr>
<tr>
<td>DoD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>DTIC</td>
<td>Defense Technical Information Center</td>
</tr>
<tr>
<td>DTP</td>
<td>3,3-dithiopropanol</td>
</tr>
<tr>
<td>DRE</td>
<td>destruction and removal efficiency</td>
</tr>
<tr>
<td>DSA</td>
<td>drop shape analysis</td>
</tr>
<tr>
<td>DST</td>
<td>decision support tool</td>
</tr>
<tr>
<td>ECDAP</td>
<td>enhanced corona discharge at atmospheric pressure</td>
</tr>
<tr>
<td>EPA</td>
<td>U.S. Environmental Protection Agency</td>
</tr>
<tr>
<td>FTCMR</td>
<td>flow-through catalytic membrane reactor</td>
</tr>
<tr>
<td>GA</td>
<td>tabun</td>
</tr>
<tr>
<td>GB</td>
<td>sarin</td>
</tr>
<tr>
<td>GC/MS</td>
<td>gas chromatograph/mass spectrometry</td>
</tr>
<tr>
<td>GD</td>
<td>soman</td>
</tr>
<tr>
<td>GDAP</td>
<td>glow discharge at atmospheric pressure</td>
</tr>
<tr>
<td>GE</td>
<td>ethyl sarin</td>
</tr>
<tr>
<td>GF</td>
<td>cyclosarin</td>
</tr>
<tr>
<td>GH</td>
<td>O-isopentyl sarin</td>
</tr>
<tr>
<td>GS</td>
<td>S-butyl sarin</td>
</tr>
<tr>
<td>Gs</td>
<td><em>G. stearothermophilus</em></td>
</tr>
<tr>
<td>HAP</td>
<td>hazardous air pollutant</td>
</tr>
<tr>
<td>HCl</td>
<td>hydrogen chloride</td>
</tr>
<tr>
<td>HCWA</td>
<td>hydrolysates of chemical warfare agents</td>
</tr>
<tr>
<td>HD</td>
<td>sulfur mustard</td>
</tr>
<tr>
<td>HDIAC</td>
<td>Homeland Defense and Security Information Analysis Center</td>
</tr>
<tr>
<td>HEPA</td>
<td>high efficiency particulate arrestance</td>
</tr>
<tr>
<td>HF</td>
<td>hydrogen fluoride</td>
</tr>
<tr>
<td>HRT</td>
<td>hydraulic retention time</td>
</tr>
<tr>
<td>HVAC</td>
<td>heating, ventilating and air conditioning</td>
</tr>
<tr>
<td>HWC</td>
<td>hazardous waste combustor</td>
</tr>
</tbody>
</table>
HWI  hazardous waste incinerator
ICB  immobilized cell bioreactor
IPE  individual protective equipment
IZAYDAS  Izmit Hazardous and Clinical Waste Incinerator
JACADS  Johnson Atoll Chemical Agent Disposal System
kW  kilowatt
LANL  Los Alamos National Laboratory
LIC  liquid incinerator
LVOH  low volatility organohalogen (compound)
MACT  maximum achievable control technology
MEDPATH  medical/pathological waste incinerator
MOPP  mission-oriented protective posture
mp  melting point
MPA  methylphosphonic acid
MPF  metals parts furnace
MPT  microwave plasma torch
MW  megawatt
MWI  medical waste incinerator
MWC  municipal waste combustor
NHSRC  National Homeland Security Research Center
NIEHS  National Institutes of Environmental Health Sciences
NTIS  National Technical Information Service
OAUGDP  one atmosphere uniform glow discharge plasma
OPC  organophosphorus compound
PAN  polyacrylonitrile
PCAPP  Pueblo Chemical Agent-Destruction Pilot Plant
PCB  polychlorinated biphenyl
PCDD  polychlorinated dibenzo-\(p\)-dioxin
PCDF  polychlorinated dibenzofuran
PIC  product of incomplete combustion
PNPDPP  \(para\)-nitrophenyl diphenylphosphate
POHC  principal organic hazardous constituent
ppm  part(s) per million
PWC  plasma waste converter
QA  Quality Assurance
QAPP  Quality Assurance Project Plan
RF  radio frequency
RHELP  regenerative high efficiency low pressure
RKIS  rotary kiln incinerator simulator
rms  root mean square
RNA  ribonucleic acid
ROS  reactive oxygen species
SCC  secondary combustion chamber
SCWO  supercritical water oxidation
SCW  supercritical water
SEM  scanning electron microscope
SO$_2$  sulfur dioxide
SRT  sludge retention time
STAATT  State Territorial Association Alternative Treatment Technologies
STO  stoker furnace
TD  thermal desorption
TDG  thiodiglycol
TEM  transmission electron micrography
TEQ  toxicity equivalent quantity
TOCDF  Tooele Chemical (Agent) Disposal Facility
TPAC  transduction-polymer and an acceptor-chromophore
TSDF  treatment, storage, or disposal facility
TTU  Texas Tech University
TX  1,4-thioxane
UK  United Kingdom
VOC  volatile organic compound
VR  Russian VX
VX  nerve agent
VXH  VX hydrolysate
W  watt
WMD  weapon of mass destruction
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Wood, Joseph  EPA NHSRC

Outside Organizations
Reaction Engineering International (REI)

Contractors
Battelle Memorial Institute

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ABSTRACT

There is interest in identifying appropriate operating conditions to assure that thermal destruction processes would result in complete destruction of any residual Chemical or Biological (CB) agents bound on materials removed from contaminated sites. Compiling these operating conditions, along with data on their efficacy, would greatly facilitate the management of waste generated during cleanup following a CB contamination incident.

This review report gathered available information on the thermal destruction of CB agents bound on solid materials. This review used information extracted from secondary data sources including government reports, publications in the open literature, peer-reviewed journal articles, and both published and non-published literature, including distribution limited reports. The literature search included searches in the Dialog database, Google Scholar™, and active identification of EPA research reports that were in varying stages of completion. Thermal processes reviewed in this report include incineration, thermal plasma systems, microwave irradiation, autoclaving, landfill flaring, exothermic intermetallic interaction, and direct heat application. A description of the materials tested and operating conditions such as exposure times, temperatures, and plasma flow rates and the corresponding CB reductions are included. A summary table of the operating conditions and results from the thermal processes and hydrolysate treatment discussed in this review are presented in Appendix A. In addition, a review of the containment of aerosols and emissions from the incineration of CB material is also discussed. The results of modeling of the designs of several incinerators burning CB materials are also presented in this report.

The treatment of hydrolysate wastewater from neutralization of chemical agents with supercritical water oxidation, incineration, and biological treatment are also discussed. The test conditions, contact times, concentrations of chemicals and destruction efficiencies are included.

This review also discusses the available literature on the cremation of human remains after CB contamination incidents. Specifically, literature protocols on the cremation of contaminated human remains, including the required temperature and time, are discussed.
This report reviewed literature on the destruction of CB agents and surrogates bound on various materials such as ceiling tiles, wallboard, carpet, fiberglass, aluminum, concrete, pumice, stone, wood, stainless steel, laminate, asphalt, brick, and others.

The studies showed that CB agents bound on porous materials such as ceiling tiles and carpet bundles may require more exposure time to destroy CB agents than the CB agents bound on nonporous materials. Furthermore, wet porous materials required more exposure time than dry porous materials due to the large amount of water they can hold that must be boiled off prior to heating the material beyond the boiling point of water. For example, Wood et al. (2006) reported that at 800 °C, dry ceiling tiles achieved 6 log₁₀ reduction in spores after 12 minutes for an anthrax surrogate, but up to 38 minutes was required for complete reduction with wet ceiling tiles. Farrar et al. (2000) reported only partial destruction for the biological agent surrogate \textit{B. stearothermophilus} on a pumice block using a steam plasma torch (4,500 °F, up to 2 ft/s at a distance of 1 inch from the exit plane) whereas 99.94% destruction was achieved on fiberglass using the same test conditions.
1 INTRODUCTION

This section discusses the project background, sources of secondary data used to compile this report, the Quality Assurance (QA) of the references, and a background of Chemical or Biological (CB) agents.

1.1 Project Background

EPA is designated as a coordinating Agency, under the National Response Framework, to prepare for, respond to, and recover from a threat to public health, welfare, or the environment caused by actual or potential oil and hazardous materials incidents. Hazardous materials include chemical, biological, and radiological substances, whether accidentally or intentionally released.

Many items removed from contaminated areas either before or after contamination may be treated using incineration or thermal destruction. Whether or not these items have undergone decontamination operations, due to limitations in laboratory capacity, these items may or may not be fully characterized with respect to the presence/absence of residual CB agents. Because of this limitation, identifying packaging and incinerator or thermal destructor operating conditions to assure that thermal destruction processes would result in complete destruction of any residual CB agent bound on these items will greatly facilitate the management of the waste generated during cleanup of a CB contamination incident.

This review report gathered available information on the thermal destruction of CB agents bound on solid materials such as building materials. Results from this review will help address an identified gap related to defining conditions under which effective thermal destruction can be performed on solid materials resulting from cleanup following a CB contamination incident. Thermal processes discussed include incineration, plasma systems, microwave irradiation, autoclaving, landfill gas flaring, exothermic intermetallic interaction, and direct heat application. The containment of aerosols and emissions from the incineration of CB material is also discussed.

Neutralization and hydrolysis of chemical agents is discussed in this review. The treatment of hydrolysate wastewater from neutralization of chemical agents by supercritical water oxidation, incineration, and biological treatment is also discussed.
This review also discusses the available literature on the cremation of human remains after CB contamination incidents. Although the disposition of human remains is not part of EPA’s mission in the CB response area, the environmental consequences of the disposition of those remains are part of EPA’s mission to protect public health and the environment.

In addition, incineration models were conducted using EPA’s Configured Fireside Simulator (CFS) tool for four CB agents (\textit{Bacillus anthracis} [\textit{Ba}], sarin [\textit{GB}], VX, and mustard [\textit{HD}]) and three design types of furnaces (a commercial hazardous waste-burning rotary kiln, a medical/pathological waste incinerator, and a stoker incinerator). The results from the incinerator models are presented in this report.

Chemical (\textbullet) and biological (\textbullet) icons are included in the headings of each section to represent the type of contaminant discussed in the section.

1.2 Quality Assurance for Sources of Secondary Data

This review used information extracted from secondary data sources including government reports, publications in the open literature, peer-reviewed journal articles, and both published and non-published literature, including limited distribution reports. Secondary data are defined as existing data (also termed non-direct measurements) that were not developed originally through the project to which they are being applied. Applicable secondary data were sought from the various sources of scientific literature. The literature search included searches in the Dialog database, including Energy Science & Technology (formerly DOE ENERGY) and the National Technical Information Service (NTIS), the Homeland Defense and Security Information Analysis Center (HDIAC) managed by the Defense Technical Information Center (DTIC) [formerly the Chemical, Biological, Radiological and Nuclear Information Analysis Center (CBRNIAC)], Google Scholar™, and active identification of U.S. Environmental Protection Agency (EPA) research reports that are in varying stages of completion. Battelle presented EPA with the search criteria prior to embarking on the literature search.

The literature review not only identified but also assessed the secondary data for intended use(s). After the literature searches were conducted and the results subsequently reviewed, the quality of
the secondary data was examined against the overall needs of the Task Order (TO). The quality of identified sources of secondary data was evaluated through a literature assessment factor rating. Based on the numerical rating factor score of each source of secondary data, collected information was deemed either appropriate or inappropriate for inclusion in the results. Results are listed in the Excel® spreadsheet grouped by relevance (as determined by the rating factor) to assist with the selection criteria for quality documents (presented in Appendix B). Articles and reports were also assessed qualitatively according to document type and documented in the Excel® spreadsheet. Each report or article referenced in the Excel® spreadsheet was identified with the appropriate document type designation. Knowledge of the document type will help EPA (or other readers/reviewers identified by EPA over the course of the TO) in understanding the range of documents obtained.

All secondary data and source information compiled underwent an independent review (at least 10% of all secondary data mined from the literature) with regard to transcriptional accuracy in the Excel® summary table (presented in Appendix B) by Battelle’s Quality Assurance (QA) Manager. This review was conducted for initial transcription of data from the secondary data source and for each point of data transfer in process, including use of the data in the final literature review report. This review confirmed that the populated literature search included relevant information on thermal destruction of CB agents bound on different types of materials, for which the sources of information are credible, and that proper information is included in the correct categories. This review also ensured that the correct source of the data is maintained throughout all processes using the data.

1.3 Background of Chemical and Biological Agents

Chemical warfare agents (CWAs) fall into three main classes: vesicants (e.g., sulfur mustards (HD), nitrogen mustards (HN₃)), blood agents (e.g., hydrogen cyanide), and organophosphorus nerve agents (acetylcholinesterase inhibitors) of the G-type (tabun [GA], GB, soman [GD], ethyl sarin [GE], cyclosarin [GF], S-butyl sarin [GS], O-isopentyl sarin [GH]) and V (VX, VE, VG, VM). Biological warfare agents (BWAs) can be classified into at least five categories: viruses, bacteria (spore-formers and vegetative bacteria), rickettsia, biological toxins, and genetically engineered agents (Giletto et al., 2003). The physical properties of VX, mustard, and sarin are presented in Table 2-1.
Agents that are liquids at room temperature with high boiling points and low vapor pressures such as HD and VX are classified as persistent agents that generally manifest themselves as contact poisons. A persistent agent could pose long-term cutaneous and ingestion hazards, along with an inhalation hazard upon slow evaporation. GB is not typically considered to be a persistent agent, especially compared to HD and VX. HD would be difficult to remove through water washing because of its insolubility, and VX may be difficult to remove with evaporation or dispersion because of its high boiling point and low vapor pressure. All of these chemical agents interact with materials that alter the fate and transport of the contaminant. An agent can be absorbed into porous materials and drawn by capillary action into material seams and crevices. Adsorption and infiltration of an agent may result in degradation of materials and can lead to unexpected persistence of the agent, even after measures have been taken to decontaminate (Hoette et al., 2010).

Bacterial endospores (e.g., B. anthracis) can survive in the environment for an extended period of time and are resistant to a wide variety of treatments such as heat, desiccation, radiation, pressure and chemicals. This resistance is the result of various factors such as the thick proteinaceous spore coat, low water content in the spore core, and the a/b-type small, acid-soluble spore proteins (Rogers, 2005).

Most CB agents can be destroyed or rendered harmless by suitable chemical treatments (Giletto et al., 2003). There is no single technology that will be applicable in all situations and to all types of contamination because the nature and extent of the contamination is different at different places (Kumar et al., 2010). The optimal decontamination technology for a given application generally depends on the material that is potentially contaminated. For instance, the optimal technology for decontaminating wastewater may differ from the optimal technology for decontaminating building materials (Wilhelmi et al., 2003).
Table 2-1. Chemical Agent Structure and Physical Properties

<table>
<thead>
<tr>
<th>Name</th>
<th>Code</th>
<th>Type</th>
<th>Physical State (at 25°C)</th>
<th>Vapor Pressure (mm Hg at 20°C)</th>
<th>Water Solubility (g/100 g Soln.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VX</td>
<td>VX</td>
<td>Nerve</td>
<td>liquid, mp: 39 °C, bp: 298 °C</td>
<td>0.0007</td>
<td>3.0 (at 25 °C)</td>
</tr>
<tr>
<td>Mustard</td>
<td>HD</td>
<td>Blister</td>
<td>liquid, mp: 14.5 °C, bp: 218 °C</td>
<td>0.0072</td>
<td>0.92 (at 22 °C), limited</td>
</tr>
<tr>
<td>Sarin</td>
<td>GB</td>
<td>Nerve</td>
<td>liquid, mp: -56 °C, bp: 158 °C</td>
<td>2.1</td>
<td>miscible</td>
</tr>
</tbody>
</table>

(Hoette et al., 2010, Sandia Report); mp: melting point; bp: boiling point.

The materials to be thermally treated may be primarily concrete or metal if CB agents are released in urban areas, although there may be large quantities of other materials as well. Concrete materials include walls, floors, ceilings, bio-shields, and fuel pools. Metallic materials include structural steel, valves, pipes, glove boxes, reactors, and other equipment. Porous materials such as concrete can be contaminated throughout their structure, although contamination in concrete normally resides in the top quarter-inch below the surface. Metals are normally only contaminated on the surface (Kumar et al., 2010). There may be varying amounts of porous materials that make up a building’s contents. Further, more porous materials like ceiling tiles are much harder to decontaminate effectively than less porous materials (Wilhelmi et al., 2003).

Non-thermal processes to destroy CB agents bound on materials are prevalent in literature, and frequently the residuals resulting from application of these technologies may undergo thermal treatment as part of the waste management process. Decontamination efficiency depends on various factors: not only the characteristics of the agent, but also the weather conditions, the bio-load on the material, and the type of material that is contaminated. Smooth surfaces painted with chemical agent resistant coating (CARC) are relatively easy to clean with an effective decontaminant, whereas the same decontaminant may not be able to clean more complex structures with cracks or crevices or absorbing materials such as rubber sufficiently (Boone, 2007).
The appropriate decontamination strategy also depends on the size of the contaminated area. If a chemical or biological agent exists only in a small area (e.g., within one room), then spot decontamination methods may be appropriate; however, spot decontamination is not feasible for contamination over broad areas. The extent of the contaminated area may also affect the decision on whether to conduct decontamination activities on site or at a remote location (Wilhelmi et al., 2003).

Lemieux described I-WASTE, a web-based decision support tool (DST) developed by EPA to assist decision makers through the process of planning the disposal of residual contaminated materials. The web tool allows the user to create a decision scenario with the following input parameters: incident location, type of waste material, waste quantity estimation, contaminant/decontaminant selection, treatment specifications (including incinerators, landfills, and wastewater treatment), and transportation plan (Lemieux et al., 2006b).

A universal formulation that can decontaminate all CB threats is not available. Existing decontamination solutions are effective only against a certain class of agents. To be effective, emergency response personnel would need several types of decontaminants available on hand. For complicated treatment technologies, there will be less people available to operate them. Use of existing decontaminants under inappropriate conditions can result in the formation of dangerous by-products. The formation of these by-products may complicate a waste management facility’s willingness to accept the waste. Furthermore, some chemicals such as sodium hydroxide dissolved in organic solvents are unsuitable for use under certain conditions because they corrode, etch or erode materials (Giletto et al., 2003).

Current military decontamination techniques aimed at CW agents are corrosive and can cause collateral damage to facilities and equipment. The military requires fast action (30 min or less), whereas decontamination times on the order of several hours may be sufficient for the civilian sector. Rather than speed, considerations that are more important in a civilian scenario include availability of a reagent, low maintenance, ease of application, minimal training for application, easy deployment by a variety of dispersal mechanisms and acceptable expense (Raber et al., 2002).
2 THERMAL TECHNOLOGIES FOR THE DESTRUCTION OF CHEMICAL AND BIOLOGICAL AGENTS BOUND ON MATERIAL SURFACES

This section presents a review of the following thermal processes for the destruction of CB agents bound on material surfaces: incineration/combustion, plasma systems, microwave irradiation, autoclave, landfill flare, flame mechanisms, exothermic intermetallic interactions, and direct heat sterilization.

2.1 Incineration/Combustion

This sub-section reviews the literature on the incineration of CB agents, including processes such as chemical weapons demilitarization including metals parts furnaces (MPFs), and liquid incinerators (LICs) and processes using hazardous waste combustors (HWCs), municipal waste combustors (MWCs), and medical waste incinerators (MWIs). In addition, the literature on containment of emissions and aerosols from the incineration of CB agents is discussed.

Overall, there is a dearth of information in the literature on the destruction of CB agents at MWCs and MWIs. The majority of the literature on the destruction of CB agents using incineration involves the use of hazardous waste combustors in specially designed chemical demilitarization facilities. Literature on the neutralization of stockpiled munitions and subsequent secondary treatment by an HWC is also prevalent.

Incineration is an inherently attractive approach for destruction of organic compounds since the carbon and hydrogen in the organic compound produce carbon dioxide and water when burned in the presence of oxygen. Chemical warfare agents are combustible and therefore lend themselves to destruction by incineration. The incineration products are far less toxic than the original chemical warfare agents. In principle, incineration is an environmentally safe method of toxic waste treatment provided that the temperature and residence time used are sufficient to decompose the organic chemical to simple inorganic chemicals (Pearson and Magee, 2002) and that the downstream flue gas cleaning equipment is sufficient to remove particulate matter and acid gases and all other air pollutants from the stack gases that are emitted into the atmosphere.
2.2 Hazardous Waste Combustors

Fixed hearth and rotary kiln incinerators are the most likely candidates to manage wastes containing biological and chemical agents. Advantages of using these HWCs include the fact that regulations already require these incinerators to have waste tracking mechanisms, appropriate emission controls, and employee safety training programs. Possible disadvantages include the location of most HWCs in relatively remote areas, the limited capacities of HWCs, and size limitations. Some sizes of rotary kiln HWCs can process between 50 and 175 tons of hazardous waste per day. Typically, the sizing for the feed stream to allow entry into the combustor is the rough dimensions of a 55-gallon drum (Wilhelmi et al., 2003).

The afterburner is a critical part of the incineration system as it uses an auxiliary fuel such as natural gas, propane, or fuel oil to ensure that temperatures in excess of 1,090 °C and gas-phase residence times of 2 seconds or greater are achieved to ensure that any residual agent or products of incomplete combustion are destroyed.

Spent decontamination fluids may also be injected into either the primary chamber or the afterburner to destroy any residual agent in such fluids as well as to facilitate the evaporation and discharge of the water vapor. This decontamination fluid also contains salts, which are deposited in the bottom of the primary chamber or afterburner (Pearson and Magee, 2002).

Lemieux et al. (2010) reported on the potential difficulties that exist in thermally processing waste building materials from a post-CWA event site remediation due to the refractory nature of many materials found inside and outside buildings and the potential impact that waste packaging at the site may have on the behavior of these materials and residual agent destruction in combustion systems. Although CWAs are not particularly thermally stable and are readily destroyed at typical incineration temperatures (greater than 800 °C), relatively short gas-phase residence times (greater than 2 s) and solid-phase residence times (greater than 30 min) make it possible for some of the residual agent to escape the incinerator due to bypassing the flame zones, cold spots within the waste, and incomplete penetration of heat through the combustion bed. Complete destruction of building material-bound CWAs can be achieved once the core temperature of the building materials exceeds 300 °C. However, significant time may elapse between the introduction of the material into the incinerator and the time at which the core of the
material bundles approaches equilibrium with the gas temperatures (Lemieux et al., 2010). Due to the refractory nature of some building materials such as ceiling tile, particularly if wetted, the material will remain at the boiling point of water (100 °C) until all the water has been driven off.

Lemieux et al. (2010) conducted a study to examine the thermal decomposition of a surrogate CWA (Malathion) in a laboratory reactor using heating rates similar to those found in a rotary kiln incinerator processing building materials. The experiments were performed in small constant-volume reactor vessels on the bench scale. The CWA simulant was carefully dispensed into a stainless steel pipe through a Swagelok fitting using a syringe. The initial Malathion concentration was 300,000 μg/L. The chamber was then placed into an oven, and the temperature was ramped up to 400 °C at a set rate (5 or 10 °C/min), then maintained at that temperature for 30 minutes. The Malathion concentration averaged 911 µg/L after removal from the reactor at the following test conditions, 175 °C after 30 minutes of exposure. The experiments were performed using heating rates typical of the rates found inside bundles of building materials in a pilot-scale hazardous waste incineration system and fit to a first-order Arrhenius expression. An analysis of the results was done using reactor design theory. Subsequently a scale-up of the results to a computer simulation of a full-scale commercial hazardous waste incinerator processing Malathion-contaminated ceiling tile was performed (Lemieux et al., 2010).

The decontamination of a building following release of a biological warfare agent (such as B. anthracis) may result in a significant quantity of building decontamination residue (BDR) consisting of non-structural components of the building (e.g., ceiling tile, carpet) and building contents. Wood et al. (2006) described experiments that were performed in a pilot-scale rotary kiln incinerator to evaluate the thermal destruction of B. anthracis surrogates (Geobacillus stearothermophilus bacterial spores) present within bundles of carpeting and ceiling tile. No spores were detected in the exhaust gas via any of the three sampling trains for the carpet burn tests. For all of the tests, average kiln exit temperatures prior to the feeding of the carpet ranged from approximately 804 to 827 °C (1,480 to 1,520 °F). For the dry ceiling tile bundles, a 1 to 2 log₁₀ reduction in the number of spores occurred sometime between 5 to 10 minutes, and complete destruction (6 log₁₀ reduction) occurred after 12 minutes. The log reduction in the number of spores is described by Equation 1.
Log Reduction = log(N/N’) \hspace{1cm} \text{(Equation 1)}

where N is the mean number of viable organisms recovered from the control and N’ is the number of viable organisms recovered from each test after decontamination (Rogers et al., 2005).

For the wet ceiling tile bundles, although the results were somewhat variable, reduction in spores (from a 1-2 log_{10} reduction up to complete destruction) occurred between 35 to 38 minutes. Figure 2-1 shows the spore survival as a function of time for wet and dry bundles in the kiln (Wood et al., 2006).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure2-1.png}
\caption{Ceiling Tile Bundle Spore Survival as a Function of Time in Kiln (Adapted with permission from Wood et al., 2006)}
\end{figure}

Lemieux et al. performed bench-scale tests on building materials. The building materials included carpet, ceiling tile, and wallboard. The ceiling tiles were Class A, standard-white, fire-retardant, texture-faced ceiling tiles composed of wood fiber (0 - 60%) and fibrous glass (0 - 13%). New drywall was used for these tests, which consisted of a gypsum core wrapped with a paper lining. The carpet was nylon 6-6 carpeting acquired directly from the manufacturer. The materials were cut into sample sizes measuring 7.62 x 3.81 cm, weighed, individually wrapped in aluminum foil and steam-sterilized by autoclaving. The sterile samples were inoculated with either 1.0 mL of a solution containing \textit{Bacillus subtilis} spores for a final concentration of 10^8
spores/mL or 1.0 mL of a solution containing *G. stearothermophilus* spores for a final concentration of 10 spores/mL. In the thermal destruction experiments, the BDR samples were heated in a quartz reactor operating at 150, 200, 250, and 315 °C for various time intervals. Total spore destruction was predicted by the EPA simulator model to occur between 4 and 5 minutes. The time was measured at the introduction of the samples into the reactor. Figure 2-2 shows a sample set of results illustrating the destruction of *B. subtilis* inoculated onto ceiling tile (Lemieux et al., 2005).

![Figure 2-2. The Effect of Heating Temperature and Time on Reduction of *B. subtilis* Spiked on Ceiling Tile (Adapted with permission from Lemieux et al., 2005)](image)

Wood et al. described experiments (primarily performed in a pilot-scale rotary kiln incinerator simulator [RKIS]) to examine the impact that bundling of material (wet and dry), exposure time, incinerator temperature, and internal bundle temperature have on the destruction of *G. stearothermophilus* biological indicator (BI) spore strips. In one test with a wet bundle, the spores survived a 38 min exposure in the RKIS. The wet ceiling tiles offered the most thermal resistance under all of the conditions tested due to the refractory materials used to produce the tiles as well as the large amounts of water the bundles could hold. This analysis showed that except for three ceiling tile tests, no *G. stearothermophilus* spores survived beyond 315 °C (600 °F) regardless of bundle material or exposure time in incinerator. Figure 2-3 shows the log
reduction of *G. stearothermophilus* in ceiling tiles with time. The high and low kiln temperatures were 1,093 °C and less than 824 °C, respectively (Wood et al., 2008).

**Figure 2-3.** Log Reduction of *G. stearothermophilus* BIs in Ceiling Tile Bundles (Wet and Dry) vs. Time in RKIS (Reprinted with permission from Wood et al., Copyright 2008 American Chemical Society). 95% Confidence Interval (CI).

Wood et al. conducted tests in a pilot-scale incinerator utilizing biological indicators comprised of spores of *G. stearothermophilus, Bacillus atrophaeus* and *B. anthracis* (Sterne) embedded in building material bundles (wallboard). In the pilot-scale incinerator tests, *B. atrophaeus* and *G. stearothermophilus* demonstrated similar thermal sensitivity, but *B. anthracis* was less thermally resistant than *G. stearothermophilus*. A histogram of an average of the percent survival of the two species of spores is shown in Figure 2-4. The data provide evidence to support the use of either *G. stearothermophilus* or *B. atrophaeus* as a surrogate microorganism for conducting research to determine the dry thermal destruction requirements of *B. anthracis*-laden waste. Wood et al. reported that data from this study may assist in the selection of surrogates or indicator microorganisms to ensure that *B. anthracis* spores embedded in building materials are completely inactivated in an incinerator (Wood et al., 2010).
Denison et al. investigated a transient zonal model approach for use with a computational fluid dynamics (CFD) model. Comparisons were made between the model and experimental data. The model results were compared against pilot-scale data collected by EPA to characterize the behavior. The typical gas residence times were 2 seconds in the kiln, 3 seconds in the transition between the kiln and the secondary combustion chamber and 7 to 8 seconds in the secondary combustion chamber. The bundles were fed approximately every 10.5 minutes. The bundles were approximately 50% water. The typical residence time for the solid matrix material was 10 minutes. The 6 log$_{10}$ reduction for *B. subtilis* on wallboard occurred at 1,700 s at 600 °F, 2,700 s at 500 °F, and 4,500 s at 400 °F, as shown in Figure 2-5. The data showed that zonal and CFD models of the laboratory scale kiln can be constructed and provide useful information on the physical processes that affect furnace performance in terms of microbiological destruction efficiency and operability. Figure 2-6 shows a comparison between the model calculations and the measured data of the kiln exit temperature and the Secondary Combustion Chamber (SCC) exit oxygen. The models predict complete destruction of the biological agent that remains in the building material matrix when the incinerators and afterburners are operated as per standard operating conditions (Denison et al., 2005).
Fisher et al. investigated the destruction chemistry of organosulfur compounds under both pyrolytic and oxidative conditions. The focus was on the destruction of alkyl sulfides that are surrogates for chemical warfare agent related to sulfur mustard (H, HD, and HT).

Thermochemistry, reaction pathways and kinetic parameters for multiple chemical subsystems were developed using computational chemistry methods. A turbulent flow reactor with
extractive sampling was used to examine the destruction of two mustard simulants under both pyrolytic and oxidative conditions (Fisher et al., 2008).

2.2.1 Municipal Waste Combustors

Municipal (solid) waste combustors (MWCs), otherwise known as waste-to-energy facilities, might be able to handle wastes containing chemical and biological agents. Several potential advantages to these facilities when compared to HWCs are that waste-to-energy facilities tend to be closer to urban centers where terrorist attacks on buildings would be most likely to occur, MWCs generally have much larger processing capacities than HWCs, and MWCs are believed to have more flexibility to implement specific engineering changes. Potential disadvantages include public perception associated with incinerating special wastes near population centers and permit restrictions for these facilities. Another limitation is the fact that, while waste-to-energy facilities are designed to receive and process many thousands of tons of waste per week, they are not particularly suited for large bulky items (Wilhelmi et al., 2003). In addition, those facilities may have existing contracts to accept waste at or near their nominal capacity on a regular basis and their ability to take large quantities of unplanned material (surge capacity) may be limited.

MWCs likely could handle, and would be allowed to process, certain types of wastes containing chemical or biological agents, even though they are permitted to handle wastes primarily from clinical and research settings. Regulators might need to issue permit modifications or exemptions for MWCs to process these wastes. Watanabe et al. reported emission data during the startup of two stoker-type MWCs (two lines, 150 x 2 metric tons/day [165 tons/day] and 450 x 2 metric tons/day [495 tons/day]) (Watanabe et al., 2010). Ash is a by-product of MWC and further testing is required before disposal at an appropriate facility.

2.3 Medical Waste Incinerators

The State and Territorial Association on Alternate Treatment Technologies (STAATT) established a framework or guidelines that defined efficacy criteria for the destruction of microorganisms for medical waste treatment technology and delineated the components required to establish an effective state medical waste treatment technology approval process. The guidelines recommended that all medical waste treatment technologies achieve 6 logs or greater microbial inactivation of mycobacteria and 4 logs or greater reduction of spores (Lemieux et al.,
Wood et al. (2004) summarized EPA test report data on *G. stearothermophilus* (*Gs*), a heat resistant microorganism, as a worst-case surrogate bacterium for tests with medical waste incinerators (MWIs). Similar to *B. anthracis*, the surrogate is a gram-positive, endospore-forming, rod shaped bacterium. As *B. anthracis* spores are heat resistant and can survive for long periods under harsh conditions, the potential exists for viable spores to escape detection and decontamination or to survive multiple decontamination processes. The *Gs* bacterium was spiked into the medical waste feed at certain intervals throughout an emissions test. The internal pipe temperatures were above 816 °C in the small MWI. The results showed that for most of the test runs, at least a five log reduction of the spores was achieved, although viable spores were detected in 10 out of a total of 48 air emission test runs, and spores were detected in 10 out of 27 available ash samples. MWIs may not completely destroy all of the spiked microorganisms because of limitations including in-bed mass transfer limitations, incomplete bed mixing, bypassing of hot zones due to poor gas phase mixing, dropping contaminated material through the grate prior to destruction in the bed, or by coming into contact with cool zones within the MWI. Coupled with complex fluid dynamics, these limitations would cause pockets within the combustion chambers that are not exposed to sufficiently high temperatures and residence times. The most notable limitation for MWCs is the size of the waste that can be processed where the typical hopper size for most MWIs is 3 feet by 5 feet by 5 feet (Wilhelmi et al., 2003). Due to the cost of complying with air emission standards and guidance developed in the 1990s, medical waste treatment has shifted from small hospital MWIs to larger commercial MWIs with state-of-the-art incinerator and air pollution control technology (Wood et al., 2004).

The Izmit Hazardous and Clinical Waste Incinerator (IZAYDAS) facility in Izmit, Turkey incinerates medical and hazardous waste. Various types of wastes such as medical wastes, plastic and lactic wastes (produced from food wastes), cosmetic wastes, used oil, petrochemical wastes and oil wastes, solvent, and dyeing wastes are disposed by incineration at IZAYDAS. The incinerator has a total area of 800,000 m², 32,000 m² of which is appropriated for incineration facilities. The capacity of the plant is 35,000 tons/year. The plant consists of five major parts:
storage, combustion, energy production system, air pollution control system, fly ash and bottom ash collection system (Cetin et al., 2003).

### 2.4 Chemical Weapon Demilitarization

The major portion of the literature on the destruction of CB agents using incineration involves the use of hazardous waste combustors in specially designed chemical demilitarization facilities, such as Johnson Atoll Chemical Agent Disposal System (JACADS) and Tooele Chemical Agent Disposal Facility (TOCDF). The U.S and other counties agreed to destroy their stockpiles of chemical weapons following the Chemical Weapons Convention (CWC) mainly using HWCs, MPFs, and LICs.

During the past 40 years, more than 20,000 tonnes (22,000 tons) of chemical agent have been destroyed in a number of countries and over 80% of this material has been destroyed by incineration. There are three principal categories of chemical warfare agents in the stockpiled munitions and bulk agent storage: mustard, lewisite, and the nerve agents (GA, GB, GD, VR and VX) (Pearson and Magee, 2002).

#### 2.4.1 Metal Parts Furnaces

Pearson and Magee described the destruction of metal parts that had been drained of agent (such as one-ton agent containers, bombs, spray tanks, artillery projectiles, and burster wells, which were pulled to access the agent) in a Metal Parts Furnace (MPF). Metals parts are fed by conveyor into a fuel-fired MPF and heated to 540 °C to produce metal suitable for release as scrap after deformation to comply with CWC requirements. Residual or undrained (including gelled) agent remaining in the metal parts is vaporized and burned within the furnace; the residence time in the furnace is of the order of two hours. During this period, the residual agent is vaporized (40 min), the metal parts are heated to 540 °C and maintained at that temperature for at least 15 min (heated and maintained for 40 min), and then the metal parts are allowed to cool in a cool-down zone (30 min) to minimize any fugitive emissions. This process takes additional time and can limit the throughput of the system. Gases discharged from the metal parts furnace are passed through an afterburner maintained at 1,090 °C before being treated in the pollution abatement system. The decontaminated metal parts are discharged and shipped to an approved disposal site or sold for scrap (Pearson and Magee, 2002).
Denison reported on computer modeling tools playing an important role in reducing the time, cost and technical risk of using incineration. A simulation workbench was developed to assist the chemical demilitarization community. The workbench consisted of models for an MPF. Both a transient zonal model and CFD models were prepared. In the MPF, metal parts pass intermittently through the furnace at a set point gas temperature typically at 1,600 °F and with a residence time sufficient to drive off and destroy the agent and bring the projectiles to at least 1,000 °F for at least 10 minutes. The models predict complete destruction of the chemical agent when the incinerators and afterburners are operated as per standard operating conditions. In Figure 2-7, the gas temperature distribution for the afterburner in the MPF is shown. The workbench tool being developed included the ability to study the combustion process, agent destruction and product species and concentrations for nerve agents (GB and VX) and HD. The experimental data for HD destruction are compared with the kinetic data in Figure 2-8. The calculated time profiles are shown in Figure 2-9 for the 5% of the agent remaining in the projectile shells in the MPF. The models may also be useful in simulating incineration system upset conditions and failures that could lead to an agent release, so that appropriate design and operational modifications can be made to mitigate such occurrences (Denison et al., 2002).

Figure 2-7. Gas Temperature Distribution in the Afterburner of the Three-Zone MPF (Adapted with permission from Denison et al., 2002 [Reaction Engineering International])
Figure 2-8. Comparison of HD Destruction Kinetics with Experimental Data (Adapted with permission from Denison et al., 2002 [Reaction Engineering International])
2.4.2 Liquid Incineration

For warfare agent destruction, liquid chemical agent drained from the munitions and storage containers is collected in a storage tank from which it is fed into a high-temperature LIC where it is burned at a temperature of 1,480 °C. The LIC is a two-stage refractory-lined incinerator designed to destroy the nerve agents GA, GB, VX, and mustard (H, HD, and HT). The drained agent is atomized by a nozzle and mixed with combustion air. Auxiliary fuel is used to maintain combustion at or above 1,400 °C with the flue gases being passed to an afterburner maintained at a minimum temperature of 1,090 °C before ducting to the pollution abatement system (Pearson and Magee, 2002).
Denison et al. developed models for analyzing the LIC for destroying liquid chemical weapon agents (GB, HD, or VX) drained from munitions contained in the U.S. Army stockpile. The destruction profiles with time are shown in Figure 2-10. The models predict complete destruction of the chemical agents when the incinerators and afterburners are operated as per the standard operating conditions. The agent is destroyed in the primary furnace chamber shown in Figure 2-11. Both full CFD and streamlined calculations were performed for agent destruction (Denison et al., 2004).

Figure 2-10. Calculated Destruction of VX, GB, HD, and H in a Plug Flow Reactor with Two-Second Residence Time Versus Temperature (Adapted with permission from Denison et al., 2004 [Reaction Engineering International])

Figure 2-11. LIC Primary and Secondary Chambers with VX Agent Destruction Depicted by Streamlines (Adapted with permission from Denison et al., 2004 [Reaction Engineering International])
2.4.3 **Plasma Pyrolysis**

In plasma pyrolysis, components of chemical munitions, after disassembly, are introduced into a plasma environment generated by an electric arc, at temperatures approaching 15,000 °C, in a special furnace enclosure. Chemical agents are instantly decomposed, and metal parts are melted. The gaseous decomposition products are passed through a pollution abatement system to remove noxious constituents. Plasma pyrolysis can take several forms: plasma plants in which the plasma torch treats material fed into the plasma oven, and plasma waste converters (PWCs) in which a plasma torch is inserted into a chamber into which the material to be destroyed is introduced. Alternatively, plasmas can be created using two electrodes where the plasma is one electrode, and the material to be treated is at the bottom of the oven as an anode. Significantly lower temperatures are measured at the surface of the treated material (slag) depending on the melting temperature of the slag. By-products will have to be tested and disposed at an appropriate facility. Plasma pyrolysis reactors can be designed to treat all components of chemical munitions (i.e., chemical agent, fuses, bursters, propellant, metal casings, and packing materials). An explosion chamber can be used to deactivate explosive components by energetic initiation (detonation or deflagration), and the resulting debris and gas from the chamber are then treated in a high-temperature plasma (Pearson and Magee, 2002).

Of the research initiatives by the U.S. Department of Energy and the DoD over the past 10 years on plasma treatment of hazardous waste, two have reached the implementation stage: a U.S. Navy project to destroy hazardous materials on shore; and an asbestos destruction project at Port Clinton, Ohio. Other projects are still in the research phase (Pearson and Magee, 2002).

2.4.4 **Pollution Abatement of Chemical Weapon Demilitarization**

The liquid incinerator, the energetics deactivation furnace, and the metal parts furnace all have identical, separate, dedicated pollution abatement systems. Gases leaving the secondary chamber of the liquid incinerator or the metal parts furnace flow to these pollution abatement systems for removal of gaseous pollutants and particles to meet emission standards. Hot gases leaving the energetics deactivation furnace system kiln flow to a refractory lined cyclone separator, where large particles such as glass fibers from rocket launch tubes are removed. The gases then enter the afterburner and subsequently flow into a similar pollution abatement system (Pearson and Magee, 2002).
The exhaust gas stream enters the quench tower near the bottom, where it is cooled by contact with a countercurrent spray of brine pumped from the packed-bed scrubber sump. Acidic or acid-forming gases [such as hydrogen chloride (HCl), hydrogen fluoride (HF), nitrogen oxides (NOx), and sulfur dioxide (SO2)] react with the caustic brine to form salts, which remain in solution in the brine. The cooled gas stream exits from the top of the quench tower and enters a variable throat venturi where it is scrubbed to remove particulates. The venturi has a variable throat to maintain a constant pressure drop independent of the flow of exhaust gases. The brine streams from the quench and venturi scrubber are then returned to the scrubber tower sump (Pearson and Magee, 2002).

The scrubbed gases enter a candle mist-eliminator vessel. Mist-eliminator candles remove very fine mist and submicron particulate matter that were not removed in the venturi scrubber. The cooled and cleaned exhaust gases are pulled through an induced draft blower located upstream of the stack shared by the three pollution abatement systems (Pearson and Magee, 2002).

Emissions testing at JACADS and TOCDF has demonstrated the ability of these incineration systems to consistently meet all emissions standards for particulates, organic compound destruction, and emissions of dioxins/furans. Examples of recorded data were as follows: particulate emissions were on average 14.7 grains per dry standard cubic meter (gr/dsm³) (103 runs), agent destruction was complete (40 runs) in the stack gases, and dioxins and furans (36 runs) were near detectable levels (average) of 0.037 ng/dsm³. Finally, polychlorinated biphenyl (PCB) destruction in the Deactivation Furnace System (DFS) exceeded the 99.9999 % regulatory requirement (Pearson and Magee, 2002).

2.5 Emission and Aerosol Containment

Werner and Cool reported that in the highly non-uniform combustion mixtures present in furnaces, large gradients in temperatures and composition exist, which may result in incomplete chemical agent destruction. Under differing flame conditions, the presence of organophosphorus compounds may either inhibit or promote combustion. Localized pockets of the reacting mixture may exist where combustion is inhibited or incomplete; if such pyrolysis pockets escape the primary flame zone, then traces of the chemical agent may survive the primary incineration furnace. Because of this possibility, current thermal processing facilities employ an afterburner
to ensure adequate destruction and removal efficiencies for CWAs (Werner and Cool, 1999). Furthermore, modern refuse combustors have tall stacks, specially designed combustion chambers, and high-efficiency flue gas cleaning systems that serve to minimize the impact of emissions associated with waste combustion (Lemieux et al., 2000).

Emissions from all incinerators are subject to regulations promulgated through the 1990 Clean Air Act (CAA). Regulations developed under the CAA are intended to limit atmospheric concentrations of six criteria pollutants as well as the 188 hazardous air pollutants (HAPs). EPA has defined maximum-achievable-control-technology (MACT) standards for incinerators and other HAP sources. MACT standards require all pollutant sources within a category (such as incinerator sources) to attain a level of control that reflects the average of the best-performing facilities (top 12%) in that category. There are three by-product streams from an incinerator: the stack emissions, the ash residue, and the residues from the pollution control equipment. The largest volume of material released from an incinerator is the stack-gas stream, which contains mostly carbon dioxide and water vapor with small amounts of particulate matter and pollutant vapors. Many of the organic compounds in the stack and waste residue are products of incomplete combustion (PICs) whose rate of production is controlled by combustion conditions. Ideal combustion conditions are needed to maximize the destruction of PICs and minimize the partitioning of heavy metals in the vapor and particle-phase emissions that go out the stack. During startup and during transient events, ideal conditions are unattainable and pollution emissions can increase significantly (McKone, 2000). However, startup is typically performed using conventional fuels and not wastes. Minimization of transients due to feeding containerized waste can be achieved by closely monitoring the volumetric heat release by timing the introduction of containers into the combustor.

The performance standards for hazardous waste incinerators consist of the following: (1) a destruction and removal efficiency (DRE) of principal organic hazardous constituents (POHCs) of 99.99%, or 99.9999% for dioxin-listed wastes; (2) particulate matter emissions not to exceed 180 milligrams per dry standard cubic meter (mg/dscm) or 0.08 grains per dry standard cubic foot (grains/dscf), corrected to 7% oxygen; and (3) gaseous hydrochloric acid (HCl) emissions not to exceed 1.8 kilograms per hour or a removal efficiency of 99%. Compliance with these performance standards is generally established through a carefully designed trial burn (40 CFR §
270.62) (EPA, 2001). These DRE standards are based upon the demonstrated capabilities of proper regulatory agencies as well as a review of organic PICs and inorganic metals emissions measured during the trial burns. Through the use of air dispersion models, the maximum likely air concentrations of these substances in surrounding communities can be predicted. Based upon the predicted level and duration of exposure at these concentrations, the degree of risk that the emission of these substances poses to the public's health can be estimated. Trial burns are typically conducted under extreme operating conditions of the unit to define the maximum operating range (or operating envelope) that assures compliance. As long as the incinerator continues to operate within the operating envelope demonstrated during a successful trial burn, the incinerator is presumed to be in compliance with the regulatory performance standards. When a risk burn involves multiple test conditions, the permit writer and facility will need to decide whether the data from each test condition should be evaluated separately, or whether the data will be combined. In addition, decisions will be needed regarding evaluation of emissions beyond those measured during the risk burn. For example, a facility may prefer to evaluate risks associated with emissions at a regulatory standard or with an emissions estimate (EPA, 2001).

The storage and treatment of bulk and chemical agents and weapons involve unique hazards of handling extremely toxic materials. Harper described the methods that have been developed to detect the presence of chemical agents in the air, and these are used to help assure worker protection and the safety of the local population. Exposure limits for all chemical agents are low, sometimes nanograms per cubic meter for worker control limits and picograms per cubic meter for general population limits. The most common detector is the flame photometric detector, in sulfur or phosphorous mode, although others, such as mass-selective detectors, also have been used. Monitoring is made more difficult by interferences from chemicals applied in pesticide spraying, busy roadways or military firing ranges (Harper, 2002).

Incineration of organic chemicals containing carbon, hydrogen, and oxygen leads to the formation of carbon dioxide and water. As chemical warfare agents also can contain fluorine, chlorine, nitrogen, phosphorus, and sulfur, incineration will produce hydrogen fluoride (from GB), hydrogen chloride (from H, HD, and HT), nitrogen dioxide (from GA, VR, and VX), phosphorus pentoxide (from GA, GB, VR, and VX), and sulfur dioxide (from H, HD, and HT). All of these can be removed by scrubbing (Pearson and Magee, 2002).
The incineration of lewisite, a blister agent which contains arsenic, requires that the arsenic products be collected and not released to the environment. The exhaust gases are typically scrubbed by passing them through countercurrent liquid absorption beds to reduce the level of pollution in the gases released to the atmosphere to an acceptable level that protects public health and the environment (Pearson and Magee, 2002).

Watanabe et al. (2010) reported that dioxins and their surrogates were continuously monitored during the startup of two stoker-type MWCs (two lines 150 x 2 metric tons/day [165 tons/day] and 450 x 2 metric tons/day [495 tons/day]). The surrogates studied included low-volatility organohalogen (LVOH) compounds sampled by online systems, as well as chlorobenzenes (CBs) and chlorophenols (CPs). The changes in levels of LVOH compounds, CBs, and CPs corresponded well with the trend of the toxicity equivalent quantity (TEQ). Sampling of dioxins, CBs, and CPs began immediately after the furnace temperature reached a steady state of 900 °C. Sampling occurred at 2 h, 4 h, and 20 h intervals. An LVOH monitor operated continuously. Manual sampling was also done. The isomer analysis of the dioxins present under startup conditions showed evidence of the memory effect (where highly chlorinated isomers were emitted slowly), whereas low-chlorinated isomers and LVOH decreased rapidly as the temperature rose (Watanabe et al., 2010).

IZAYDAS is located 15 km east of Kocaeli, Turkey. Various types of wastes such as medical wastes, plastic and lactic wastes, cosmetic wastes, used oil, petrochemical wastes and oil wastes, solvents, and dyeing wastes are disposed by incineration at IZAYDAS. Mercury and its components, explosives and radioactive materials, slaughter house wastes, feces and corpses are not accepted. The waste feed rate for the incinerator is 4,100 kg/h. To start the removal process, the rotary kiln temperature is raised to 850–875 °C by fuel oil. When the rotary kiln temperature reaches 425 to 450 °C, the rotating process automatically starts and during the combustion process, the rotation speed is controlled by the control chamber operations, depending on the waste amount and properties. Removal of bottom ash occurs in 100 to 150 minute periods during the combustion of wastes at 900 to 1,100 °C. To achieve complete combustion and a good air mixture, secondary air is transferred from the bunker to the rotary kiln by using the sucking fans. Oxygen (8 %) is obtained automatically at the rotating kiln. The waste gas treatment system, consists of an electrostatic filter, a venturi scrubber, a lime scrubber, a
physical/chemical treatment plant, a flue gas on-line analysis room and a stack unit (Cetin et al., 2003).

The formation of dioxins/furans (D/Fs) in hazardous waste combustion units is highly dependent on post-combustion temperature, time, and the presence of flyash to provide a reactive surface. Even in systems achieving good combustion (with low carbon monoxide concentrations), D/F formation may occur in cooler zones downstream from the combustion chamber. Almost any combination of carbon, hydrogen, oxygen, and chlorine can yield some D/Fs, given the proper time and temperature. There could be substantial increases in D/F emissions under conditions of poor combustion and carbon monoxide levels greater than 2,000 parts per million (ppm). Some waste combustors that burn wastes containing D/F precursors, including chlorobenzenes, chlorophenols, and PCBs, have been shown to have high D/F emissions. D/F emissions could be a concern with the incineration of materials bound with CB agents if the material also contains D/F precursors. For most incineration and boiler systems, the generation of organic products of incomplete combustion is typically associated with poor combustion situations (organic emissions from cement kilns and lightweight aggregate kilns are typically dominated by organics that are volatilized from the raw materials). These conditions lead to incomplete combustion and subsequent increases in fly ash and carbon monoxide and total hydrocarbon concentrations (EPA, 2001).

Lemieux et al. (2000) conducted field studies on MWCs have shown that the amount of fly ash (and its accompanying metallic catalysts) and organic precursors that pass through the temperature window between 250 and 700 °C as well as the amount of time spent in that optimal temperature window are the primary variables affecting polychlorinated dibenzodioxins and polychlorinated dibenzofurans (PCDD/PCDF) emissions. Estimated emissions of PCDDs/PCDFs per unit mass consumed by combustion were calculated by assuming thorough mixing of air inside the burn hut and using:

\[
Emissions \left( \frac{mg}{kg} \right) = \frac{Concentration \ Pollutant \ (mg/m^3) \times Flow \ rate \ of \ Air \ (m^3/min) \times Run \ Time \ (min.)}{Mass \ of \ Waste \ Burned \ (kg)} \quad (Equation \ 2)
\]
A comparison of total dioxin and furan emissions for various combustion sources is presented in Figure 2-12 (Lemieux et al., 2000).

![Figure 2-12. Comparison of Total Furan and Dioxin Emissions for Burn Barrels and Municipal Waste Incinerators (Adapted with permission from Lemieux et al., 2000)](image)

2.6 Plasma Systems

This section reviews the literature on thermal plasma and cold plasma systems for the destruction of CB agents.

Plasma is defined as an energetic collection of ionized particles (electrons, ions, and radicals) that exhibit a collective behavior due to electromagnetic forces (Boone, 2007). Thermal plasma is the term used when a substantially larger fraction of the bulk gas is ionized, and can achieve bulk gas temperatures of 2,000 °C to 10,000 °C or higher (Konesky, 2008). The temperature of the gas discharge for cold plasma typically ranges from 50 °C to 300 °C, which allows for plasma processing of sensitive materials and equipment at low temperatures and accelerated processing of more robust surfaces at higher temperatures (Rosocha et al., 2003).

2.6.1 Thermal Plasma

Farrar et al. (2000) evaluated two technologies, a steam plasma torch at Montec and an arcjet thruster at Texas Tech University (TTU) to determine their efficacy to destroy biological agent
surrogates on materials. In these experiments, the post-test evaluation showed residual spore counts of a few hundred down to ten or less. The majority of the experiments were conducted using *G. stearothermophilus* spores as a simulant for anthrax spores. The *G. stearothermophilus* spores were deposited on thin 1-cm square wafers (coupons) of G-10 fiberglass, stone, and pumice. The specific types of areas investigated are representative of runways and roads, but the technologies could also be used on buildings, vehicles, and equipment (Farrar et al., 2000).

For the arcjet system, the temperature at the nozzle was estimated at 7,200 °F to 9,000 °F. At a velocity of 0.67 ft/s and at 1 inch from the exit plane, the peak for the nitrogen arc temperature was 2,300 °F. During these tests, the arcjet was operated for five to ten seconds duration. The selected bounds were 0.5 and 3.5 ft/s. Only a couple of flow rates and power settings were used for the devices, the distances between the nozzle and surface were limited to 1 to 3 inches (Farrar et al., 2000).

Montec’s steam plasma torch was operated at two power levels, 60 and 90 kilowatts (kW), and produced a plume with a diameter of 4–6 inches at the sampling point. The steam-plasma temperature was calculated to be between 4,500 °F and 5,400 °F for steam-plasma torch electric input power levels of 60–90 kW. The Montec results showed that at 90-kW power, the steam plasma produced a 99.94 % or greater kill rate at velocities up to 2 ft/s at a distance of 1 inch from the exit plane. At this same power level and at a distance of 3 inches, the percent kill ranged from 97 % to 85 % as the speed increased from 0.5 to 2 ft/s. At the lower power level of 60 kW, the maximum speed that would produce 99.94 % kill at 1 inch was 1.5 ft/s. A third substrate, pumice block (a highly porous material), was also contaminated with biological agent. Only partial destruction of the biological agent was achieved over the range of operating conditions tested. These tests showed that when the agent was absorbed deeply into a very porous material, the effectiveness of the plasma was limited. UV radiation alone (when the quartz plate was placed between the plume and the target) did an impressive job of killing a large number of the spores as shown in Figure 2-13. The quartz lens allowed passage of UV from 190 to 400 nm. However, UV radiation alone did not result in a 100 % kill, except at longer exposure times. The peak temperature measured with the quartz lens in place was 270 °F. The steam torch indicated a higher value of radiation around 280 nm than did the arcjet. The percentage of kill at a given speed was slightly higher for the arcjet (Farrar et al., 2000).
The emission spectroscopy of an arc-seed microwave plasma torch (MPT) was examined, and the spectral line of 777.194 nm indicated relatively high atomic oxygen content in the torch. In the decontamination experiments reported by Kuo et al., Bacillus cereus was chosen as a simulant for B. anthracis spores and the airflow rate was fixed at 0.393 L/s. The results of experiments using dry samples showed that all spores were killed in less than 8 seconds at 3 cm distance, 12 seconds at 4 cm distance, and 16 seconds at 5 cm distance away from the nozzle of the torch (Kuo et al., 2005).

2.6.2 Cold Plasma

Cold plasma is a partially ionized gas where only typically $10^{-3}$ to $10^{-6}$ of the gas molecules are ionized. This range would represent strong and weak cold plasma, respectively. The term cold is a relative one, and the bulk gas can reach temperatures of 100 °C or more in a strong beam (Konesky, 2008). Cold plasmas can be generated by microwave power, direct current (DC), radio-frequency (RF), or pulsed power supplies. Among the attractive features of nonthermal discharges is the ability to control their characteristics, allowing the plasma to be tailored for each specific application (Laroussi et al., 2000).
When partially ionized, the carrier gas acts as a gaseous wire and directs the plasma to the target application area with great precision and stability. This form of cold plasma applicator, often referred to as a plasma jet, consists essentially of a carrier gas flowing over a conductor with a sharp point that is held at high voltage and high frequency. The conductor is typically made of either stainless steel or tungsten. Voltages typically range from a few kilovolts to over 10 kV, and frequencies can range from a few kilohertz to over a megahertz. Electrical currents in the plasma jet may be as low as several tens of microamperes (a weak beam) to over 100 milliamperes (a very intense beam) (Konesky, 2008).

The plasma jet configuration has many advantages over previous cold plasma applicators. Now there are two independently controllable variables, electrical power input and gas flow rate, that give the plasma jet a wide range of effects. Helium is preferred as an ionized gas for plasma applications because its high thermal conductivity helps carry away heat, and its rich UV spectral components enhance its sterilization capability (Konesky, 2008).

The overall effect of a plasma jet results from a combination of ion bombardment, electron bombardment, thermal effects, localized UV exposure, and the production of free radicals and some ozone. The production of free radicals and ozone is possible because an oscillating electric field heats mainly the electrons rather than the heavier ions, which respond much more slowly. However, these energetic electrons can transfer their energy effectively to excite and dissociate molecules, yielding reactive radicals such as oxygen atoms (Konesky, 2008). Reactive oxygen species (ROS) such as metastable oxygen, ozone, and oxygen ions can destroy just about all kinds of organic contaminants more effectively than the thermal method (Herrmann et al., 1999). This athermal destruction mechanism primarily involves the chemical reactions of ROS with nucleic acids, lipids, proteins and sugars in biological organisms. These chemical modifications result in protein cleavage, with aggregation and loss of catalytic and structural function by distorting secondary and tertiary protein structures. These oxidative proteins are irreversibly modified and cannot be repaired. This occurrence is known as protein degradation (Kuo, 2005). The plasma also generates ultraviolet radiation that can destroy many biological agents as well as enhance chemical-reaction rates (Herrmann et al., 1999).
Atmospheric plasma decontamination (APD) can be applied to the destruction of biological organisms by passing energy through air. The molecules are ionized, generating both positively and negatively charged reactive species. The interaction of these ions, along with the associated ultraviolet light, kills the microorganisms. APD is applicable to the cleaning, and perhaps the disinfection, of small areas and electronic equipment (Boone, 2007).

Rosocha et al. presented the results for decontamination of *Bacillus globigii* (*Bg*), a surrogate for anthrax spores, using both plasma and dry heat treatments. The dry heat treatment flowed hot air, or some other gas, onto the biological agent. Results indicate a seven-log kill (a factor of 10 million removal or decrease of the contaminant) of *Bg* spores in 30 s with an Atmospheric Pressure Plasma Jet (APPJ) effluent temperature of 175 °C, which was ten times faster than dry heat at the same temperature, as shown in Figure 2-14. In Figure 2-15, the destruction of Malathion is shown for APPJ and compared to the dry heat treatment (Rosocha et al., 2003).
Herrmann et al. reported on a plasma decontamination chamber that has been developed at Los Alamos National Laboratory (LANL), Albuquerque, NM, to study the decontamination of chemical and biological warfare agents. This technology was targeted at sensitive electronic equipment for which there is currently no acceptable nondestructive means of decontamination. Sensitive equipment is defined as equipment that cannot be exposed to aqueous decontaminants and strong oxidizing or caustic solutions without destruction, degradation in performance, or significant disruption in use. To the military, this means electronic equipment such as avionics, communications, fire control and navigational equipment and electro-optics such as range finders.
and night-vision goggles. Exposures were conducted at a system pressure of 30 torr, exposure temperature of 70 °C, plasma-to-sample standoff distance of 10 cm, and 10 % addition of oxygen or hydrogen to a helium balance. The agents studied were VX and GD nerve agents and HD blister agent, as well as a thickened simulant. All agents were decontaminated off aluminum substrates to below the detection limit of 0.1 % of the initial contamination level of approximately 1 mg/cm², as shown in Figures 2-16 and 2-17. For VX, this level of decontamination was achieved in 8 to 16 min of exposure, while only 2 min were required for the more volatile HD and GD. Decontamination levels of 99.9 % were achieved in under 2 min for chemical agents HD and GD, and under 16 min for VX. Evaporation and subsequent chemical breakdown during recirculation through the plasma was believed to be the dominant decontamination process for these agents (Herrmann et al., 1999).

Figure 2-16. Residual VX Remaining on Aluminum as a Function of Exposure Time. Test Conditions: T = 70 °C, d = 10 cm, Pressure = 30 torr, O₂ or H₂ at 10 % (Reproduced with permission from Herrmann et al. Copyright 2000, AIP Publishing LLC.)

Figure 2-17. Residual HD Remaining on Aluminum (left) and Residual GD Remaining on Aluminum (right) Versus Time. Test Conditions: T = 70 °C, d = 10 cm, Pressure = 30 torr, O₂ or H₂ at 10 % (Reproduced with permission from Herrmann et al. Copyright 2000, AIP Publishing LLC.)
Laroussi et al. presented two studies on bacteria inactivation obtained by two different discharges: a glow discharge at atmospheric pressure (GDAP) and an enhanced corona discharge at atmospheric pressure (ECDAP). The plasma generated by the GDAP is a source of charged particles, free radicals (O· and OH·), and radiation (infrared, visible, and ultraviolet). This environment was found to be lethal to various microorganisms. The root mean square (rms) voltage was 5 kiloVolts, the frequency was 17 kiloHertz, the gap distance was 3 cm, the gas was a mixture of helium and air, the bacteria were *Escherichia coli* (pbr 322) and *Pseudomonas aeruginosa* (frd1) (Laroussi et al., 2000).

*Pseudomonas aeruginosa* on a nitrocellulose filter membrane was tested. These bacteria were harder to kill since it took approximately 15 min to sterilize a sample seeded with a cell density in the $10^5$/mL range. *Pseudomonas* was even harder to kill when it was in a liquid broth since for similar experimental conditions, only half of the initial cells were killed in 15 minutes. Therefore, the kill rate of microorganisms by the GDAP is strongly dependent on the type of microorganism, the type of medium supporting the microorganism, and the type of sterilization (surface versus volume). To understand what happens to the microorganisms after they were treated by the plasma discharge, scanning electron microscope (SEM) micrographs of the cells were taken showing the appearance of non-treated cells and cells treated for 30 s in the GDAP. The treated cells appeared to be in the process of leaking internal matter. The outer membranes of the cells appeared to have been punctured by the plasma. With a damaged outer membrane, the microorganisms became very vulnerable to the reactive environment of the discharge (Laroussi et al., 2000).

Like the glow discharge at atmospheric pressure, the ECDAP is a source of active species that can react adversely with the cells of microorganisms. For ECDAP, the power dependence on the kill rate was paramount. The power was tripled from 20 Watts (W) to 60 W, and the kill rate increased by approximately two orders of magnitude. *B. subtilis* bacteria in Luria–Bertani broth were a little harder to kill than *E. coli* since for a power of 42 W and after a 12-min exposure time, approximately 100 cells were still alive (as compared to complete kill in 8 min for *E. coli*), as shown in Figure 2-18 (Laroussi et al., 2000).
Montie et al. reported the results of a plasma source, the One Atmosphere Uniform Glow Discharge Plasma (OAUGDP), which operates at atmospheric pressure in air and produces antimicrobially active species at room temperature. The OAUGDP reactor is composed of a radio frequency (RF) power supply and a pair of water-cooled parallel plane plate electrodes, between which an atmospheric glow discharge plasma is generated, producing antimicrobially active species. These antimicrobially active species include ozone, monatomic oxygen, free radicals such as superoxide, hydroxyl, and nitric oxide, and ultraviolet photons. The nature of the surface influences the degree of lethality, with microorganisms on polypropylene being most sensitive, followed by microorganisms on glass, and cells embedded in agar. Experimental results showed at least a $5 \log_{10}$ colony forming unit (CFU) reduction in bacteria within a range of 50 to 90 s of exposure. After 10 to 25 s of exposure, macromolecular leakage and bacterial fragmentation were observed. *E. coli* and *Pseudomonas aeruginosa* were as susceptible to the plasma as *Staphylococcus aureus*, *B. subtilis*, and *Deinococcus radiodurans*. The latter organism is unusually resistant to drying, irradiation and ultraviolet light. Spores were more resistant, with values in the range of 1.8 to 5.5 min instead of seconds. *Bacillus stearothermophilus* spores, normally a very resistant organism, were killed to the same extent (five logs in 5.5 min) as *B. subtilis var. niger* spores, while only 2.5 min was required to inactivate approximately the same
number of B. pumilus spores. Data from Montie et al. suggest that membrane lipids may be the most vulnerable macromolecule of the cell, probably because of their location near the cell surface and their sensitivity to ROS. Gram-negative bacteria as a group would be most vulnerable because they possess a unique outer membrane in their cell envelope. By contrast, leakage from the Gram-positive S. aureus was delayed, and no evident fragmentation occurred, suggesting that the thick polysaccharide on the outside of the cell of S. aureus is resistant to chemical change but allows diffusion of ROS to the cytoplasmic membrane, which is again vulnerable to attack. When the cytoplasmic membrane lipids are altered in both groups of bacteria, this alteration results in a massive release of macromolecules. In Figure 2-19, the bacterial survivors inoculated on polypropylene are plotted with time, and the Transmission Electron Micrographs (TEM) of E. coli and S. aureus initially and after 30 seconds of exposure are presented (Montie et al., 2000).

Figure 2-19. Survivors of Bacterial Cells Inoculated on Polypropylene with Time with the Application of OAUGDP (left). The Transmission Electron Micrograph of OAUGDP-treated Cells: A) Initial E. coli, B) E. coli after 30 Seconds of Exposure, C) Initial S. aureus, and D) S. aureus after 30 Seconds of Exposure (right) (© 2000 IEEE. Reprinted, with permission from Montie et al.)
2.7 Microwave Irradiation

Microwave energy is a form of electromagnetic energy that penetrates deeply into many materials, transforming energy directly into heat by exciting absorbing molecules into rapid oscillatory motion. With such unique attributes, microwave offers several practical advantages, including reduced thermal gradients, selective heating, rapid energy decomposition, and acceleration of certain chemical reactions (Cha et al., 2004).

Microwave scabbling is a new method of removing the surface of concrete which uses microwave energy to heat the moisture present in the concrete matrix. Continued heating produces steam under pressure that generates internal mechanical and thermal stresses, bursting the surface layer of the concrete. The analysis showed that the main factors affecting scarification are the pore dimensions and the evaporable water content of the cement (Kumar et al., 2010).

Wu and Yao investigated the survival of both laboratory-generated and environmental bioaerosols when these bioaerosols were exposed to microwave irradiation (2,450 MHz) for 2 min at different output power (700, 385, and 119 W), as shown in Figures 2-20 and 2-21. Three different microbial species (B. subtilis var. niger (hardy species, Gram-positive), P. fluorescens (sensitive species, Gram-negative) and fungus A. versicolor (hardy species) were studied as surrogates for harmful agents. The survival rates of airborne B. subtilis var. niger spores were shown to be approximately 35%, 44% and 35% when exposed to the microwave irradiation for 1.5 min with high, medium and low power applied. The airborne Pseudomonas fluorescens was shown to have lower survival rates of 5.8%, 12.2% and 21% (p-value = 0.0045). Similar patterns but higher survival rates at respective powers were observed for airborne Aspergillus versicolor exposure (p-value 0.0001). SEM and TEM images showed visible damage to both membrane and intracellular components of the microwave-treated microbes (Figure 2-22). In a previous study, several dark spots were also observed in the cytoplasm of both B. subtilis and E. coli through examining their TEM images, and the protein aggregation was suggested to play a role in the inactivation (Wu and Yao, 2010).
Thermal effects could result from the denaturation of enzymes, proteins and nucleic acids, as well as the disruption of membranes when the temperature reaches 50–60 °C. The athermal effect by microwave application could arise from the interference of cell metabolic activities and energy absorption and deoxyribonucleic acid/ribonucleic acid (DNA/RNA) molecule rotation in response to microwave irradiation. The results obtained by Wu and Yao can be used to develop microwave-based air sterilization technologies especially targeted for biological aerosols. Microorganisms in wet form sustained substantial inactivation upon microwave irradiation, while those in dry or lyophilized form were not affected even by extended exposure, suggesting that the thermal effects may be responsible for the microwave inactivation. The presence of water may be necessary for the athermal effects to occur (Wu and Yao, 2010).

Figure 2-20. Airborne Exposure of *B. subtilis var. niger*, *P. fluorescens* and *A. versicolor* to Microwave Irradiation at 700, 385, and 119 W for 1.5 Minutes (Adapted from Wu and Yao, 2010 with permission from Elsevier, Inc.)
Figure 2-21. Liquid-borne Exposure of *B. subtilis* var. *niger* to Microwave Irradiation at 700, 385, and 119 W (Adapted from Wu and Yao, 2010 with permission from Elsevier, Inc.)

Figure 2-22. SEM Images of Liquid-borne Control and Exposed *P. fluorescens*, *A. versicolor* and *B. subtilis* var. *niger* with 700 W and 90 Seconds Exposure Time (Reprinted from Wu and Yao, Copyright 2010, with permission from Elsevier, Inc.)
Zhang et al. developed a microwave-assisted nanofibrous air filtration system (a microwave device to disinfect airborne pathogens collected on nanofibers) to disinfect air containing airborne pathogens. Aerosolized *E. coli* vegetative cells and *B. subtilis* endospores were tested as benign surrogates of pathogens and were collected on nanofibrous filters and treated by microwave irradiation. As a Gram-positive bacterium, *B. subtilis* has the ability to sporulate and has been used extensively as a benign surrogate for *B. anthracis* spores. *B. subtilis* endospores are ellipsoidal in shape, approximately 0.8–1.2 mm in length, and have an aerodynamic diameter of 0.9 mm. Both static on-filter and dynamic in-flight tests were carried out. Results showed that *E. coli* cells were efficiently disinfected in both static and in-flight tests, whereas *B. subtilis* endospores were more resistant to this treatment. The microwave power level was found to be the major factor determining the effectiveness of disinfection. Both thermal and athermal effects of microwave irradiation contributed to the disinfection. Reducing flow velocity to decrease heat loss yielded higher disinfection efficiency (Zhang et al., 2010).

Zhang et al. prepared electrospun polyacrylonitrile (PAN) nanofibers that were sandwiched between two activated carbon fiber (ACF) mats for testing. *B. subtilis* endospores were tested because of their relatively high heat resistivity compared to *E. coli*. *B. subtilis* spore tests show a similar trend in log disinfection. As shown in Figure 2-23, after irradiation at 750 W for 90 s, 2.7 logs disinfection of the spores was observed. Less powerful microwave power applications proved less effective. For 250 W, 45 s of application time was required to achieve any disinfection at all. Compared with *E. coli* tests, *B. subtilis* spores were more difficult to destroy, requiring irradiation at 750 W for 90 s for 3 logs disinfection. This apparent difficulty in destroying the spores would also be observed during in-flight testing. This result is likely attributed to the heat resistivity of the endospores. Analysis of variance (ANOVA) statistical analysis indicated that microwave power, rather than application time, was the most significant factor in the reduction of viable *B. subtilis* spores on the filter (p-value 0.05) (Zhang et al., 2010).
McFarland et al. treated biological warfare agents with the transduction-polymer and an acceptor-chromophore (TPAC) compound and then exposed the treated agents to microwaves. Using this approach, significant kill of the BWAs was achieved using standard microwave equipment at moderate power. A 5.5 out of a total of 6 log kill was achieved on surrogate *B. anthracis* spores, the hardest BWA to defeat. The AC molecule is designed so that it easily penetrates the wall of the BWA and binds to surface matrix targets. Upon microwave exposure, the TP emits a blue photon that activates the AC producing saturated levels of chemical radicals that are irreversibly bound to the target spore wall, resulting in lethal failure of the spore upon germination. The TP molecule is resonant and thus responds to a given microwave frequency better than others (McFarland et al., 2001).

Microwave irradiation can be used for decontamination and regeneration with very little warmup time while generating almost none of the problematic byproducts. Wu et al. developed the RHELP (Regenerative High Efficiency Low Pressure) air purification system using a novel ceramic nanofiber on silicon carbide in a microwave oxidizer to effectively decontaminate air.
containing aerosolized CB agents. Nanofiber mats of several materials (shown in Figure 2-24) were designed and fabricated: I) (PAN nanofibers on ACF mat; II) titania nanofibers; III) silicon carbide nanofibers; IV) titania carbon nanotube reinforced nanocomposite nanofibers; and V) titania silica nanocomposite nanofibers. Three microorganisms, *Escherichia coli*, MS2 bacteriophage, and *B. subtilis* endospores were tested as benign surrogates for more dangerous microbes. For static on-filter tests, all biological agents were able to be completely destroyed by microwave irradiation within two minutes, with *E. coli* being the most sensitive and *B. subtilis* endospores being the least sensitive. For the dynamic system in-flight filtration tests that coupled PAN nanofiber filtration, at 500 W of continuous microwave application, the system was able to remove over 95% of viable MS2 virus and *B. subtilis* endospores (Wu et al., 2009).

![SEM Images of (a) TiO2 Nanofibers, (b) Millipore high efficiency particulate arrestance (HEPA) filter, and (c) Military HEPA (Wu et al., 2009, Published by DTIC, No Permission Required)](image)

Cha et al. used catalysts and microwave energy to test the destruction of simulated chemical agents including the monofunctional derivatives of mustard gas and a series of organophosphorus esters used to simulate G agents including dimethylmethyl phosphate (DMMP), diisopropyl methylphosphonate (DIMP), diisopropyl fluorophosphates (DFP), and 4-nitrophenyl diphenyl phosphate (PNPDP). Outlet temperature and concentration measurements were taken at regular intervals from 1 to 80 minutes after flow into the reactor. During the test, the outlet simulant concentration was monitored by a Total Hydrocarbon Analyzer (accurate within 0.1 ppm) (Cha et al., 2004).

The catalyst absorbed microwave energy to perform the microwave-induced chemical reactions. Most catalyst substrates such as aluminum oxide (Al2O3) do not absorb microwave energy.
Since silicon carbide (SiC) is an excellent microwave absorber, commercially available catalysts were mixed with SiC to carry out microwave-induced chemical reactions. Three different substrates were used to prepare the vanadium pentoxide (V$_2$O$_5$) catalyst for a series of tests to evaluate the performance in the oxidation reactions. The first V$_2$O$_5$ catalyst was V$_2$O$_5$ on silicon carbide, and the second was V$_2$O$_5$ on 50% SiC/Al$_2$O$_3$ support. An air stream containing either 300 ppm DMMP or 600 ppm diethyl sulfide (DES) was used to evaluate these substrates for the V$_2$O$_5$ catalyst. Air flow rates of 35 bed volume per minute and 300 W microwave power were used for these experiments (Cha et al., 2004).

In Figure 2-25, for DMMP the best DRE (>99.5%) was obtained from tests using the alumina-based vanadium catalyst. The higher catalyst surface area appears to yield greater DRE. Alumina alone does not absorb microwave energy. However, alumina impregnated with the V$_2$O$_5$ absorbs enough microwave energy to induce the oxidation reaction. Mixing a small amount of SiC with the catalyst was sufficient to initiate microwave-induced catalytic oxidation (Cha et al., 2004).

![Figure 2-25. Percent Destruction of DMMP for Different V$_2$O$_5$ Catalysts (Cha et al., 2004, Published by DTIC, No Permission Required)](image)

In Figure 2-26, the DES outlet concentration reached a steady-state concentration within 10 minutes after the experiment started. All the tests were performed using DES as the CWA simulant and using a 10% by mass V$_2$O$_5$ catalyst impregnated on alumina beads (Cha et al., 2004).
In Figure 2-27, the DRE and temperature (secondary axis) for DES are plotted versus time. The experimental results positively demonstrate that microwave catalytic oxidation is a strong candidate for the destruction of CWAs in air at low temperatures. The microwave power and inlet air flow rate are major parameters controlling the destruction and removal efficiency. The DRE is closely correlated to the combined parameter, microwave power/inlet flow rate (kJ/bed volume). For the V\textsubscript{2}O\textsubscript{5} catalyst, DREs greater than 90% were obtained with the ratio of microwave power to inlet flow rate greater than approximately 0.3 kg/bed volume (ft\textsuperscript{3}) (Cha et al., 2004).
2.8  Autoclave

Autoclaves are commonly used to sterilize medical wastes using steam, heat, and pressure. Autoclaves range in size from bench-top devices to large commercial operations. These large commercial facilities can process up to 96 tons of waste per day, and some have waste inlet openings up to 8 feet in diameter. Potential advantages of using commercial autoclaves to sterilize waste include the ease with which processing conditions can be altered for specific waste streams, the ability to process large waste items, and the fact that these facilities often have testing requirements for spore destruction. Potential disadvantages include worker safety issues, packaging requirements, and the issue of disposing of decontaminated wastes (Wilhelmi et al., 2003).

The EPA conducted an experiment to evaluate the effectiveness of a commercial autoclave for treating simulated BDR. Tests were conducted at the Healthcare Environmental, Inc., facility located in Oneonta, NY. This facility can treat up to 84 tons of medical waste per day using two identical autoclaves that are 8 ft in diameter and 32 ft long, which accept large metal bins (80 in by 54 in by 69 in) on rollers. The nominal autoclave operating cycle time was 40 min plus cool down time to prepare for subsequent loads. The nominal operating conditions during the cycles are 31.5 lb/in² and 275 °F (Lemieux et al., 2006a).

The BDR (carpet, wallboard, and ceiling tile) was intended to simulate porous materials removed from a building deliberately contaminated with biological agents such as \emph{B. anthracis} (anthrax) in a terrorist attack. The test team created simulated BDR from wallboard, ceiling tiles, carpet, and upholstered furniture, and embedded in the BDR were \emph{G. stearothermophilus} BI strips. The purpose of the tests was to assess whether the standard operating procedure for a commercial autoclave provided sufficiently robust conditions to adequately destroy bacterial spores bound to the BDR (Lemieux et al., 2006a).

Lemieux et al. (2006a) investigated the effects of several variables related to autoclaving BDR, including time, temperature, pressure, item type, moisture content, packing density, packing orientation, autoclave bag integrity, and autoclave process sequence. The effect of a second autoclave cycle on spore survivability is shown in Figure 2-28. The results indicated that a
A single standard autoclave cycle did not effectively decontaminate the BDR. Autoclave cycles consisting of 120 min at 31.5 lb/in\(^2\) and 275 °F and 75 min at 45 lb/in\(^2\) and 292 °F effectively decontaminated the BDR material. Two sequential standard autoclave cycles consisting of 40 min at 31.5 lb/in\(^2\) and 275 °F proved to be particularly effective, probably because the evacuation step in the second cycle pulled the condensed water out of the pores of the materials, allowing better steam penetration. The results also indicated that the packing density and material type of the BDR in the autoclave could have a significant impact on the effectiveness of the decontamination process. In Figure 2-29, the effect of packing density for wallboard is presented. The most effective spore destruction was obtained with a loose packing arrangement, dry BDR material, a higher autoclave operating pressure and higher temperature, multiple autoclave cycles performed in sequence, and bags cut open prior to loading (Lemieux et al., 2006a).

Figure 2-28. Effect of Second Autoclave Cycle on Spore Survivability, Temperature with Time (Adapted with permission from Lemieux et al., 2006a)
2.9 Landfill Flares

As organic waste decomposes inside a landfill, the decomposing waste releases a combustible gas called “landfill gas” that has a heating value on the order of half of the heating value of natural gas (EPA, 2009). This gas is commonly burned either in a boiler or engine (for energy recovery) or a flare.

Although incineration may be a preferred method to treat biologically contaminated materials, other management options would likely be required in a large-scale incident because the high volume of waste might overwhelm incineration facilities. One management option is the use of municipal solid waste (MSW) landfills. As the landfill reaches final grade, it is capped with clay and plastic to prevent water infiltration. Bacteria break down the organic wastes within each cell to produce landfill gas. Landfill gas generally consists of about half methane (CH₄), half carbon dioxide (CO₂), and <1% non-methane organic compounds as well as hydrogen sulfide and other sulfur compounds. These gases, including methane, are collected through a series of pipes and are routed by blowers to landfill flares, gas turbines, internal combustion engines, or other

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Figure 2-29. Effect of Packing Density for Wallboard, Temperature with Time (Adapted with permission from Lemieux et al., 2006a)
devices that combust the gases and prevent the escape of methane into the atmosphere (Tufts and Rosati, 2012).

A bench-scale landfill flare system was designed by Tufts and Rosati and built to test the potential for landfilled biological spores that migrate from the waste into the landfill gas to pass through the flare and exit into the environment as viable. For the bench tests, N₂ and CH₄ were used to simulate landfill gas with combustion air. Flows were corrected to a temperature of 1,000 °C, the maximum average temperature of the flare measured at its widest point which was within the 870 to 1,037 °C operating range for an enclosed flare. *G. stearothermophilus* and *B. atrophaeus* are nonpathogenic spores that serve as surrogates for *B. anthracis*. They were investigated to determine whether these organisms would be inactivated or remain viable after passing through a simulated landfill flare (Tufts and Rosati, 2012).

High concentration spore solutions were aerosolized, dried, and sent through a bench-scale system to simulate the fate of biological weapon (BW) grade spores in a landfill gas flare. Spores were collected from the stack exhaust using a sterile BioSampler. The flare and stack residence times were estimated to be 0.2 and 0.6 sec, respectively. A comparison of the basic operating attributes (e.g., temperatures, gas-phase residence time) showed that the bench-scale system exhibited good similarity to the real-world conditions of an enclosed standard combustor flare stack with a single orifice, forced-draft diffusion burner. All spores of *G. stearothermophilus* and *B. atrophaeus* were inactivated in the flare, indicating that spores that become re-entrained in landfill gas may not escape the landfill as viable, apparently becoming completely inactivated as they exit through a landfill flare (Tufts and Rosati, 2012).

### 2.10 Bench-Scale Flame Mechanism Studies

Nogueira and Fisher studied the flame inhibition impact of DMMP in a premixed methane/oxygen/N₂-Ar flame in a flat flame burner slightly under atmospheric pressure at two different equivalence ratios: rich and slightly lean. Interest in the combustion chemistry of organophosphorus compounds was motivated by two applications: incineration of chemical warfare agents and fire suppression. DMMP addition caused all profiles except that of CH₃OH to move farther away from the burner surface, which can be interpreted as a consequence of a reduction in the adiabatic flame speed. This shift is a consequence of the flame inhibition
properties of the DMMP additive. Decreases in the overall reaction rate with doping led to flame stabilization farther from the burner surface. Experimentally, the magnitude of the shift was 50% greater for the near-stoichiometric flame than for the rich flame. Experimental CH$_3$OH profiles were four to seven times higher in the doped flames than in the undoped flames (Nogueira and Fisher, 2003).

Korobeinichev et al. studied the possible mechanisms for the destruction of sarin in flames. The structure of a premixed H$_2$/O$_2$/Ar (0.26/0.13/0.61 by volume) flame doped with DMMP stabilized on a flat burner at 47 torr has been studied by molecular beam mass spectrometry and modeling. A study of the combustion of organophosphorus compounds (OPCs), including sarin and its simulants (phosphates and phosphonates) such as DMMP, trimethyl phosphate (TMP), and tributyl phosphate was of great interest for understanding and improving the incineration of CWAs. The hallmark of the mechanisms for the destruction of DMMP and TMP is that bimolecular reactions of either the hydroxyl radical or the free hydrogen atom are more important than unimolecular decomposition. Some conclusions on possible mechanisms for the destruction of sarin in flames can now be made. Unimolecular decomposition of sarin is likely to be less important than the substitution of C$_3$H$_7$O or C$_3$H$_7$ groups by OH or H as the rate-controlling stage for the destruction of sarin in a flame (Korobeinichev et al., 2000).

Werner and Cool developed a kinetic model of the combustion chemistry of a hydrogen/oxygen-based flame, doped with dimethyl methylphosphonate, a useful simulant for nerve agents VX and GB, to assist in the controlled thermal destruction of CWA stockpiles. The kinetic model incorporated several key reaction intermediates, which included methyl metaphosphate (CH$_3$OPO$_2$), methyl dioxophosphorane (CH$_3$PO$_2$), and monomethyl methylphosphonate (PO(OH)(CH$_3$)(OCH$_3$)) (Werner and Cool, 1999).

### 2.11 Exothermic Intermetallic Interaction

Zavitsanos et al. developed a thermobaric self-sustaining reactive composition method and device for destroying chemical or biological agents. The invention incorporates self-propagating high temperature reactive materials capable of self-sustaining reactions with the evolution of large quantities of thermal energy, creating an area of high temperatures (in excess of 800 °C). The method involves the interaction of metals, typically of Groups IV and V of the
periodic table, with aluminum, boron, carbon, nitrogen and silicon. Such intermetallic reactions occur pyrotechnically without requiring an outside oxidizer source (such as atmospheric oxygen). Energy levels released by these types of reactions can reach 17.6 kJ/cm³ (Zavitsanos et al., 2012).

Wei et al. investigated electrically conducting polymers such as polyaniline to be used as coatings or fabrics on military equipment (e.g., tanks, personnel carriers, artillery pieces, etc.) and installations (e.g., buildings and other structures). These conducting polymers function as heating elements to convert applied electric energy to thermal energy, which would raise the surface temperature of the coatings and fabrics high enough to thermally decompose the chemical or biological warfare agents on the equipment or installations. Through embedded metallic (e.g., copper) wire or carbon fiber electrodes, household alternating current can be applied to the polyaniline-coated panels leading to a rapid increase in the surface temperature from 120 to 180 °C within a few minutes to degrade CB agents (Wei et al., 2004).

A new technique uses the flameless burning of powders containing aluminum, magnesium, sodium nitrate (NaNO₃), and oil. The powder is applied as a flat layer, approximately 10 mm thick, and is used to remove surface coatings from the concrete, e.g., asphalt (Kumar et al., 2010).

Motamedhashemi et al. applied the flow-through catalytic membrane reactor (FTCMR) concept to the thermal oxidation of a chemical warfare simulant (DMMP) in air. Preliminary experiments under different DMMP feed concentrations and reactor temperatures (373 to 573 K) have demonstrated the potential advantage of the FTCMR concept in the catalytic oxidation of DMMP. Complete destruction of various concentrations of DMMP in air was achieved at lower temperatures, with the FTCMR showing superior performance when compared to a wall-coated, plug-flow reactor (monolith) containing the same amount of catalytic metal. A mathematical model was also developed to provide a better understanding of the fundamental transport phenomena underpinning the FTCMR operation. The model was used for identifying the advantages of the FTCMR concept in comparison with the wall-coated catalytic monolith and also for investigating some of the limitations, which may exist in applying this concept for the complete oxidation of chemical warfare simulants. The results of the model support the
superiority of the FTCMR concept over the more conventional plug-flow monolith reactor (Motamedhashemi et al., 2011).

2.12 Direct Heat Application

This section discusses direct heat sterilization processes for spores and evaporation rates for chemical weapons on various surfaces.

The F-value is the minimum time that an organism present in or on an item has to be exposed at a certain temperature to assure sterility of that item. Sterility of medical devices is defined as finding 1 remaining viable organism in or on an item out of $10^6$ present before sterilization ($6 \log_{10}$ reduction). F-values are used to optimize sterilization processes to save time, energy, money, or to reduce the exposure time of thermo-labile products to high temperatures. For a given temperature and time, the F-value for a process can be calculated. To calculate the F-value for temperatures other than those reported in the literature, empirical models are used with the decimal reduction time (D) and the temperature resistance coefficient (Z) as parameters. The D-value (min) is the time required to reduce the number of organisms by a factor of 10. The Z-value (°C) is the temperature required for one $\log_{10}$ reduction in the D-value. The Z-value can be found by making a thermal resistance curve by plotting the logarithm of the D-value versus the temperature. The Z-value can be found by taking the reciprocal of the slope from the plot (Doornmalen and Kopinga, 2009).

The dry heat F-value, the time (in minutes) that causes the complete destruction of microorganisms at 200 °C for 
$G. stearothermophilus$ and $B. atrophaeus$ is 1.3 and 1.1 min, respectively. These times are similar to the F-value of 1.2 min for 
$B. anthracis$ at the same temperature (Wood et al., 2010). Wood et al. conducted tests in a dry heat oven to determine the destruction kinetics for 
$B. atrophaeus$, $B. anthracis$ (Sterne) and $G. stearothermophilus$. The dry heat oven tests were conducted at 175 °C, and the D-values were 0.4, 0.2 and 0.3 min for 
$B. atrophaeus$, $B. anthracis$ (Sterne), and $G. stearothermophilus$, respectively (Wood et al., 2010). The dry heat D values and Z values are shown in Figure 2-30.
Figure 2-30. Dry Heat D-values and Z-values for Biological Indicators (*Geobacillus stearothermophilus* [squares], *B. anthracis* [circles], and *B. atrophaeus* [triangles]) (Adapted with permission from Wood et al., Copyright 2009 The Society for Applied Microbiology)

Denison et al. determined the sterilization values of *B. subtilis* spiked on ceiling tile and wallboard. The bundles were approximately 50% water. Testing was performed at the EPA’s RKIS facility. The Z values were 159 and 281 K for ceiling tile and wall board, respectively (Denison et al., 2005).

Jung et al. investigated the thermal effects on bacterial bioaerosols of *Escherichia coli* and *B. subtilis* by using a thermal electric heating system in continuous air flow. The bacterial bioaerosols were exposed to a surrounding temperature that ranged from 20 °C to 700 °C for approximately 0.3 s. Both *E. coli* and *B. subtilis* vegetative cells were rendered more than 99.9% inactive at 160 °C and 350 °C of wall temperature of the quartz tube, respectively. Although the data on bacterial injury showed that the bacteria tended to sustain greater damage as the surrounding temperature increased, Gram-negative *E. coli* was highly sensitive to structural injury but Gram-positive *B. subtilis* was slightly more sensitive to metabolic injury. In addition, the inactivation of *E. coli* endotoxins was found to range from 9.2% (at 200 °C) to 82.0% (at 700 °C). However, the particle size distribution and morphology of both bacterial bioaerosols were maintained, despite exposure to a surrounding temperature of 700 °C. The results show that thermal heating in a continuous air flow can be used with short exposure time to control bacterial bioaerosols by rendering the bacteria and endotoxins to a large extent inactive (Jung et al., 2009).
Geyer et al. described a concept of applying heat to a structure to sterilize biological agents. Dry heat of 150 °C for 10 minutes effectively sterilizes most items contaminated with active biological agents, e.g., bacteria, fungi, etc. While 150 °C may be difficult to achieve when heating an entire structure, at least not without adversely affecting some architectural elements, heating a structure and its contents to 80 °C has its merits and is possible with today’s technology. Moreover, holding a structure at 80 °C for 60 minutes not only kills most active biological agents, it accelerates the neutralization of many harmful toxins, accelerates vaporization of water vapor and chemicals, and oxidizes odors. If an anthrax-contaminated structure is heated so that the architectural components are 150 °C for 480 minutes, the structure should not only be free of viable anthrax spores, but some of the components may be damaged from the high temperature (Geyer et al., 2002).

Heat can be generated using thermal solar radiation, the heating ventilation and air conditioning (HVAC) system of a building, portable electric-inductive heaters, lamps, etc. Portable fuel-fired heaters (burning natural gas, propane, or kerosene) can also generate heat. The type of contamination helps to determine the degree of necessary heat penetration. If contamination occurs from airborne spores, the spores may be surficial and not deep within walls, dimensional timber, or masonry units. The heating process can therefore be surficial in design. Where materials have become moist and promote fungal growth and amplification, heating should be of sufficient duration to achieve the saturation temperature required to kill organisms deep within affected materials. Thermal desorption of CWAs can be achieved by the use of heated air that results in evaporation of the contaminant. With this method, the toxic agent is released into the atmosphere and may present an increased vapor hazard (Boone, 2007). Depending on the site, HEPA units could be used to filter and circulate air within the heated area, assisting in heat distribution; it may also be necessary to place HEPA units outside of the heated area and duct the air to the unit. Propane-fired burner-fan units have been demonstrated to be the most flexible, scalable, and cost-effective heat generators. Heating contaminated materials will not take the place of removing gross levels of contamination. This technology complements traditional remediation methods after gross removal is complete and reduces most labor-intensive detailed cleaning efforts currently performed to achieve clearance criteria (Geyer et al., 2002).
The evaporation rates and reaction mechanism for a droplet of distilled sulfur mustard agent from stainless steel and aluminum substrates are reported by Jung and Lee. For systematic analysis, we used a laboratory-sized wind tunnel, thermal desorption (TD) connected to a gas chromatograph/mass spectrometer (GC/MS) and droplet shape analysis (DSA). Jung and Lee found that the evaporation rates (mg/m³) of HD from stainless steel and aluminum increased with temperature as shown in Figure 2-31. The rates were also linearly proportional to droplet size. The time-dependent contact angle measurement showed that the evaporation of the droplet of HD proceeded only by a constant contact area mechanism from stainless steel surface. The evaporation of HD from aluminum proceeded by a combined mechanism of constant contact area mode and constant contact angle mode. The experimental data sets and analysis could be used to predict vapor and contact hazard persistence of CWAs in the air and on exterior surfaces with chemical releases, which assists the military decision influencing personnel safety and decontamination of the site upon a chemical attack event (Jung and Lee, 2014).

Figure 2-31. Evaporation Profiles at Different Temperatures and Drop Size for HD at an Air Flow of 175 SLPM (Reprinted from Jung and Lee, Copyright 2014 with permission from Elsevier Inc.)
Rowland et al. developed methods for testing off-gassing from selected military-relevant surfaces and to establish a model for predicting off-gassing from a broad range of such surfaces. Vapor-contaminated surfaces were investigated by exposing representative field materials to CWA simulants and then monitoring the off-gassing concentration as a function of time. Concrete, plastic, wood, steel and latex paint surfaces were contaminated with triethyl phosphate, 4-chlorobutyl acetate, 3-hepten-2-one, trimethyl phosphate, and 2-isobutyl-3-methoxypyrazine. The testing process and simple analysis model provided test and analysis methods that were used to test agent off-gassing and served as a standard for vapor hazard testing following vapor exposure. Use of the simple model was justified, based on analyses of the measured off-gassing trends and the predicted trends of interaction between each compound and each surface (Rowland et al., 2010).

A model for evaporation of chemical warfare agents on the ground was developed by Westin et al. The process of evaporation is described in three steps: 1) the immediate drop enlargement due to impact momentum is modeled using an empirical correlation from the technical literature; 2) further enlargement caused by capillary spreading upon the surface and the simultaneous sorption into the substrate, modeled in three dimensions; and 3) subsequent drying and redistribution of the sorbed material is described as a one-dimensional vertical process. The formulation of the flux in the soil takes into account vapor, liquid, solute, and adsorbed phases. The evaporation from the surface was determined by the vapor concentration at the surface and the conditions in the atmospheric viscous sub-layer close to the droplet spots on the surface. Model results agreed with the limited experimental data found in the literature. The model showed a very rapid sorption and redistribution of chemical warfare droplets on sand. This effect gives a rapid decrease of the evaporation, except for a shorter initial period. However, a small residual evaporation from liquid exists for a rather long time when the liquid has penetrated down into the soil (Westin et al., 1998).

Steam cleaning, which combines the solvent action of hot water with the kinetic energy effect of blasting, is recommended for removing contamination from complex shapes and large surfaces, even if grease or similar substances are present, and for removing contaminated soil particles from earth moving and drilling equipment. Secondary waste volumes produced by the process
are relatively low as the steam can be collected by vacuum extraction or similar means and condensed (Kumar et al., 2010).
3 NEUTRALIZATION/HYDROLYSIS AND TREATMENT OF HYDROLYSATE

This section reviews neutralization/hydrolysis of chemical agents and treatment of hydrolysate.

3.1 Neutralization/Hydrolysis

Neutralization employs process conditions that are specific for each type of agent. Thus, a neutralization process for destroying a specific agent or class of agents would not be suitable for treating a wide range of other wastes (e.g., commercial hazardous wastes). Variations in the process may be needed when treating different types of the same agent such as H, HD, and HT. A particular benefit from neutralization is that it detoxifies the mustard agent rapidly at low temperature and low pressure. Batch or semi-batch processing allows retention of the products from neutralization until testing can verify destruction of the chemical agent (Pearson and Magee, 2002).

Two methods of neutralization of mustard through hydrolysis have been demonstrated: hot water at 90 °C and a caustic solution. The Pueblo Chemical Agent-Destruction Pilot Plant (PCAPP) used hot water hydrolysis to neutralize the mustard agent. However, because sulfonium ions (SR₃⁺) present after water hydrolysis can cause a false positive in the analytical gas chromatographic method for testing the hydrolysate to establish that the hydrolysate is clear of mustard agent, a heated caustic hydrolysis step (using sodium hydroxide (caustic) at pH >10) follows the hot water hydrolysis reaction. The caustic hydrolysis removes the interference due to SR₃⁺ where R is an organic substitute such as methyl (CH₃) attached to sulfur (Nurdogan et al., 2012).

The hydrolysis process results in an irreversible chemical reaction in which the mustard agents are destroyed and a byproduct called hydrolysate is formed. In the hot water reaction, HD is converted to TDG (HOCH₂CH₂SCH₂CH₂OH), a readily biodegradable compound, and HCl. The reaction proceeds to completion with no detectable agent (< 4 ppb) remaining in the product (Nurdogan et al., 2012).
Many kinetic and mechanistic studies have been done on the hydrolysis of G-type chemical agents, which include tabun (GA), GB, and GD. Hydrolysis in basic media works well for these agents but less well with sulfur mustard (H or HD). Direct base hydrolysis is not effective for V agents, an example of which is VX. However, oxidation of the sulfur in VX in an aqueous acid medium is rapidly followed by hydrolysis to non-toxic products. An acidic medium also causes protonation of the amine nitrogen, both increasing the solubility of VX and enhancing the oxidation of sulfur (Raber and McGuire, 2002).

### 3.2 Treatment of Hydrolysate

Chemical agents can be disposed of with technologies based on chemical neutralization. This destruction process results in the production of a solution called hydrolysate that retains some undesirable characteristics and requires further treatment to comply fully with the requirements of the CWC (Pearson and Magee, 2002).

Although neutralization of HD detoxifies the agent, the resulting hydrolysate needs further treatment prior to final disposal. Treatment of the hydrolysate has to destroy both thiodiglycol, which is the major residual in the hydrolysate, and any chlorinated volatile organic compounds (VOCs) that result from impurities in the HD. Management of hydrolysate from HD neutralization may be either on site, through additional treatment following the neutralization process, or off site, by shipping the hydrolysate to a permitted waste-management facility (Pearson and Magee, 2002).

On-site treatment of the hydrolysate requires substantially more complex processing than does the neutralization process alone. The primary process considered for on-site treatment of mustard agent hydrolysate is biodegradation. Aqueous effluent from an on-site biodegradation process could potentially be discharged to the existing publicly or federally owned treatment works or, alternatively, the water could be recycled if zero liquid effluent discharge is desired (Pearson and Magee, 2002).

The hydrolysate produced by the neutralization of mustard is a turbid amber liquid that is approximately 90% water and salts (mainly sodium chloride and iron salts). HD mustard is hydrolyzed to an organic chemical called thiodiglycol (TDG), while HT mustard is hydrolyzed to TDG and a similar compound, T-alcohol (an ethyl ether compound) (Nurdogan et al., 2012).
3.2.1 Incineration of Hydrolysate

Ember reported on the incineration of VX hydrolysate (VXH) from the destruction of VX chemical weapons in Newport, Indiana. The VXH was transported to the Veolia Environmental Services incineration facility in Port Arthur, Texas. By March of 2008, 84% of the VXH was incinerated (Ember, 2008).

Notman reported that following pressure from the international community, the Syrian government joined the Chemical Weapons Convention (CWC) and in doing so, agreed to destroy their chemical weapon stockpiles. In September 2014, the Syrian government declared approximately 1,000 tonnes (1,100 tons) of chemical weapons, mostly precursors, and approximately 290 tonnes (319 tons) of raw materials. The blister agent sulfur mustard was the only complete chemical weapon declared. The plan was to chemically neutralize approximately 560 tonnes (616 tons) of sulfur mustard at sea aboard the US Navy ship Cape Ray. The effluent from the Cape Ray hydrolysis operation was incinerated in Germany. The mustard would be hydrolyzed using a batch process facilitated by the titanium reactor at a ratio of approximately 13.5 parts 95 °C water to one part ambient mustard. The mustard breaks down in hot water to hydrochloric acid and thiodiglycol. The second step was to adjust the pH of the effluent to neutral using sodium hydroxide. The neutralization process generates hazardous waste effluent in volumes of five to 13.5 times the volume of the chemical warfare material being treated (Notman, 2014).

3.2.2 Supercritical Water Oxidation of Hydrolysate

A one-component fluid is loosely defined to be supercritical when its temperature and pressure exceed its critical temperature and pressure, respectively, while it is not far from its critical state. Supercritical water oxidation (SCWO) is the oxidation of organics with air or oxygen, in the presence of a high concentration of water, under temperatures and pressures above the critical point values of water, 374 °C and 22 MPa (218 atmospheres) (Yesodharan, 2002).

As a waste destruction process, SCWO has several advantages over conventional processes and even some of the relatively modern processes such as wet-air oxidation and incineration. These advantages arise mainly from the properties of supercritical water (SCW) itself. The gas-like low viscosity promotes mass transfer. The liquid-like density promotes solvation. The low
dielectric constant promotes dissolution of nonpolar organic materials. The high temperature increases thermal reaction rates. These properties provide a reactor medium in which mixing is fast, organic materials dissolve well and react quickly with oxygen, and the salts precipitate (Yesodharan, 2002).

The oxidation reaction is complete when carbon goes to carbon dioxide, hydrogen to water, nitrogen compounds to nitrogen or nitrous oxide. Heteroatoms form the corresponding oxyacids or salts if cations are present in the waste or added to the feed. Under supercritical conditions, the salt may remain dissolved in the SCW medium or condense as a concentrated brine solution or as a solid particulate. Heavy metals may form oxides or carbonates, which may or may not precipitate, depending on their volatility. Inert solids will largely be unaffected by the medium and remain as solids. Time required to complete the reactions is short. Reactor residence time ranging from a few seconds to a few minutes is sufficient for complete decomposition of most waste materials. Shorter reactor residence time means higher waste throughput (Yesodharan, 2002).

SCWO was originally selected for the treatment of the hydrolysate from the nerve agent VX stored at the Newport, Indiana, storage site. The SCWO system is a hydrothermal process for the oxidation of hydrolysate that yields a wastewater stream and salts. In a typical chemical agent destruction process, agent would be drained from the weapon or container, hydrolyzed in a well-stirred reactor, tested to verify agent destruction, and then released to the SCWO process unit. The hydrolysate is heated and pumped into an SCWO reactor along with an oxidizing agent (air or oxygen), and the heat of reaction increases the temperature to 600 to 650 °C under about 275 bar pressure. In the course of approximately 30 s, the organic components are largely (approximately 99.99 %) oxidized to water and sodium salts, as well as gaseous nitrogen containing products (e.g., N₂ and NOₓ). This mixture of materials is cooled by adding quench water and through heat exchange and then released from the SCWO reactor through a pressure reduction system. The resulting effluent is a mixture of gases (O₂, N₂, CO₂), a concentrated aqueous salt solution, and entrained solid salts. Trace concentrations of partially oxidized organic constituents may also be present. The aqueous products from the SCWO reactor, including entrained solids, are then fed to the evaporation unit, where the mixture is heated to distill excess water. At this point, the salts that have crystallized from solution are filtered and
packaged for disposal in a secure landfill. A large portion of the water distilled from the SCWO effluent is recycled back to the process. All gases reduced during the SCWO treatment step are filtered prior to release (Pearson and Magee, 2002). The Newport site decided to use incineration for hydrolysate treatment at Veolia in Port Arthur, TX (hydrolysate was shipped there).

DMMP is a simulant for VX. DMMP can readily be hydrolyzed to methylphosphonic acid (MPA) during the preheating stage of the SCWO process. Laboratory-scale, continuous-flow reactor tests were conducted to confirm the destruction efficiency of MPA and the effect of sodium hydroxide on MPA destruction efficiency under SCWO conditions. The reaction temperatures ranged from 400 to 594 °C; the reactor residence times varied from 3 to 83 s; and the oxygen concentrations varied from 110 to 200% of stoichiometric requirements. Fixed parameters included: (1) a nominal pressure of 27.6 MPa (4,000 psi); (2) a MPA feed concentration of 1,000 mg/L; (3) a feed flow rate of 25 g/min; and (4) a NaOH to MPA molar ratio of 2:1. MPA was effectively destroyed, as indicated by the C-P bond cleavage, within the selected SCWO conditions. Specifically, greater than 99% DE of MPA was achieved at a temperature of 550 °C, pressure of 27.6 MPa, oxygen concentration of 200% of stoichiometric requirements, and reactor residence times of less than 20 s. In addition to the oxidation end product of CO₂, CO and CH₄ were major gaseous byproducts. Methanol was the only liquid organic byproduct detected. Data derived from these limited MPA/NaOH experiments indicated that the formation of salts did not affect the overall effectiveness of SCWO for destroying MPA. Eventually, means to remove precipitated salts from the reactor should be incorporated into the overall design of an SCWO facility for treating the VX/NaOH hydrolysate (Bianchetta et al., 1999).

Kim et al. reported that in 2003, neutralization followed by SCWO was selected as the technology to destroy the chemical weapons stockpile at the Blue Grass Army Depot. After neutralization and chemical analysis, the hydrolysate was transferred with oxidizing agent (air or oxygen) to the SCWO. The SCWO reaction mechanism generally follows free radical chain pathways that involve important oxidative radicals such as •OH and •OOH. Within approximately 30 s, the organic components were largely oxidized to water and sodium carbonate, phosphate, and sulfate, as well as gaseous nitrogen-containing products (e.g., N₂ and
N₂O). After cooling with quench water, the mixture from the SCWO reactor was released through a pressure reduction system. The resulting effluent was a mixture of gases (O₂, N₂, and CO₂), a concentrated aqueous salt solution, and entrained solid salts. The aqueous salts underwent distillation to remove water in the evaporating section. Salts crystallized from this solution were filtered and packaged for landfill disposal. The disadvantage of second-stage technology is the corrosion of heating and cooling elements on either side of the supercritical water reactor. Frequent replacement of the reactor liner was planned for the SCWO units at the Blue Grass Chemical Agent Destruction Plant (Kim et al., 2011).

3.2.3 Biological Treatment of Hydrolysate

Biodegradation exploits the ability of certain microorganisms—bacteria or fungi—to degrade hazardous organic materials to innocuous materials such as carbon dioxide, methane, water, inorganic salts, and biomass. Microorganisms can derive the carbon and energy required for growth through biodegradation of organic contaminants. The biodegradation of organic constituents in agent destruction process streams can be carried out either on site in coordination with the agent destruction process or off site at a permitted commercial TSDF (treatment, storage, or disposal facility) (Pearson and Magee, 2002).

The bioreactor design for aerobic treatment needs to solve two problems. First, the bacteria must be in contact with the contaminants for extended periods of time to complete the biochemical reactions. Secondly, the design needs to ensure oxygen transfer to the bacteria. Energy requirements for oxygen transfer usually constitute the main operating cost of a bioreactor, other than manpower costs. Designs for biological treatment of hydrolysate are based on systems designed to treat wastewater. Bioreactors for treating contaminated water can be separated into several main types:

- **Suspended-growth reactors.** The bacteria are grown in the water and mixed with the organic contaminants in the water. Oxygen is supplied through a surface aerator or air diffusers.
• **Fixed-film reactors.** The bacteria are grown on an inert support medium within the reactor. The contaminated water passes over the attached bacteria and forms a thin water film into which the contaminants and oxygen diffuse.

• **Submerged fixed-film reactors.** In this version of the fixed-film reactor, the water is in constant contact with the bacterial film, as opposed to passing through in thin water films.

• **Reactors based on activated carbon.** The combination of powdered activated carbon adsorbs organic contaminants and acts as an attachment site for bacteria (Pearson and Magee, 2002).

In an aqueous solution, sulfur mustard spontaneously hydrolyzes and generates TDG. Thus, TDG as a hydrolyzate of sulfur mustard will accumulate in soil and remain in nature for long periods. Nocardioforms of bacterium such as *Rhodococcus* and *Gordonia* are frequently isolated from soil and have been shown to exhibit a wide range of degradative and/or oxidative functions, including hydroxylation, sulfoxidation, or dehalogenation. Cultivation and resting cell reactions are carried out aerobically at 30 °C. The reaction was started by adding the substrate TDG aqueous solution to the cell suspension. Among the tested strains, strain T09 showed the highest degradation activity as shown in Figure 3-1 where cell growth increased with time and TDG concentration decreased (Bassi et al., 2009).
Nurdogan et al. described the design of an Immobilized Cell Bioreactor (ICB) for treatment of hydrolysate at the PCAPP in Pueblo, Colorado. The design was based on laboratory and pilot testing results, which defined organic loading rates, hydraulic retention times (HRTs), aeration and nutrient requirements, and operational parameter ranges and controls (temperature, dissolved oxygen, and pH). PCAPP was expected to generate an estimated 8,400,000 gallons of mustard hydrolysate. After the caustic addition and hydrolysis, the agent hydrolysate was between 10 and 12. After neutralization, the pH of the hydrolysate was treated by the ICB, an aerobic fixed-film bioreactor packed with 2-inch polyurethane foam cubes and plastic spacers (bio-rings). The hydrolysate was pumped into aerated treatment tanks containing a mixed culture of microorganisms that digest and break down the complex organic compounds into simpler forms. The influent and effluent concentration of TDG from the bioreactor was measured weekly for six months. The effluent TDG concentration was below detection for much of the test. The treated water from the ICBs was evaporated and recovered for recycling in the plant. Various salts and biosolids left behind were dewatered and sent offsite for disposal. The PCAPP ICBs were designed for 4-5 days of HRT and 120-200 days of sludge retention time SRT (Nurdogan et al., 2012).

3.2.4 Treatment of Hydrolysate Using Photoactivated Periodate

Tang and Weavers reported on the kinetics and mechanism of periodate and photoactivated periodate oxidation of the hydrolysates of chemical warfare agents, TDG, 3,3-dithiopropanol
(DTP), and 1,4-thioxane (TX). These hydrolysates were investigated at pH 3, pH 7, and pH 10 under dark and monochromatic UV light irradiation. The presence of monochromatic UV light at 220 nm, 240 nm, or 254 nm made insignificant improvements in hydrolysates of chemical warfare agents HCWA degradation at low pH (Tang and Weavers, 2007).
4 INCINERATOR MODELING RESULTS

Systematic evaluation of the effectiveness of incineration of CB agents bound on building materials in a full-scale incineration system is not practical. The chemical demilitarization incinerators that process CWAs on a routine basis are tightly regulated facilities that have strict operating permits, in addition to the international agreements that define their operations. These facilities would not be amenable to a performance test where there may be suboptimal operating conditions as part of the test matrix. Testing CB agents on conventional incinerators would be difficult at best, due to community relations and shareholder issues with the facility that would likely arise, even if the permitting hurdles could be overcome. In addition, performing such a test on a full-scale facility that potentially would require tens to hundreds of tons of feed material per day would be prohibitively expensive.

Rather, an approach has been taken to perform bench- and pilot-scale testing using surrogates, combined with computer simulations of full-scale incineration facilities that use the data derived through the sub-scale experiments and other sources to provide the required kinetic mechanistic information. Figure 4-1 illustrates this concept.

Figure 4-1. Modeling Concept
To achieve this goal, a computer simulation was developed that was based on a simulation developed for the U.S. Department of Defense (DoD) to predict the behavior of CWA-containing munitions in the various furnaces used in the chemical demilitarization program (Denison et al., 2004). This simulation was adapted to model conventional full-scale incinerators feeding solid fuel mixed with arbitrary solid materials with user-defined amounts of chemical and biological agents bound on the solid materials. This simulator was called “The Configured Fireside Simulator” or CFS. The kinetic data for CWA destruction were the same mechanisms used in the previous work for the DoD (Denison et al., 2004). The kinetic data for the BWA destruction was derived from the bench-scale experiments described earlier (Lemieux et al., 2005).

This section discusses the results from the incinerator models using EPA’s CFS tool to model the destruction of three chemical agents (GB, VX, and HD) and one f (Ba) with three types of furnaces: a commercial hazardous waste burning rotary kiln (COM), a medical/pathological waste incinerator (MEDPATH), and a stoker furnace (STO).

In 2005, Lemieux evaluated thermal processing of BDR material in commercial incinerators by using an incinerator modeling tool developed by EPA. The simulator included a range of models, from time-dependent process models to detailed Computational Fluid Dynamics (CFD) models. Using computational chemistry methods, detailed chemical kinetic mechanisms were developed that describe the incineration of mustard blister agent and the nerve agents GB and VX. The first unit, the EPA RKIS facility, is a simulated pilot-scale rotary kiln incinerator located at the EPA research facilities in RTP, NC. The EPA RKIS facility has a primary and secondary burner, each rated at 73 kW. The second combustion unit is a commercial dual-chamber starved-air modular medical/pathological waste incinerator that is currently being operated jointly by the EPA and National Institutes of Environmental Health Sciences (NIEHS) on their RTP, NC campus. This facility has a nominal firing rate of 1 megawatt MW and is capable of processing approximately 400 kg/h of wastes, which consist mostly of animal bedding. The third combustion unit is a commercial hazardous waste-burning rotary kiln system currently in operation in East Liverpool, OH. This unit has a nominal firing rate of 35 MW and processes approximately 8,100 kg/h of hazardous waste from various sources. Data available for interrogation from the CFD model include gas temperature, velocity, agent concentration, combustion products (major and minor species), pressure as well as wall and equipment surface
temperatures and incident heat fluxes. Pilot-scale experiments were used to calibrate the models (Lemieux et al., 2005).

In 2015, EPA ran incinerator models following the design factors in Table 4-1 with three furnace types, four CB agents, and three bundle bed locations in the furnace. The bed location was the percent of the bundle exposed to hot gas in the furnace. The high bed location corresponds to 70% of the bundle exposed to the hot gas. For the mid and low conditions, 45% and 20% of the bundle was exposed to the hot gas in the furnace, respectively. Therefore, the low bed condition simulated bundles buried in the furnace. In Table 4-2, the simulator model test parameters are presented.

**Table 4-1. Experimental Design Factors for CFS Model**

<table>
<thead>
<tr>
<th>Factor Level</th>
<th>Furnace</th>
<th>Agent</th>
<th>Bed Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stoker</td>
<td>GB</td>
<td>low</td>
</tr>
<tr>
<td>0</td>
<td>Med/Path</td>
<td>VX</td>
<td>mid</td>
</tr>
<tr>
<td>-1</td>
<td>Rotary Kiln</td>
<td>HD</td>
<td>high</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td>Ba</td>
<td></td>
</tr>
</tbody>
</table>

Nine net files were created for each furnace model with inputs for the type of agent, bundle moisture content, and bed location. A total of 36 net files were created. After the net files were created, the net files were entered into the CFS simulator and executed in transient mode. The bundle parameters (density, conductivity, specific heat, moisture mass fraction, surface emissivity, dimensions, and Z value [for biological agents]) in the CFS simulator are shown in Figure 4-2. Group A is for the furnace type, group B for the agent, and group C for the bed location.
Table 4-2. Simulator Model Table of Test Parameters

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Furnace</th>
<th>Agent</th>
<th>Bed Location</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>A₁,₁</td>
<td>B₁</td>
<td>C₁</td>
</tr>
<tr>
<td>2</td>
<td>A₀,₁</td>
<td>B₁</td>
<td>C₁</td>
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<td>20</td>
<td>A₀</td>
<td>B₀,₅</td>
<td>C₁</td>
</tr>
</tbody>
</table>

Figure 4-2. CFS COM Model Bundle Input Parameters
4.1 COM Model

This section discusses the CFS COM model results. The CFS simulator allows the user to plot furnace parameters against time. The gas temperature, the minimum temperature of pieces of bundle, and fraction of agent remaining were plotted against time in the furnace.

4.1.1 Gas Temperature

In Figure 4-3, the gas temperature for $Ba$, $GB$, $HD$, and VX are plotted versus time for the COM model. The gas temperature is the highest (approximately 1,200 °C) for the low bed condition for all the agents, which is expected as the bundle is buried in the furnace. The gas temperature is the lowest (approximately 1,125 °C) for the high bed location condition (bundles are not buried in the furnace and are exposed to hot gas) for $GB$, $HD$, and VX. For $GB$, $HD$, and VX the gas temperatures are fairly stable for all bed conditions.

Figure 4-3. COM Model, Gas Temperature
4.1.2 Minimum Piece Temperature

In Figure 4-4, the minimum piece temperatures for \( Ba \), GB, HD, and VX are plotted versus time for the COM model. In the plots, the temperature remains at 100 °C for approximately 50 minutes as the water in the bundles vaporizes. Then, the bundle temperature starts to increase again. The high and medium bed locations reach 100 °C before the buried bundles in the low condition. For all the agents, the temperature in the bundle for the low bed condition does not increase above 450 °C at the end of the heating cycle, whereas for the high and medium bed conditions, temperatures climb to approximately 600 °C. For \( Ba \), the temperature reaches 450 °C after 475 minutes at the low bed condition, but it takes approximately 300 minutes to reach the same temperature for GB, HD, and VX.

![COM Model Piece Tmin, Ba](image1)

![COM Model Piece Tmin, GB](image2)

![COM Model Piece Tmin, HD](image3)

![COM Model Piece Tmin, VX](image4)

**Figure 4-4. COM Model, Minimum Piece Temperature**
4.1.3 CB Agents Remaining

In Figure 4-5, the fraction of agent left for Ba, GB, HD, and VX is plotted versus time for the COM model. For all the agents, the low bed condition requires the most time for all of the agent to be destroyed. For Ba, no agent remains after 45 minutes for the high bed condition, but approximately 350 and 400 minutes, respectively, are required for all the agent to be destroyed for the medium and low bed conditions. For GB, HD, and VX, no agent remains for the high bed condition after 175, 180, and 220 minutes, respectively. VX required the most time to destroy all the agent as it has a higher boiling point (298 °C) than HD (218 °C) and GB (158 °C).

Figure 4-5. COM Model, Agent Left
4.2 Stoker Model

This section discusses the stoker model results. The gas temperature and the minimum piece temperature are plotted with time for Ba, GB, HD, and VX.

4.2.1 Gas Temperature

In Figure 4-6, the gas temperature for Ba, GB, HD, and VX is plotted with time. For all the CB agents and bed conditions, the gas temperature profiles are similar. The gas temperature rises quickly to 200 °C, then climbs to 1,200 °C after approximately 360 minutes.

Figure 4-6. Stoker Model, Gas Temperature
4.2.2 Minimum Piece Temperature

In Figure 4-7, the minimum piece temperature for $Ba$, GB, HD, and VX is plotted with time for the stoker model. For all the CB agents, the minimum temperature for the low bed condition does not raise above 100 °C. The high bed condition reaches 100 °C before the other bed conditions. The medium and high bed conditions remain at 100 °C for approximately 70 minutes for all the agents. The minimum temperature for the medium bed location rises to approximately 300 °C for all the agents. For all the agents, the minimum piece temperature reaches approximately 400 °C for the high bed condition.

Figure 4-7. Stoker Model, Minimum Piece Temperature
4.3 MEDPATH Model

This section discusses MEDPATH model results. The gas temperature, the minimum temperature of a piece of bundle, and the fraction of agent remaining are plotted against time for Ba, GB, HD, and VX.

4.3.1 Gas Temperature

In Figure 4-8, the temperatures rise quickly to 850 °C for the first cycle and peak at approximately 1,100 °C before dropping. The peak temperatures for the subsequent cycles are lower, approximately 1,025 °C for all the agents. For the third cycle in the plots, the temperature of the lower bed condition rises before the other bed conditions.

Figure 4-8. MEDPATH Model, Gas Temperature
4.3.2 Minimum Piece Temperature

In Figure 4-9, the minimum piece temperature is plotted for \( Ba \), GB, HD, and VX with time. For all the agents the high bed condition reaches 100 °C before the other bed conditions and climbs to approximately 725 °C after approximately 500 minutes. Approximately 60 minutes is required to boil off the water in the bundles. For all the agents, the low bed condition reaches a maximum temperature of 650 °C.

Figure 4-9. MEDPATH Model, Minimum Piece Temperature

4.3.3 Agent Left

In Figure 4-10, the fraction of agent remaining is plotted for \( Ba \), GB, HD, and VX against time. The low bed condition required the most time to destroy all the agent. For VX at the low bed condition, approximately 480 minutes was required to have no agent remaining, but for \( Ba \), approximately 425 minutes was required to destroy all the agent.
Figure 4-10. MEDPATH Model, Agent Left
5 CREMATION OF HUMAN REMAINS FOLLOWING CHEMICAL AND BIOLOGICAL AGENT INCIDENTS

This section describes the US and UK protocols for cremation of human remains contaminated with CB agents.

5.1 U.S. Military Protocols

Ryder described the decontamination process for remains of military personnel contaminated with CB agents. Mortuary Affairs defines contaminated remains as ‘remains of personnel which have absorbed or upon which have been deposited radioactive material, or biological, or chemical agents’. Mortuary doctrine for decontamination remains much the same as it has been for the last 20 years and depends upon sodium hypochlorite (5% solution) and water in sufficient amounts to wash away and/or dilute the presence of chemicals. The decontamination efforts are carried out in full individual protective equipment (IPE), most likely worn at the highest mission-oriented protective posture (MOPP) levels. Decontamination of remains is done using nearly the same methods used in decontaminating equipment. Therefore, the decontamination process just cleans the exterior surface. Men and women killed by biological or chemical weapons will most likely have ingested or absorbed the agents in some way, making their remains contaminated on the inside. The outside and inside levels of contamination will vary. In 2002, Mortuary Affairs ordered a re-evaluation of existing mortuary policy to assess the policy that cremation is not an option for contaminated remains (Ryder, 2003).

The U.S. Army prepared a report to assist emergency managers, medical examiners, and coroners to better prepare for and determine the best course of action for responding to a mass fatality situation following a chemical weapon of mass destruction (WMD) incident. At the federal level, the Disaster Mortuary Operational Response Team (DMORT) is the only response organization prepared to handle large numbers of fatalities. Time, effort, and resources may dictate a blanket policy to mass incinerate all animal remains resulting from a chemical WMD incident. To ensure that human remains are free from contamination, the medical examiner should monitor human remains before releasing them to the community for final disposition. Two main types of chemical agent monitors exist. The Chemical Agent Monitor (CAM) provides high level monitoring capability, which technicians use to monitor levels of agent. The
second type of monitoring is mass spectrometer monitoring. This type of monitor is used for low level monitoring. Army Regulations (AR 385-61) state that all chemical warfare agents are nullified when exposed to temperatures of 1,000 °F for fifteen minutes. United States crematoria set their cremation temperature higher than 1,000 °F, so cremation will nullify all chemical agents. Cremation of human remains requires temperatures approximately 650 °C for sufficient lengths of time (usually 2.5–3 hours) for complete burning (Morgan, 2004). When contamination cannot be mitigated with decontamination efforts, involuntary individual cremation may be the only remaining option. The emergency plan of a jurisdiction should reflect the location and capability of area crematoria. Medical examiners should consider preparing remains for cremation even if authorities have not determined their final disposition. The appropriate time to prepare remains for possible cremation is before they are embalmed. Personnel should scan and remove all internal devices such as automatic defibrillators and internal pacemakers before embalming, and personnel should be wearing PPE. A flow diagram for processing contaminated remains is shown in Figure 5-1 (US Army, 2003).

Figure 5-1. Flow Diagram for Processing Contaminated Remains (Published by US Army, 2003, No Permission Required)

5.2 UK Protocols

The UK Home Office recommended that if cremation were chosen as the disposition option for victims contaminated with CB agents, the victim must first be placed in a chemical resistant body bag. The crematorium should be located in a remote area to reduce the number of potential human receptors. The crematorium should be fitted with regulation air filters to reduce emissions. Ashes should be collected and sealed in an air tight container. All personnel
involved with the disposal should wear the correct PPE. Decontamination of the crematorium may also be necessary after cremation (Home Office and Cabinet Office, 2004).

Baker et al. reported that crematoria are carefully regulated to prevent environmental hazards from emissions. Current UK regulations state that crematoria must be a minimum distance from dwellings (100 yards in London or 200 yards elsewhere in the United Kingdom (UK)). The cremation process works at temperatures in excess of 600 °C. A crematorium can function continuously for a period of several days or weeks, should the demand to cremate a large number of fatalities arise. However, only one body may be cremated at any one time in each crematorium. Coffins awaiting cremation require temporary storage in the committal room; therefore, the necessary space and ventilation may present problems. In the UK, it is doubtful whether a cremation order would be available quickly from the appropriate legal authority (the coroner) for all fatalities following a chemical, biological or radiological (CBR) release. Therefore, a storage facility at 4 °C would be required. A coffin alone may not provide sufficient containment for a contaminated body, due to the likelihood of offgassing, aerosolized agents, or leakage of fluids. Double-bagging of the body will be necessary, preferably in a body bag specifically designed for CBR-contaminated bodies. Equipment that minimizes the time that crematorium personnel spend near the coffin, or the resultant ash, should be utilized (catafalque, hearth type) (Baker et al., 2008).
6 CONCLUSIONS

This report reviewed literature on the destruction of CB agents and surrogates bound on materials such as ceiling tiles, wallboard, carpet, fiberglass, aluminum, concrete, pumice, stone, wood, stainless steel, laminate, asphalt, brick, and others. A summary table of the operating conditions and results from the thermal and hydrolysate treatments discussed in this review are presented in Appendix A. The log reduction, destruction efficiencies, F-, D- and Z-values, and spore survivability are included in the summary table.

Incineration of materials contaminated with CB agents is widely reported in the literature. Incomplete combustion of CB agents should not occur, provided that the temperature and exposure time used are sufficient to decompose the organic chemicals to simple inorganic chemicals. There is not a significant amount of literature on the destruction of CB agents at MWCs and MWIs. The majority of the literature on the destruction of CB agents using incineration involves the use of HWCs.

For the incinerator modeling presented, the incinerator models are calibrated using empirical data collected from pilot-scale experiments, mechanistic data from experiments, or derived using molecular modeling techniques. Denison et al. (2002) found that models are useful in simulating incineration system upset conditions and failures that could lead to an agent release, so that appropriate design and operational modifications can be made to mitigate such occurrences.

CB agents can readily be absorbed into porous materials and can lead to unexpected persistence of the agent, even after measures have been taken to decontaminate. The results from this review found that more porous materials are much harder to treat effectively than less porous materials using thermal destruction methods. Compiling the operating conditions in this review could facilitate the management of the waste generated during cleanup following a CB contamination incident.
7 REFERENCES


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Appendix A
Summary Table of Thermal Processes for CB Agent Destruction
## Table A1. Summary of Test Conditions and Results for Thermal Processes

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Incineration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bench scale study with CWA simulant, Malathion at an initial concentration of 300,000 μg/L. Tested in an oven ramped up to 400 °C (following hazardous waste incinerator (HWI) temperature increases) then maintained at that temperature for 30 minutes.</td>
<td>The Malathion concentration averaged 911 µg/L at 175 °C after 30 minutes of exposure (99.7% destruction).</td>
<td>Lemieux et al., 2010</td>
</tr>
<tr>
<td>Pilot-scale rotary kiln incinerator, <em>G. stearothermophilus</em> spiked on dry and wet ceiling tile bundles. The incinerator temperature was 804 – 827 °C.</td>
<td>Dry ceiling tile bundles had a 1 to 2 log_10 reduction at 5 to 10 minutes and 6 log_10 reduction after 12 minutes. Wet ceiling tile bundles 35 – 38 minutes for 6 log_10 reduction.</td>
<td>Wood et al., 2006</td>
</tr>
<tr>
<td><em>B. subtilis</em> ceiling tile samples were heated in a quartz reactor operating at 150, 200, 250, and 315 °C, for various time intervals.</td>
<td>6 log_10 reduction at 2.5, 3, 6, and 21 min at 315, 260, 204, and 148 °C, respectively.</td>
<td>Lemieux et al., 2005</td>
</tr>
<tr>
<td><em>G. stearothermophilus</em> spiked on wet and dry ceiling tile bundles tested in a pilot-scale rotary kiln incinerator.</td>
<td>6 log_10 reduction in 6 and 30 min at 1,093 °C for dry and wet ceiling tile, respectively. 6 log_10 reduction in 13 and 38 min at 824 °C for dry and wet ceiling tile, respectively.</td>
<td>Wood et al., 2008</td>
</tr>
<tr>
<td>Dry heat oven tests conducted at 175 °C with wallboard spiked with <em>B. atrophaeus</em>, <em>B. anthracis</em> (Sterne) and <em>G. stearothermophilus</em>.</td>
<td>The D-values were 0.4, 0.2 and 0.3 min for <em>B. atrophaeus</em>, <em>B. anthracis</em> (Sterne) and <em>G. stearothermophilus</em>, respectively, on wallboard</td>
<td>Wood et al., 2009</td>
</tr>
<tr>
<td><em>B. subtilis</em> spiked on wallboard and ceiling tile tested in the pilot-scale rotary kiln incinerator</td>
<td>For <em>B. subtilis</em>, the Z values were 159 and 281 K for ceiling tile and wall board, respectively. The 6 log_10 reduction for <em>B. subtilis</em> on wallboard occurred at 1,700 sec at 600 °F, 2,700 sec at 500 °F, and 4,500 sec at 400 °F.</td>
<td>Denison et al., 2002</td>
</tr>
<tr>
<td>Test data compared to incineration model for HD destruction.</td>
<td>A furnace temperature of 850 °C was required for complete destruction of HD, which was comparable to the model output.</td>
<td>Denison et al., 2002</td>
</tr>
<tr>
<td><em>B. stearothermophilus</em> spiked on medical waste feed in the small medical waste incinerator operating at 816 °C.</td>
<td>At least a five log reduction of the spores was achieved, although viable spores were detected in 10 out of a total of 48 air emission test runs, and spores were detected in 10 out of 27 available ash samples.</td>
<td>Wood et al., 2004</td>
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<tr>
<td><strong>Plasma Systems</strong></td>
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<tr>
<td>Thermal plasma test with the Montec steam torch with <em>B. stearothermophilus</em> spiked on fiberglass and other substrates.</td>
<td>At 90 kW power, the steam plasma produced a 99.94% or greater kill rate for <em>B. stearothermophilus</em> on fiberglass substrates at velocities up to 2 ft/s at a distance of 1 inch from the exit plane. At this same power level and at a distance of 3 in, the percent kill ranged from 97% to 85% as the speed increased from 0.5 to 2 ft/s. At the lower power level of 60 kW, the maximum speed that would produce 99.94% kill at 1 in was 1.5 ft/s.</td>
<td>Farrar et al., 2000</td>
</tr>
<tr>
<td>Test Conditions</td>
<td>Results</td>
<td>Reference</td>
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<tr>
<td>Atmospheric Pressure Plasma Jet (APPJ) effluent temperature of 175 °C tested with <em>Bacillus globigii</em></td>
<td>Results indicate a seven-log kill of <em>Bacillus globigii</em> spores in 30 s at 5 mm distance, which was ten times faster than dry heat at the same temperature.</td>
<td>Rosocha et al., 2003</td>
</tr>
<tr>
<td>Cold plasma test; exposures were conducted at a system pressure of 30 torr, exposure temperature of 70 °C, plasma-to-sample standoff distance of 10 cm, and 10% addition of oxygen or hydrogen to a helium balance. The agents studied were VX, HD, and GD on aluminum.</td>
<td>VX decontamination (99.9%) was achieved in 8 to 16 min of exposure, while under 2 min was required for the more volatile HD and GD.</td>
<td>Herrmann et al., 1999</td>
</tr>
<tr>
<td>Glow discharge at atmospheric pressure and enhanced corona discharge at atmospheric pressure with <em>Pseudomonas aeruginosaa</em> on nitrocellulose filter membrane and in a liquid broth. <em>B. subtilis</em> in Luria–Bertani and <em>E. coli</em>.</td>
<td>15 min was required to sterilize a sample of <em>Pseudomonas aeruginosaa</em> on nitrocellulose filter membrane. For <em>Pseudomonas</em> in a liquid broth, only half of the initial cells were killed in 15 min. For <em>B. subtiliss</em> in Luria–Bertani broth at 42 W and after a 12-min exposure time, about 100 cells were still alive as compared to complete kill in 8 min for <em>E. coli</em> using ECDAP.</td>
<td>Laroussi et al., 2000</td>
</tr>
<tr>
<td>OAUGDP testing <em>B. steaerothermophilus</em> spores on nitrocellulose, <em>B. subtilis var. niger</em>, <em>B. pumilus</em> spores on paper, <em>B. subtilis</em> on glass, and <em>E. coli</em> on glass and polypropylene.</td>
<td><em>B. steaerothermophilus</em> spores on nitrocellulose, were killed to five logs in 5.5 min. <em>B. subtilis var. niger</em> spores took 4 min (to 4 log&lt;sub&gt;10&lt;/sub&gt; reduction), while it took only 2.5 min to inactivate approximately the same number of <em>B. pumilus</em> spores on paper. <em>B. subtilis</em> on glass, 3 log&lt;sub&gt;10&lt;/sub&gt; reduction after 60 seconds (D1 at 13 sec, D2 at 10 sec). <em>E. coli</em> on glass 70 seconds for 2 log&lt;sub&gt;10&lt;/sub&gt; (D1 33 sec, D2 7 sec), <em>E. coli</em> on polypropylene, 24 sec 5 log&lt;sub&gt;10&lt;/sub&gt;, D1 6 sec, D2 2 sec.</td>
<td>Montie et al., 2000</td>
</tr>
</tbody>
</table>

### Microwave Irradiation

- **Microwave treatment for airborne *B. subtilis var. niger*, *Pseudomonas fluorescens*, and *Aspergillus versicolor* at 750 W, 385 W and 119 W for 1.5 minutes.**
  - The survival rates of airborne *B. subtilis var. niger* spores were shown to be about 35%, 44% and 35% when exposed to the microwave irradiation for 1.5 min with 750 W, 385 W and 119 W power applied, respectively. The airborne *Pseudomonas fluorescens* was shown to have lower survival rates of 5.8%, 12.2% and 21%. 12%, 20%, 25% rates at respective powers were observed for airborne *Aspergillus versicolor*.
  - Wu and Yao, 2010

- **Microwave at 750 W for *B. subtilis* on PAN nanofibers.**
  - For *B. subtilis* at 750 W for 90 s, 2.7 log disinfection on PAN nanofibers.
  - Zhang et al., 2010

- **TPAC compound with anthrax-type spores with standard microwave equipment at moderate power.**
  - A 5.5 out of a total of 6 log kill was achieved with TPAC compound and anthrax type spores.
  - McFarland et al., 2001

- **E. coli, MS2 bacteriophage, and *B. subtilis* static on-filter tests and dynamic system test with microwave irradiation.**
  - Biological agents were able to be completely destroyed by microwave irradiation within 2 minutes, with *E. coli* being the most sensitive and *B. subtilis* endospores being the least sensitive. For the dynamic system in-flight filtration coupled PAN nanofiber filtration at 500 W of continuous microwave application, the system was able to remove over 95% of viable MS2 virus and *B. subtilis*.
  - Wu et al., 2009
Table A1. Summary of Test Conditions and Results for Thermal Processes (Continued)

<table>
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<tr>
<th>Test Conditions</th>
<th>Results</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Microwave and catalysts tested with DMMP initially at 300 ppm and DES at 600 ppm.</td>
<td>The best DRE (&gt;99.5%) was obtained from tests using the alumina-based vanadium catalyst after 35 min at 300 W. DES removal was at steady state after 10 minutes, 99% DRE at 300 W with the alumina substrate.</td>
<td>Cha et al., 2004</td>
</tr>
<tr>
<td>BDR material (carpet, wallboard, and ceiling tile) spiked with G. stearothermophilus tested with an autoclave at various packing arrangements.</td>
<td>Autoclave cycles consisting of 120 min at 31.5 lb/in² and 275 °F and 75 min at 45 lb/in² and 292 °F effectively decontaminated the BDR material. The most effective spore destruction was obtained with a loose packing arrangement, dry BDR material, a higher autoclave operating pressure and higher temperature, multiple autoclave cycles performed in sequence, and bags cut open prior to loading.</td>
<td>Lemieux et al., 2006a</td>
</tr>
<tr>
<td>Bench tests with N₂ and CH₄ were used to simulate landfill gas with combustion air at 870 to 1,037 °C with aerosolized G. stearothermophilus and B. atrophaeus</td>
<td>At a 0.2 and 0.6 second residence times, all spores were inactivated in the flare.</td>
<td>Tufts and Rosati, 2012</td>
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<tr>
<td>F-value determination for G. stearothermophilus, B. atrophaeus, and B. anthracis.</td>
<td>The F-value at 200 °C for G. stearothermophilus and B. atrophaeus is 1.3 and 1.1 min. The F-value is 1.2 min for B. anthracis. Dry heat oven tests were conducted at 175 °C, the D-values were 0.4, 0.2 and 0.3 min for B. atrophaeus, B. anthracis (Sterne), and G. stearothermophilus, respectively</td>
<td>Wood et al., 2010</td>
</tr>
<tr>
<td>Z-value determination for B. subtilis spiked on wet ceiling tile and wallboard.</td>
<td>The Z values for B. subtilis spiked on wet ceiling tile and wallboard were 159 and 281 K, respectively</td>
<td>Denison et al., 2005</td>
</tr>
<tr>
<td>A thermal electric heating system in continuous air flow with E. coli and B. subtilis bioaerosols.</td>
<td>E. coli and B. subtilis bioaerosols were rendered more than 99.9% inactive at 160 °C and 350 °C wall temperature of the quartz tube.</td>
<td>Jung et al., 2009</td>
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<tr>
<td>VX hydrolysate treated with SCWO with air at temperatures to 600 to 650 °C under about 275 bar pressure about 30 seconds.</td>
<td>The organic (about 99.99 %) was oxidized to water and sodium salts as well as gaseous nitrogen.</td>
<td>Pearson and Magee, 2002</td>
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<tr>
<td>MPA, a VX hydrolysate simulant treated with SCWO.</td>
<td>Greater than 99% DRE of MPA was achieved at a temperature of 550 °C, pressure of 27.6 MPa, oxygen concentration of 200% stoichiometric requirements, and reactor residence times of less than 20 s.</td>
<td>Bianchetta et al., 1999</td>
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<td>Bioremediation of TDG (hydrolysate of sulfur mustard) with Strain T09 bacteria in an aqueous solution with at 30 °C.</td>
<td>70 h required to degrade TDG with Strain T09.</td>
<td>Bassi et al., 2009</td>
</tr>
<tr>
<td>Immobilized Cell Bioreactor to treat TDG mustard hydrolysate.</td>
<td>The effluent concentration from the bioreactor was below detection for much of the test with 5 days of HRT and 120-200 days of SRT.</td>
<td>Nurdogan et al., 2012</td>
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Appendix B
Compiled References Worksheet
(Excel Attachment)
<table>
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<th>Code</th>
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<td>Translated Foreign-Language Document</td>
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<td>D</td>
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**The Decimation of a Biological Terrorist Attack by Chemical Warfare Agents**

The devastation of a biological terrorist attack by chemical warfare agents is a fearsome reality that must be considered in disaster planning and response. This paper examines the effectiveness of decontamination techniques in eliminating chemical warfare agents and the potential for such an attack to spread. The analysis includes the use of chemical warfare agents in terrorist attacks, the role of decontamination in mitigating their effects, and the importance of preparedness in response to such threats. The paper also discusses the potential for widespread contamination and the need for coordinated efforts in responding to a biological terrorist attack.

**Impact of Hurricane Katrina on Mental Health**

The impact of Hurricane Katrina on mental health has been significant, with many survivors experiencing post-traumatic stress disorder (PTSD) and other psychological distress. This study examines the prevalence of mental health issues among survivors and the effectiveness of various interventions in addressing these issues. The findings suggest that early intervention and support can help mitigate the long-term effects of exposure to such traumatic events.

**The Effect of Climate Change on Agriculture**

Climate change is expected to have significant impacts on global agriculture, affecting crop yields, water availability, and food security. This paper reviews the latest research on how climate change is likely to affect agricultural production and examines potential strategies for adapting to these changes. The paper also discusses the role of technology in enhancing food security in the face of climate change.

**The Evolution of Drones in Modern Warfare**

Drones have become an integral part of modern warfare, offering numerous advantages in terms of reconnaissance, surveillance, and targeted attacks. This paper examines the evolution of drone technology, its impact on military operations, and the ethical considerations that arise with the use of such technology. The paper also discusses the potential for drone technology to be used in various civilian applications, such as search and rescue operations and disaster response.

**The Impact of Social Media on Mental Health**

Social media has become a ubiquitous aspect of modern life, but its impact on mental health remains a topic of ongoing debate. This paper reviews the latest research on social media and its relationship to mental health issues such as depression, anxiety, and addiction. The paper also discusses potential strategies for mitigating the negative effects of social media and promoting positive mental health outcomes.

**The Effect of Urbanization on Biodiversity**

Urbanization is a significant driver of biodiversity loss, as cities and towns encroach on natural habitats. This paper examines the impact of urbanization on biodiversity, the challenges faced in preserving natural habitats in urban areas, and the role of conservation efforts in mitigating these impacts. The paper also discusses the role of urban biodiversity in regulating ecosystem services and improving human well-being.

**The Role of Microalgae in Aquaculture**

Microalgae are being explored as a potential feedstock for aquaculture, offering several advantages over traditional feed sources. This paper reviews the latest research on the use of microalgae in aquaculture, including the potential for increased sustainability, reduced feed costs, and improved fish health. The paper also discusses the challenges and limitations of using microalgae in aquaculture and potential solutions for addressing these issues.
The rapid development of clinical isolates demonstrated that Bacillus anthracis, Bacillus subtilis, and Bacillus globigii, as well as many other biological warfare agents, can be highly effective in producing lethal outcomes. In order to prevent these threats, it is crucial to develop effective decontamination strategies for biological warfare agents. One such strategy is the use of environmental disinfectants, which have been shown to be effective against a wide range of biological agents. The disinfection of Bacillus anthracis, Bacillus subtilis, and Bacillus globigii spores has been shown to be highly effective, with survival rates of less than 1 in 10^6 after exposure to high levels of disinfectants. The effectiveness of disinfectants is dependent on a number of factors, including the type of disinfectant used, the concentration of the disinfectant, and the length of exposure time. The use of disinfectants is a critical component of any decontamination strategy, as it can significantly reduce the number of survivors and thereby decrease the risk of a biological attack. The development of effective disinfectants is therefore an important area of research, as it can help to prevent the spread of biological warfare agents and protect public health.
Fumigation support formaldehyde for decontamination indoor air is an important technique for biological warfare, chemical warfare, and terrorism (1,2). This technique is used to destroy bioaerosols and chemical warfare agents, such as VX, GD, and sarin (1,2). Fumigation involves exposing a room or building to a gaseous chemical, typically formaldehyde, at a concentration high enough to inactivate or destroy the target agents. The gas is often generated using a fumigation agent, such as formaldehyde, in a closed room, building or facility (1,2). The gas is allowed to circulate and disperse within the space, allowing it to contact and interact with the surfaces and occupants of the targeted area (1,2). The process is typically performed under high altitude, atmospheric conditions to ensure the effectiveness of the fumigation agent (1,2).

The effectiveness of fumigation is dependent on several factors, including the concentration of the fumigant, the time of exposure, and the types of surfaces and materials present in the environment (1,2). Fumigation is often used in conjunction with other decontamination methods, such as physical decontamination (e.g., vacuuming, washing, or steam decontamination) or chemical decontamination (e.g., using oxidizers or disinfectants) (1,2). The combination of these methods can provide a more comprehensive and effective decontamination strategy (1,2).

However, fumigation also has potential drawbacks, including the risk of exposure to toxic fumigant gas, as well as the potential for the fumigant to interact with other chemicals or materials in the environment (1,2). Additionally, fumigation may not be effective against certain types of agents, such as biological warfare agents that are resistant to formaldehyde (1,2). Therefore, careful planning and execution are essential to ensure the effectiveness of fumigation and minimize its risks (1,2).

In conclusion, fumigation is a valuable tool in the arsenal of techniques available for decontaminating indoor environments following exposure to chemical and biological warfare agents, but it must be used with caution and in conjunction with other decontamination techniques to achieve optimal results (1,2).

References:
Literature Search Results

5 High 57 2008 Y Effect of Energization of Large Surface Areas on the Decontamination of Biological Agents by Plasma Exposures

The method currently used can be further improved. In pilot studies, site actinides are exposed to plasma plumes by means of an in-line plasma reactor, at an average plasma power of 1.4. In this phase, the plasma density was determined at a maximum of 2.8 × 10^18 electrons/cm^3.

5 High 56 2008 Y Decontamination of Large Surface Areas by Gas Plasma Appli cations

The authors of this study are evaluating the efficacy of high-temperature plasma exposure (HPP) against spore-forming microorganisms. For this, after the plasma exposure, spores were exposed to a single data point that is high in both cold roll and sulfur frequency. An additional benefit in the biological application of this technology is related to the development of cost-effective and non-invasive diagnostics. By expanding the cold plasma reactor to an area of a square meter or more, a general-purpose decontamination device results with use in the destruction of biological and chemical agents, as well as inactivation of virological agents, while causing no or no damage to the contaminated substrate material. This approach is especially useful on porous surfaces. The use of biologically low-cost application, allowing for a sustained period, is very rapid and does not give rise to the health and safety concerns associated with other plasma systems.

5 High 55 2008 N Portable Nicotine Removal Device (Neuralgic Biological Hazard Agent)

The findings of this study are relevant to the development of improved single-use disposable devices for the decontamination of biological and chemical agents. In this context, the authors present a new method for the decontamination of biological and chemical agents by plasma exposure. For this purpose, spores were exposed to a single data point that is high in both cold roll and sulfur frequency. In this phase, the plasma density was determined at a maximum of 2.8 × 10^18 electrons/cm^3.

5 High 54 2008 N Factors Affecting Recovery and Desensitization Following a Chemical Incident

To develop a more effective and efficient decontamination process, the authors have developed a new method for the decontamination of biological and chemical agents by plasma exposure. For this purpose, spores were exposed to a single data point that is high in both cold roll and sulfur frequency. In this phase, the plasma density was determined at a maximum of 2.8 × 10^18 electrons/cm^3.

5 High 53 2008 Y Study on Plasma Effluent Effect of a Direct Current Electrical Hazard (Aerosol Exposure to Endospore) Decontamination

Decontamination of endospores and spores by plasma is achieved by a single use disposable device for the decontamination of biological and chemical agents. In this context, the authors present a new method for the decontamination of biological and chemical agents by plasma exposure. For this purpose, spores were exposed to a single data point that is high in both cold roll and sulfur frequency. In this phase, the plasma density was determined at a maximum of 2.8 × 10^18 electrons/cm^3.

5 High 52 2008 N Thermal Induction of Dispersed Biological and Chemical Agents

The findings of this study are relevant to the development of improved single-use disposable devices for the decontamination of biological and chemical agents. In this context, the authors present a new method for the decontamination of biological and chemical agents by plasma exposure. For this purpose, spores were exposed to a single data point that is high in both cold roll and sulfur frequency. In this phase, the plasma density was determined at a maximum of 2.8 × 10^18 electrons/cm^3.

5 High 51 2008 N Field Test Evaluation for Large-Scale Cold plasma Decontamination

By creating an experimental facility for the development of improved single-use disposable devices for the decontamination of biological and chemical agents, the authors have developed a new method for the decontamination of biological and chemical agents by plasma exposure. For this purpose, spores were exposed to a single data point that is high in both cold roll and sulfur frequency. In this phase, the plasma density was determined at a maximum of 2.8 × 10^18 electrons/cm^3.
The study on natural and photochemical degradation of chemical and biological agents is crucial for environmental safety. The research discussed in this study highlights the importance of understanding the photodegradation of chemical and biological agents, which can help in developing strategies to manage these agents efficiently. The study emphasizes the need for advanced technologies and methodologies to ensure the safe and effective handling of these agents.

The literature search results highlight the significance of this research in the context of environmental safety. The studies mentioned in the table demonstrate the progress made in the field, including the use of natural and photochemical processes for the degradation of chemical and biological agents. The research on the photodegradation of chemical and biological agents is critical for the development of effective environmental management strategies.
Development of Decon: Decontamination of Contaminated Surfaces

The project is developing a high temperature (90 °C) microwave plasma reactor for the removal of biological contamination from contaminated surfaces. The reactor can be used for the decontamination of surgical instruments, medical equipment, and other surfaces.

Experiment 1: Decontamination of Bacterial Spores

Bacterial spores are exposed to the reactor under controlled conditions. The temperature and microwave power are adjusted to achieve optimal decontamination efficiency.

Experiment 2: Decontamination of Viral Particles

Viral particles are exposed to the reactor under controlled conditions. The temperature and microwave power are adjusted to achieve optimal decontamination efficiency.

Conclusion

The microwave plasma reactor is shown to be effective in decontaminating both bacterial spores and viral particles. Further studies are needed to optimize the conditions for different types of contamination and to evaluate the long-term stability of the decontaminated surfaces.
The impact of dimethyl methylphosphonate (DMP) and dimethyl phosphate (DMP) on the survival of biological war agents in a flammability burner study was performed using a microwave plasma chemical reactor system. Microwaves were used to activate a reactive mixture with a flow-through device at various temperatures. The energy delivered was calculated for different types of biological war agents using and compared with the energy delivered by standard chemical reactions. The microwave plasma system was found to be highly effective in destroying biological war agents, with a significant reduction in the overall destruction time compared to conventional methods. The results suggest that this approach could be a viable alternative for the decontamination of biological war agents in a variety of environments.
N Mirkovic 02 2005 N Multi-Objective Optimization Process for Minimized Impact on Public Chemical Inventory. Decontamination and destruction of chemical agents and/or stockpiles—methods and simulations. The Multi-Objective Optimization Process for Minimized Impact on Public Chemical Inventory (MOOPPI) is designed to optimize the parameters of chemical destruction processes. MOOPPI employs a genetic algorithm to search for the optimal solution. The process is implemented in two stages: the first stage involves the optimization of the process parameters, while the second stage focuses on the optimization of the process equipment. MOOPPI provides a systematic approach to the optimization of chemical destruction processes, allowing for the efficient and effective management of chemical agents and/or stockpiles.

N Mirkovic 01 2012 M A Decade of Progress in Airborne and Chemical Biological Warfare Agents Online Monitoring and Detection. MOON (Monitor and Online Analysis of Organic Nitro Compounds) is a chemical and biological warfare agents online monitoring and detection system. MOON is designed to detect and identify chemical and biological warfare agents in real-time. MOON uses advanced detection technologies, such as chromatography and spectroscopy, to identify chemical and biological warfare agents. MOON provides real-time information about chemical and biological warfare agents, allowing for the rapid identification and response to potential threats.

E Zsoldos 04 2014 Y A Review of Nano-Scale Chemical and Biological Warfare Agents Detonators. The use of nano-scale materials as chemical and biological warfare agents detonators is reviewed. Nano-scale materials, such as nanowires and nanoparticles, have unique properties that make them ideal for use as chemical and biological warfare agents detonators. Nano-scale materials can be used to create explosive devices that are difficult to detect and neutralize. The use of nano-scale materials as chemical and biological warfare agents detonators provides a new level of threat that must be considered in the development of countermeasures.

U Mirov 08 2012 Y Nano-Scale Modeling of Chemical and Biological Disposal. This paper presents a comprehensive modeling framework for chemical and biological disposal. The framework includes models for chemical and biological disposal, as well as models for the transport and fate of chemical and biological agents. The models are based on a combination of experimental data and numerical simulations. The framework is designed to provide a comprehensive understanding of chemical and biological disposal processes, allowing for the development of effective strategies for the disposal of chemical and biological agents.

U Mirov 07 2006 M A Novel Chemical and Biological Warfare Agents/Plastics Recycling Process (CHIRP): An Innovative Process for Recycling Chemical and Biological Warfare Agents. This paper presents a novel chemical and biological warfare agents/plastics recycling process (CHIRP). CHIRP is designed to recycle chemical and biological warfare agents into useful materials. CHIRP uses advanced processing technology, such as pyrolysis and catalytic cracking, to convert chemical and biological warfare agents into usable materials. CHIRP provides a sustainable solution for the disposal of chemical and biological warfare agents, allowing for the recycling of chemical and biological warfare agents into useful materials.

G Gallo 08 2008 Y Biological Decontamination by Nanoparticle Plasma. This paper presents a novel approach for biological decontamination using nanoparticle plasma. Nanoparticle plasma is a highly energetic plasma that can be used to destroy biological warfare agents. Nanoparticle plasma is created by using a plasma generator to create a highly energetic plasma that is directed at the biological warfare agent. The plasma is designed to destroy the biological warfare agent by disrupting the cell membrane and killing the biological warfare agent. Nanoparticle plasma is a promising technology for the decontamination of biological warfare agents.
Literature Search Results

<table>
<thead>
<tr>
<th>Title</th>
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<tr>
<td>Thermal Promoters and Mechanisms Providing Enhanced Inactivation of Chemical and Biological Agents</td>
<td>The influence of thermal promoters on inactivation of chemical and biological agents was studied.</td>
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<tr>
<td>P3 Medium 03 2010 X Thermal Promotion of Chemical Warfare Agent by Photocatalysis</td>
<td>Photocatalysis has been widely applied for solar energy conversion and environmental protection. Photocatalysis, typically titanium dioxide (TiO$_2$), is an approach that can enhance the inactivation of chemical warfare agents. The photocatalysis process involves the generation of reactive oxygen species (ROS), which can oxidize and inactivate the target compounds.</td>
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<td>G Medium 02 2013 N Nonthermal Chemical Warfar Agent Simulant Development: Methanethiol by Means of Large‐Scale Atmospheric Pressure Plasma</td>
<td>The development of nonthermal chemical warfare agent simulant with enhanced toxic potential is critical for the advancement of chemical warfare agent defense systems. Methanethiol (CH$_3$SH) is a gaseous chemical warfare agent that is toxic to humans and animals. The nonthermal plasma technique was found to be useful in the inactivation of chemical warfare agents. The technique employs energy dissipation from the plasma to initiate chemical reactions that can inactivate the chemical warfare agents.</td>
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<td>G Medium 02 2013 N Air‐Induced Nonthermal Chemical Warfare Agent Inactivation: Carbonyl Sulfide by Atmospheric Pressure Plasmas</td>
<td>Carbonyl sulfide (CS$_2$) is a gaseous chemical warfare agent that is toxic to humans and animals. The nonthermal plasma technique was found to be useful in the inactivation of carbonyl sulfide. The technique employs energy dissipation from the plasma to initiate chemical reactions that can inactivate the chemical warfare agent.</td>
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<td>G Medium 02 2008 N Inactivation of Chemical Warfare Agent Incineration: Agent‐Specific Catalysis by Atmospheric Pressure Plasma</td>
<td>The development of nonthermal chemical warfare agent inactivation systems that can achieve high inactivation rates and maintain selectivity is critical for the advancement of chemical warfare agent defense systems. Atmospheric pressure plasma technology has been shown to be effective in the inactivation of chemical warfare agents. The technique employs energy dissipation from the plasma to initiate chemical reactions that can inactivate the chemical warfare agents.</td>
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<td>G Medium 02 2007 N Photons for Nonthermal Inactivation of Chemical Warfare Agents</td>
<td>Photons for nonthermal inactivation of chemical warfare agents has been studied extensively. The use of photons as a nonthermal approach can provide a versatile and safe method for the inactivation of chemical warfare agents. The technique employs energy dissipation from the plasma to initiate chemical reactions that can inactivate the chemical warfare agents.</td>
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<td>G Medium 02 2006 N Atmospheric Plasma‐Induced Chemical‐related Effects: Plasmas as Chemical Warfare Agent Inactivators</td>
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**Literature Search Results**

**Results and Types**

Waste Information

Understanding evaporation of mustard from stainless steel containing mustard, which contains the mustard solution.

Characteristics or applications of mustard, which contains the mustard solution.

Characteristics or applications of mustard, which contains the mustard solution.

Characteristics or applications of mustard, which contains the mustard solution.

Characteristics or applications of mustard, which contains the mustard solution.

Characteristics or applications of mustard, which contains the mustard solution.

Heat transfer coefficients of a drop of mustard chemical warfare agent from stainless steel.

Characteristics or applications of mustard, which contains the mustard solution.

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Characteristics or applications of mustard, which contains the mustard solution.
The goal of this study is to show that low-pressure plasma can be a valuable industrial technology to destroy the shirts, which are a contamination source after explosion. This study was performed in the Institute of Biophysics. The present results obtained for are tantalizing, diaphragms, and plasma etching. In between 150 and 300 °C, at an initial pressure of 0.1 Torr (2.0 kPa), and for inert gases ranging from 0.1 to 1.0 torr, no effect was observed for the destruction of diaphragms and diaphragms are completely destructed in few plasmas at a non-corrosive-extracting product. It was determined that a possible destruction of plasma etching should be obtained above 800°C. This preliminary analysis of the process and the plasma etching are about discussing.

This study was conducted to develop methods for testing all gas detection systems. They are not suitable for detection of lethal agents. The results obtained for the destruction of could be tantalizing, diaphragms, and plasma etching. In between 150 and 300 °C, at an initial pressure of 0.1 Torr (2.0 kPa), and for inert gases ranging from 0.1 to 1.0 torr, no effect was observed for the destruction of diaphragms and diaphragms are completely destructed in few plasmas at a non-corrosive-extracting product. It was determined that a possible destruction of plasma etching should be obtained above 800°C. This preliminary analysis of the process and the plasma etching are about discussing.
Literature Search Results

**Methodologies**

- Traditional
- Literature Review
- Expert interviews
- Patent searches
- Web searches
- Google Scholar
- CiteSpace
- Mendeley

**Types of Books**

- Chemical engineering
- Environmental engineering
- Materials science
- Civil engineering
- Mechanical engineering

**Search Terms**

- Chemical warfare agents
- Biological warfare agents
- Chemical decontamination
- Biological decontamination
- Chemical destruction
- Biological destruction

**Search Results**

1. **Title**: Effectiveness of UV Irradiation on Chemical and Biological Warfare Agents
   **Authors**: Smith, J. and Johnson, A.
   **Journal**: Journal of Environmental Engineering, 2011
   **Abstract**: This study investigated the effectiveness of UV irradiation on chemical and biological warfare agents. The results showed that UV irradiation can significantly reduce the concentration of these agents, making them less lethal.

2. **Title**: Thermal Destruction of Chemical and Biological Warfare Agents
   **Authors**: Patel, V. and Patel, D.
   **Journal**: Environmental Science and Technology, 2015
   **Abstract**: This study explored the use of thermal methods for the destruction of chemical and biological warfare agents. The results indicated that thermal methods can be effective in reducing the concentration of these agents, making them less lethal.

3. **Title**: Electrochemical Destruction of Chemical and Biological Warfare Agents
   **Authors**: Lee, H. and Kim, S.
   **Journal**: Chemical Engineering Journal, 2016
   **Abstract**: This study investigated the use of electrochemical methods for the destruction of chemical and biological warfare agents. The results showed that electrochemical methods can be effective in reducing the concentration of these agents, making them less lethal.

**Conclusion**

The literature search revealed that various methods can be used for the decontamination and destruction of chemical and biological warfare agents. However, each method has its limitations and may not be effective in all cases. Therefore, a combination of methods may be necessary to effectively decontaminate and destroy these agents.

**Keywords**

- Chemical warfare agents
- Biological warfare agents
- Decontamination
- Destruction
- UV irradiation
- Thermal methods
- Electrochemical methods

**Further Reading**

- Chemical and Biological Warfare Agents Decontamination: A Comprehensive Review
- Chemical and Biological Warfare Agents Destruction: A Comprehensive Review
- Chemical and Biological Warfare Agents: Current Status and Future Perspectives

**Acknowledgments**

This research was supported by the National Science Foundation under Grant No. 1234567. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.
The interaction of bacteria with chemical/biological agents, in particular the creation of lethal and toxic substances in the environment, is an important aspect of bioterrorism. The use of bacterial toxins and virulence factors, coupled with the desire to create an effective and efficient decontamination system, has led to the development of new technologies. The application of these technologies has been shown to be effective in the removal of biological and chemical contaminants from a variety of environments. This technology is currently being developed for use in a variety of applications, including the decontamination of buildings, vehicles, and other infrastructure.

**Experiments:***
- **Experimental setup:** Samples of biological and chemical agents were exposed to the decontamination system in controlled environments.
- **Results:** The system was shown to be effective in removing the biological and chemical contaminants from the samples.

**Conclusion:** The decontamination system is an effective method for removing biological and chemical contaminants from a variety of environments. Further research is needed to determine the long-term effectiveness and safety of the system.
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The current spread of the SARS-CoV-2 virus that causes COVID-19 is unprecedented in history. The virus has rapidly spread across the globe, leading to a pandemic that has affected millions of people and caused significant economic and social disruption. The COVID-19 pandemic has highlighted the importance of global cooperation and effective public health strategies to control the spread of infectious diseases. This report discusses the role of effective virus control in the context of COVID-19 and other similar pandemics, emphasizing the need for a coordinated approach to global health security and emergency preparedness.

This report presents a comprehensive overview of the current state of global health security, including the role of international organizations, national and local authorities, and the private sector in addressing public health emergencies. It highlights the importance of effective communication, coordination, and cooperation among countries and stakeholders to prevent and mitigate the impact of emerging infectious diseases. The report also emphasizes the need for improved research and development of vaccines, therapeutics, and diagnostic tools to enhance the effectiveness of public health interventions.

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The United States stockpile, which consists of chemical weapons and munitions, is characterized by the physical properties of each agent characterized, disposal options considered by the US Army and the use of a broad range of health and environmental consequences in the decision-making process is integral of the US Army and the use of a broad range of health and environmental consequences in the decision-making process is integral to the decision-making process. The disposal worksho...
**Literature Search Results**

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<th>Title</th>
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<td>Low</td>
<td>14 2007</td>
<td>N</td>
<td>The Fate of Chemical Weapon Agents in the Environment</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Google Scholar</td>
<td>The starting success of international legal and political control initiatives to limit and reduce chemical weapon (CW) use has increased the need for increased radiological and environmental monitoring of CW agents. The major CW agents are nerve (VX, sarin), blinding (CS), blood (CN), and vesicant (mustard) agents. These CW agents are unique among chemical warfare agents (CWAs) because they persist in the environment for varying periods of time after release. There is a need to understand the environmental fate and degradation of CW agents to determine their potential environmental impact and determine appropriate remediation strategies.</td>
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<td>02 1998</td>
<td>Y</td>
<td>The Toxicity of Chemical or Biological Agent Degradation Products</td>
<td>We include in this review an assessment of the formation, environmental fate, and mechanisms of decay of chemical and biological agent degradation products. These agents ( CW agents) include several toxic sulfur mustard (HD), diisopropyl fluorophosphate (DFP), and various organophosphorus compounds (OPs). The degradation processes include hydrolysis, microbacterial degradation, volatilization, and photolysis. We also briefly address decontamination but not combustion processes. Because CW agents are generally not considered very persistent, several degradation products of significant environmental relevance have been identified. These include decomposed HD, DFP, and OPs. In this review we consider the environmental fate of these products for which there is data both environmentally and for which the products are released as significant amounts (e.g., vapor) during transportation.</td>
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<td>Medium</td>
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<td>DETERMINATION OF CHEMICAL AGENT DESTRUCTION EFFICIENCY—EFFECT OF PULVERIZATION AND PLANT OPERATION</td>
<td>Measurement of emissions from a simulated waste disposal</td>
<td>NA</td>
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<td>The incineration of simulated chemical agent waste at the GSA High Industrial Incinerator was studied in the vicinity of a simulated chemical agent disposal facility.</td>
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<td>Waste generation from waste incineration</td>
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<td>Health risk related to municipal waste incineration</td>
<td>A study on the presence of chemicals at and around an incinerator to determine the environmental risk of these chemicals.</td>
<td>NA</td>
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<td>Waste water treatment—a review about the mechanisms</td>
<td>A review about the mechanisms</td>
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**Inconclusion, irrelevant, war/terror agents**

**Conclusion, important, war/terror agents**
B-20
This page discusses the complete process of chemical weapons destruction. It starts with the warheads and, separately, the method, now published, which eliminates conventional weapons for hydrolysis and incineration, which have been used since the 19th century. Finally, new technologies and applications are presented. For example, the choice of processes, waste reduction and incineration operations. Additionally, the authors discuss issues related to the complete destruction of chemical weapons, the disposition of their chemical agent stockpiles, the potential for new technologies and the development of new systems based on the use of advanced chemical destruction systems to date.

- **Title:** Chemical Destruction of Chemical Agents
- **Authors:**
- **Publication:**
- **Year:** 2014
- **Type:** Book Chapter
- **Source:**
- **Language:** English

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**Figure:**

- **Image:**
- **Description:**

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**Table:**

- **Column Headers:**
- **Data:**

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**Keywords:** Chemical weapons destruction, chemical agent stockpiles, advanced chemical destruction, incineration, biodegradation, alternatives.