Assessment of Approaches for Using Process Safety Metrics at the Blue Grass and Pueblo Chemical Agent Destruction Pilot Plants

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ASSESSMENT OF APPROACHES FOR USING PROCESS SAFETY METRICS AT THE BLUE GRASS AND PUEBLO CHEMICAL AGENT DESTRUCTION PILOT PLANTS

Committee to Assess Process Safety Metrics for the
Blue Grass and Pueblo Chemical Agent Destruction Pilot Plants

Board on Army Science and Technology

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COMMITTEE TO ASSESS PROCESS SAFETY METRICS FOR THE BLUE GRASS AND PUEBLO CHEMICAL AGENT DESTRUCTION PILOT PLANTS

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Preface

The Assembled Chemical Weapons Alternatives program was mandated to use nonincineration technologies to destroy the chemical weapons stockpiles at the Pueblo Chemical Depot (PCD) in Colorado and the Blue Grass Army Depot (BGAD) in Kentucky. These two storage sites together account for about 10 percent of the original U.S. chemical agent stockpile that is in the process of being destroyed in accordance with the international Chemical Weapons Convention treaty. Disposal operations at six other sites in the continental United States and Johnston Island in the Pacific near Hawaii have already destroyed over 80 percent of the stockpile. Incineration technology was used by the now closed disposal facility on Johnston Island, and at a facility in Pine Bluff, Arkansas, which has completed operations and has entered closure. Chemical neutralization (hydrolysis) technology was used to destroy bulk mustard agent and VX nerve agent at the now closed facilities in Aberdeen, Maryland, and Newport, Indiana, respectively. Disposal campaigns at the three other currently operating facilities, which use incineration technology, are nearing completion.

The Pueblo site contains the larger portion of the remaining stockpile inventory in the form of various mustard agent projectiles. While the Blue Grass inventory is relatively small, it is more diverse and contains both mustard agent in various projectiles and the nerve agents GB and VX in various projectiles and M55 rockets. The two facilities being built at these sites, the Pueblo and Blue Grass Chemical Agent Destruction Pilot Plants (PCAPP and BGCAPP, respectively), will use chemical neutralization to destroy chemical agent, followed by different downstream processes to treat the resulting waste streams. PCAPP will use biotreatment to treat waste streams from chemical agent disposal, and BGCAPP will use supercritical water oxidation. PCAPP and BGCAPP will also employ a number of pieces of first-of-a-kind equipment. Both facilities have been designed using established engineering codes and principles and have incorporated lessons learned from the operation of earlier chemical agent disposal operations to ensure safe operation. PCAPP is currently under construction and is planned to start agent disposal operations in 2014. BGCAPP is also under construction, with operations to commence in 2018.

As part of its focus on safe operation of the planned facilities, the Program Manager for Assembled Chemical Weapons Alternatives asked the National Research Council (NRC) to conduct a study to offer guidance on the application of process safety metrics at PCAPP and BGCAPP. The committee that was assembled by the NRC held a number of meetings, virtual meetings, and teleconferences. It also visited the offices of staff working on the PCAPP and BGCAPP projects.

Among the process safety considerations discussed in this report is the applicability of the James Reason barrier model's concept of layers of protection to the chemical processes being designed at PCAPP and BGCAPP. Also discussed extensively is the use of leading and lagging process safety metrics[1] that could provide feedback on the effectiveness of controls to mitigate risks and minimize consequences of potential

[1]"Leading metric" and "lagging metric" are defined in Appendix A.

incidents and, it is hoped, prevent incidents that might otherwise occur. Several recommendations are made to facilitate the development and application of process safety metrics at both sites.

As chair of this committee, I want to express my sincere thanks to the members of this committee. Their insights on safety culture, especially as it relates to process safety management, were invaluable in executing the statement of task. James Myska, senior research associate at the Board on Army Science and Technology, assisted Bruce Braun, director of the Board on Army Science and Technology, in running this study. Mr. Myska excelled at keeping the committee focused and ensuring that work was accomplished in a timely manner. C.T. Anderson, a safety and surety engineer at the Program Manager for Assembled Chemical Weapons Alternatives, was very helpful in providing timely responses to numerous committee requests for information. Raj K. Malhotra, deputy, Risk Directorate at the Chemical Materials Agency (CMA), approved committee access to records of incidents at CMA facilities to identify incident casual factors. This access was instrumental in allowing the committee to identify several leading process safety metrics. Lastly, I want to thank Deanna Sparger and Nia Johnson for their administrative and research support to the committee. Without their assistance, the preparation of the report would have been much more difficult.

Otis A. Shelton, *Chair*
Committee to Assess Process Safety Metrics
for the Blue Grass and Pueblo Chemical
Agent Destruction Pilot Plants

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Scott Berger, American Institute of Chemical Engineers Center for Chemical Process Safety;
Deborah L. Grubbe, Operations and Safety Solutions, LLC;
Alexander MacLachlan, NAE, E.I. du Pont de Nemours and Co. (retired);
M. Sam Mannan, Mary Kay O'Connor Process Safety Center;
James F. Mathis, NAE, Exxon Corporation (retired);
George W. Parshall, NAS, E.I. du Pont de Nemours and Co. (retired);
Ian Travers, United Kingdom Health and Safety Executive; and
Ronald Willey, Northeastern University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Elisabeth M. Drake, NAE, MIT Laboratory for Energy and the Environment. Appointed by the National Research Council, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Acronyms and Abbreviations

ACWA Assembled Chemical Weapons Alternatives
ANCDF Anniston Chemical Agent Disposal Facility
ANR agent neutralization reactor
ANS agent neutralization system
ANSI American National Standards Institute
APB agent processing building
API American Petroleum Institute

BGAD Blue Grass Army Depot
BGCAPP Blue Grass Chemical Agent Destruction Pilot Plant
BRS brine reduction system
BTA biotreatment area

CAM cavity access machine
CCPS Center for Chemical Process Safety
CMA Chemical Materials Agency
CSB Chemical Safety Board

EBH energetics batch hydrolyzer
EDT explosive destruction technology
ENR energetics neutralization reactor
ERB enhanced reconfiguration building

FOAK first of a kind

GB a nerve agent, also known as sarin

H mustard agent
HD distilled mustard agent
HSE United Kingdom Health and Safety Executive
HT mustard agent with an additive to lower its freezing point

IOD integrated operational demonstration

JACADS Johnston Atoll Chemical Agent Disposal System

LOPC loss of primary containment
LPMD linear projectile mortar disassembly

MOC management of change
MPT metal parts treater
MSM munitions storage magazine
MTU munitions treatment unit
MWS munitions washout system

NRC National Research Council

ORR operational readiness review
OSHA Occupational Safety and Health Administration
OTE offgas treatment system for EBH
OTM offgas treatment system for MPT
OTS offgas treatment system

PCAPP Pueblo Chemical Agent Destruction Pilot Plant
PCD Pueblo Chemical Depot

PMACWA	Program Manager for Assembled Chemical Weapons Alternatives
PMD	projectile mortar disassembly
PSI	process safety incident
PSM	process safety metrics
RCM	rocket cutter machine
RO	reverse osmosis
RSM	rocket shear machine
SCWO	supercritical water oxidation
SDU	supplemental decontamination unit
SFT	shipping and firing tube
SOP	standard operating procedure
VX	a nerve agent
WRS	water recovery system

Summary

DESTRUCTION OF THE U.S. CHEMICAL STOCKPILE

The Department of Defense, through the Assembled Chemical Weapons Alternatives (ACWA) program, is currently in the process of constructing two full-scale pilot plants at the Pueblo Chemical Depot in Colorado and the Blue Grass Army Depot in Kentucky to destroy the last two remaining inventories of chemical weapons in the U.S. stockpile. Destruction of this stockpile, originally comprising over 31,000 tons of chemical agents stored at eight chemical weapons depots in the continental United States and on Johnston Island in the Pacific Ocean (southwest of Hawaii), has been ongoing for two decades, and is being performed in accordance with requirements of the Chemical Weapons Convention treaty, to which the United States is a signatory. Approximately 10 percent of the original stockpile is stored at the Pueblo Chemical Depot and the Blue Grass Army Depot, with approximately 90 percent stored at sites being served by the U.S. Army Chemical Materials Agency (CMA) disposal facilities. As of January 12, 2011, the CMA had destroyed 83 percent of the stockpile being treated at its facilities.[1]

Disposal operations at the six other continental U.S. sites and Johnston Island, managed by the CMA, either have been completed or are nearing completion. The disposal facilities at these sites were either based on incineration technology to destroy the chemical agents and associated energetics (propellants and/or explosives) or used chemical neutralization (hydrolysis) to destroy nerve and mustard agents stored in bulk containers.

In contrast, the Pueblo and Blue Grass Chemical Agent Destruction Pilot Plants (PCAPP and BGCAPP) will use neutralization technology to destroy the agents that are contained in various types of *assembled* chemical munitions—that is, rockets, projectiles, and mortar rounds. Consequently the processing equipment employed at PCAPP and BGCAPP will be newer or of different design than the equipment at the other disposal facilities. These pieces of process equipment are referred to as first-of-a-kind (FOAK) equipment. The FOAK equipment the committee believes could pose the most significant challenges to operations at PCAPP and BGCAPP is described in Table S-1.

For reasons such as the use of FOAK equipment and, more broadly, in recognition of the need to conscientiously adhere to congressional mandates that destruction of chemical agent and munitions be executed with maximum protection for workers, the public, and the environment, the Program Manager for Assembled Chemical Weapons Alternatives requested that the National Research Council (NRC) undertake a study to guide the development and application of process safety metrics for PCAPP and BGCAPP. Another reason for requesting this report was the NRC report issued in 2009 *Evaluation of Safety and Environmental Metrics for Potential Application at Chemical Agent Disposal Facilities*, which responded to a request by the CMA for recommendations on additional metrics

[1] See http://www.cma.army.mil/home.aspx for updated information as the program progresses.

TABLE S-1 First-of-a-Kind Equipment and Processes That Could Pose Significant Challenges for PCAPP and BGCAPP

FOAK Equipment	Site(s)	Function	Notes
Rocket cutting machine (RCM)	BGCAPP	To separate rocket motors from the warhead.	This is an entirely new piece of equipment.
Linear projectile mortar disassembly (LMPD) machine	BGCAPP PCAPP	To disassemble projectiles and mortars and remove their bursters.	This is a new unit that replaces the PMD machine used at the baseline incineration sites operated by CMA.
Munitions washout station (MWS)	BGCAPP PCAPP	To remove the burster well from projectiles, drain the chemical agent, and wash out any agent residues.	This is an entirely new piece of equipment. It replaces the PMD machine used at the baseline incineration sites operated by CMA.
Energetics batch hydrolyser (EBH)	BGCAPP	To neutralize energetics and any chemical agent in the metal parts of the rockets and fuzes from projectiles.	This is an entirely new piece of equipment.
Metal parts treater (MPT)	BGCAPP	To decontaminate projectile bodies and secondary waste by heating to over 1000°F for more than 15 minutes.	This is an entirely new piece of equipment.
Munitions treatment unit (MTU)	PCAPP	To decontaminate projectile bodies and secondary waste by heating to over 1000°F for more than 15 minutes.	This is an entirely new piece of equipment.
Supercritical water oxidation (SCWO)	BGCAPP	To treat agent and energetics hydrolysates before releasing them for final disposal.	This is an entirely new piece of equipment and process.
Immobilized-cell bioreactors (ICBs)	PCAPP	To treat mustard hydrolysate before releasing it for final disposal.	This is an entirely new piece of equipment and process.

that could further improve the safety and environmental programs at those sites.

The statement of task for the Committee to Assess Process Safety Metrics for the Blue Grass and Pueblo Chemical Agent Destruction Pilot Plants (the committee) is the following:

> The National Research Council will establish an ad hoc committee to:
>
> - Review and evaluate plans for the use of process safety metrics to be employed at the two Assembled Chemical Weapons Alternatives (ACWA) pilot plant facilities,
> - Examine and assess the process safety metrics used in commercial and industrial operations for potentially applicable process safety metrics, and
> - Assess new initiatives at national organizations (i.e., American Institute of Chemical Engineers, etc.) that could be used by ACWA.

As previously indicated, both PCAPP and BGCAPP will use chemical neutralization technology instead of incineration to destroy chemical agents and, in the case of BGCAPP, to destroy certain energetics. Neutralization involves the hydrolysis of chemical agent and energetics using hot water for mustard agent and caustic for nerve agent and energetics. PCAPP plans to ship the energetics removed from munitions for disposal offsite and will use biotreatment to destroy the products of mustard agent neutralization, known as hydrolysate. BGCAPP will use neutralization followed by the treatment of the resultant agent and energetics hydrolysates by supercritical water oxidation.[2] Implementation of these primary and secondary destruction methods also entails numerous ancillary processes and activities—for example, munitions disassembly and waste management, which in turn require the use of additional FOAK equipment and processing.

The term FOAK implies the use of new technologies or new applications of existing technologies that could be problematic with respect to functionality, reliability, availability, and maintainability. This means that adjustments ranging from procedural modifications to varying degrees of redesign might be required as such equipment is developed, tested, and integrated into actual agent processing operations. One example of FOAK equipment, the linear projectile mortar disassembly machine, is undergoing testing at the Anniston Chemical Agent Disposal Facility. As a result of this testing, 164 specific operating criteria have been reviewed, 20 documented lessons learned will be applied to the design and operation of the system at PCAPP, and more than 110 significant code changes have been identified. Although not all FOAK equipment will be tested in an operational setting prior to systemization, as the linear projectile mortar disassembly machine has been, laboratory testing and evaluation of all FOAK equipment is performed to identify issues and needed adjustments before the equipment is placed in operation.

PCAPP and BGCAPP will both undergo preoperational systemization before starting actual agent disposal operations. Systemization involves progressive testing—from the demonstration of components to subsystems to the entire system, using surrogate munitions—to bring each system to its fully operational design function. Both facilities will follow a progression of steps consisting of the installation of process equipment, integration of process equipment, and overall plant operation using agent surrogates instead of actual chemical agent. During this phase of the project, the systems used to operate the plant will be tested and configured.

[2]Neutralization was used to destroy the chemical agents at two other sites, at Aberdeen Proving Ground, Maryland, and Newport, Indiana. These two sites, however, had only bulk agent stored in ton containers, not assembled munitions.

BACKGROUND INFORMATION RELATED TO PROCESS SAFETY METRICS

There are two types of process safety metrics: leading and lagging.[3] Defining appropriate and effective leading and lagging process safety metrics has been a subject of great interest in recent years, particularly in the chemical and petroleum industries, since those industries handle or produce reactive, toxic, and flammable materials that, if released, can cause multiple fatalities and/or injuries and have significant environmental consequences. Further details on efforts to formalize and implement industrywide approaches to process safety metrics are provided in Chapter 4. A good example of a lagging process safety metric that has been in use for over a decade is the number of unplanned major chemical or energy releases. This metric has included unintended releases of hazardous chemicals that exceed the threshold quantity listed in 40 CFR 302.4, which designates CERCLA[4] hazardous substances or events that result in serious injury or damages in excess of $25,000.

While many of the processes that will be employed for the disposal of chemical agent and munitions at PCAPP and BGCAPP are fundamentally different from those used at the other chemical agent disposal facilities, some similarities do exist with the processes that have been employed at those sites. The committee believed that evaluating the experience with process incidents at those other sites could prove useful and would offer guidance on what process safety metrics might be useful for PCAPP and BGCAPP. The committee further believed that an analysis of relevant chemical events at those sites could provide insights on the process steps and operational systems that are most subject to failure, and might identify opportunities where the use of leading and lagging metrics could help to prevent failures.

The NRC Committee on Evaluation of Chemical Events at Army Chemical Agent Disposal Facilities (the chemical events committee) examined documentation on all of the chemical events that had occurred since commencement of destruction operations through the end of 2001 and issued its report, *Evaluation of Chemical Events at Army Chemical Agent Disposal*

[3]"Leading metric" and "lagging metric" are defined in Appendix A.

[4]CERCLA is the Comprehensive Environmental Response, Compensation, and Liability Act, commonly known as Superfund; 40 CFR 302.4 lists dangerous chemicals and gives threshold quantities for the purpose of defining a process safety incident.

Facilities, in 2002. The present committee reviewed that report to identify which of the events could be classified as process incidents. It also requested an update on process-related chemical events from all currently operating sites and from the sites that completed destruction after 2001. Significantly, the frequencies of incident types, activities, and causal factors for process-related chemical events since 2001 mirror those that were noted in the 2002 Chemical Events report. From these data, it appears that the frequency and type of factors that cause process safety events are independent of the type of facility (neutralization or incineration), the type of chemical weapon (mustard agent or nerve agent), or how the agent is stored (in assembled munitions or bulk). Consequently, PCAPP and BGCAPP can reasonably be expected to experience the same types of events that have similar causal factors. However, because the processes to be employed at PCAPP and BGCAPP are unique, and FOAK equipment will be used extensively, it may be reasonable to expect more events at the outset and a possible shift in the frequency of causal factors. For example, design deficiencies might be more prevalent in new facilities with new equipment, processing steps, and unit operations than in older or second-generation facilities using proven, refined technologies and processes. Some of the personnel who will systemize and operate PCAPP and BGCAPP will come from operating chemical demilitarization facilities, providing an experience base in chemical demilitarization at the two sites.

DERIVING PROCESS SAFETY METRICS RELEVANT TO PCAPP AND BGCAPP

The committee's examination of causal factors related directly to earlier experience with chemical agent and munition destruction provides an excellent basis for the development of process safety metrics at PCAPP and BGCAPP. Some key causes of process safety incidents at former and currently operating chemical agent disposal facilities identified from that experience are discussed below.

- *Standard operating procedure (SOP) deficiencies.* SOP deficiencies were the most prevalent causal factor identified, approximately 27 percent of the total. For PCAPP and BGCAPP, developing and implementing metrics that enable early identification and avoidance of deficiencies in SOPs could be very useful.
- *Equipment malfunction.* This was the second most prevalent causal factor at other chemical agent disposal facilities, approximately 26 percent of the total. While the definition of equipment malfunction used at these facilities did not include design deficiencies, it should be noted that design deficiencies caused equipment malfunctions in some instances. Equipment malfunctions and design deficiencies together were involved in approximately 31 percent of the total incidents reviewed. Conducting design audits and basing metrics on the results could assist in finding design deficiencies before they cause an equipment malfunction or other process incidents or upsets. A system of process safety-critical equipment inspections is key to minimizing equipment malfunctions.
- *Human factors (human error, mindset, and improper technique).* Human factors, which include the three causal factors listed in the parentheses above, altogether accounted for approximately 37 percent of the causal factors. Metrics derived from training activities and job cycle checks could be useful in developing actions to mitigate these types of causal factors and to identify areas where annual or more frequent periodic training should be improved or changed.
- *Communications deficiencies.* This causal factor made up approximately 4 percent of the total. These types of deficiencies are not typically documented until after a failure, but they should be considered as integral to a full complement of process safety metrics. Among the possibilities are audits of communications systems (active and passive) and documenting communications failures.

Based on experience, a number of leading metrics recommended in the documents of the Center for Chemical Process Safety and the American Petroleum Institute and discussed in Chapter 4 could also be relevant to PCAPP and BGCAPP. These leading metrics include process safety near-miss events, closure of action items, completion of emergency response drills, management of change, and metrics related to other management systems.

Managerial leadership is responsible for setting the tone and articulating performance expectations in an organization. When process safety metrics are set for an organization, the operation's line leadership must set performance milestones and regularly review the operation's performance against those milestones with the organization's managerial leadership. Furthermore, the chemical, petroleum, and related industries have learned that maintaining a staff of trained process safety professionals is vital to the avoidance of process incidents. Several other industries—for example, the nuclear power industry—and government facilities engaged in hazardous processes have been hiring full-time staff members to develop and monitor their process safety programs, although they have not done so as quickly as the chemical and petroleum industries.

FINDINGS AND RECOMMENDATIONS

All of the committee's findings and recommendations are listed below. They are numbered according to their order in the chapters in which they appear.

Finding 2-1. Because of the unique nature of the processes at the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant and the extensive use of first-of-a-kind equipment, the use of both leading and lagging process safety metrics will be important in achieving the congressional mandate to safely destroy the chemical weapons stockpiles at the respective sites. Systemization affords an excellent opportunity to implement and evaluate leading and lagging process safety metrics.

Recommendation 2-1. During systemization, the Program Manager for Assembled Chemical Weapons Alternatives should develop and implement extensive process safety metrics that can be evaluated for relevance and utility. Metrics that are found to be meaningful should be carried forward to operations. While both leading and lagging metrics should be developed and implemented to the extent possible, both the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant should emphasize developing leading metrics to guide them in process safety management.

Finding 3-1. The causal factors involved in past events at chemical agent disposal facilities are not process specific. Consequently, the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant can reasonably be expected to experience the same types of events having causal factors similar to those experienced at the Chemical Materials Agency sites. Also, there may be an increase in the frequency of events and a shift in the relative frequency of causal factors.

Finding 4-1. At the present time, there is no definition of a process safety incident other than "release of agent" within the Assembled Chemical Weapons Alternatives program. Establishing or adopting a common definition for process safety incidents would improve consistency of reporting and sharing of lessons learned within the program.

Recommendation 4-1. The Program Manager for Assembled Chemical Weapons Alternatives should adopt the definitions of Tier 1-4 process safety events in Recommended Practice 754, *Process Safety Performance Indicators for the Refining and Petrochemical Industries,* a joint recommendation of the American National Standards Institute and the American Petroleum Institute, with the exception that the reporting threshold for chemical agents should be defined as any unintended release.

Finding 4-2. Developing metrics for the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant based on operating experience at other chemical agent disposal facilities would help to avoid failures that lead to process safety incidents.

Recommendation 4-2. The Program Manager for Assembled Chemical Weapons Alternatives should take into account the causal factors in past process safety incidents at chemical agent disposal facilities when devising process safety metrics for the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant.

Finding 4-3. Many process safety metrics that could be used by the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant are available to the public, including those in the list of metrics in the Center for Chemical Process Safety publication *Guidelines for Process Safety Metrics*. These metrics could complement process-specific metrics developed at the respective sites.

Recommendation 4-3. The Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical

Agent Destruction Pilot Plant should adopt the metrics listed below and develop process-specific leading and lagging metrics. The ACWA program should also consider a metric associated with emergency planning and response as well as published lists of process safety metrics and should adopt those that appear to be of value to these sites.

- Count of process safety near-miss events.
- Training records such as validation of job cycle checks and completion of training, including refresher training.
- Job procedures:
  - –Statistics on whether a procedure was used and, if it was, was the procedure the correct one?
  - –Validation that procedures are current and accurate.
- Statistics on the closure of action items.
- Percent of inspections of safety-critical equipment completed on time.
- Percent of sampled management of change instances that met all requirements and quality standards.

Finding 4-4. The United Kingdom Health and Safety Executive's Health and Safety Guidance 254 (UK HSE HSG 254) provides a methodology to develop process-specific leading and lagging metrics.

Recommendation 4-4. Given that the two facilities are pilot facilities and make extensive use of first-of-a-kind equipment, the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant should review their hazard assessment documents to identify and consider implementing leading or lagging metrics specific to each piece of equipment or area of the plant. These efforts should follow the approach outlined in the United Kingdom's Health and Safety Executive Health and Safety Guidance 254 (UK HSE HSG 254), *Developing Process Safety Indicators: A Step-by-Step Guide for Chemical and Major Hazard Industries*.

Finding 4-5. A formalized mechanism for a periodic review of process safety metrics by management is an established best practice in industry to verify that management is involved and can drive continuous improvement.

Recommendation 4-5. The Program Manager for Assembled Chemical Weapons Alternatives and site management should perform periodic reviews of process safety metrics utilized at PCAPP and BGCAPP and implement action plans as appropriate to drive continuous improvements.

Finding 4-6. The chemical and petroleum industries have found it very beneficial to have employees on staff with process safety expertise. These individuals partner with senior management and are accountable for monitoring industry best practices in process safety and for implementing those that are applicable within their facilities. These individuals are also tasked with assisting in embedding process safety into the organization's culture by organizing and leading grassroots process safety teams while reviewing outcomes and metrics with management.

Recommendation 4-6. The Program Manager for Assembled Chemical Weapons Alternatives should maintain process safety expertise at the programmatic level to ensure effective implementation of process safety metrics. To be successful, process safety experts must partner with and be supported by management.

Finding 4-7. There are a number of resources that the Program Manager for Assembled Chemical Weapons Alternatives can use to learn about best practices for process safety management in the chemical and petroleum industries. Process safety technology conferences such as the American Institute of Chemical Engineers' annual Global Congress of Process Safety and others hosted by organizations such as the Center for Chemical Process Safety and the Mary Kay O'Connor Process Safety Center provide ongoing programming on process safety and the identification of best practices.

Recommendation 4-7. The Program Manager for Assembled Chemical Weapons Alternatives should undertake a review of best practices in process safety management, especially in the chemical and petroleum industries. These practices are described in the Center for Chemical Process Safety book *Guidelines for Risk Based Process Safety.* Those that are applicable should be incorporated into the Pueblo and Blue Grass Chemical Agent Destruction Pilot Plants.

1

Introduction

THE CHEMICAL WEAPONS STOCKPILE DISPOSAL PROGRAM

In 1985, under a congressional mandate (Public Law 99-145), the Army instituted a sustained program to destroy elements of the chemical munition stockpile. In 1992, Congress enacted Public Law 102-484, which extended this program to destroy the entire stockpile.

In 1990, the chemical agent and munitions stockpile contained in excess of 31,000 tons of chemical agents stored at eight chemical weapons depots operated by the Army in the continental United States and on Johnston Island in the Pacific Ocean (southwest of Hawaii). Chemical weapons that had been stored overseas were brought to Johnston Island and destroyed by the Johnston Atoll Chemical Agent Disposal System (JACADS). Approximately 10 percent of the original stockpile is stored at the Pueblo Chemical Depot (PCD) and the Blue Grass Army Depot (BGAD), and approximately 90 percent of that stockpile was stored at sites being served by Chemical Materials Agency (CMA) disposal facilities. As of January 12, 2011, CMA had destroyed 83 percent of the stockpile being treated at its facilities.[1]

The stockpile originally contained two types of chemical agents: cholinesterase-inhibiting nerve agents (GB and VX) and blister agents, primarily mustard (H, HD, and HT) but also a small amount of lewisite. Both types of chemical agents are liquids at room temperature. To store the agent, the stockpile originally consisted of (1) bulk ("ton") containers of nerve and blister agent and (2) munitions, including rockets, mines, bombs, projectiles, and spray tanks loaded with either nerve or blister agents. Many of the munitions contain both chemical agent and energetic materials (propellants and/or explosives), a combination whose safe and efficient destruction poses special challenges.

JACADS completed its mission of destroying approximately 4 percent of the nation's chemical agent stockpile that had been stored on Johnston Island in November 2000. Of the eight U.S. chemical agent weapons storage sites in the continental United States, three have completed destruction operations (Aberdeen, Maryland; Newport, Indiana; and Pine Bluff, Arkansas); disposal facilities are currently in operation at Anniston, Alabama; Tooele, Utah; and Umatilla, Oregon; and two chemical agent destruction pilot plants, the subjects of this report, are under construction at Pueblo, Colorado, and Richmond, Kentucky. All mines, bombs, and spray tanks have been destroyed. All rockets and nerve agent have been destroyed except for those in the stockpile at BGAD.

The largest stockpile site in the continental United States is the Deseret Chemical Depot near Tooele, Utah. This site initially stored 13,616 tons of agent. This component of the stockpile is being destroyed by the Tooele Chemical Agent Disposal Facility, which started operation in August 1996. The Tooele facility is currently destroying mustard agent. The other disposal facilities at Aberdeen, Maryland; Anniston, Alabama; Pine Bluff, Arkansas; Newport, Indiana; and Umatilla,

[1]See http://www.cma.army.mil/home.aspx for updated information as the program progresses.

Oregon, have collectively destroyed more than 79 percent of the original stockpile. JACADS, Aberdeen, and Newport have been closed.

Chemical agent destruction pilot plants that employ nonincineration alternative destruction technologies are currently under construction at the PCD near Pueblo, Colorado (the Pueblo Chemical Agent Destruction Pilot Plant), and at BGAD in Richmond, Kentucky (the Blue Grass Chemical Agent Destruction Pilot Plant). Consequently, destruction operations have not yet begun at these sites. This report concerns the appropriate process safety metrics for use at these two sites.[2]

THE SAFETY CHALLENGE—PROCESS SAFETY METRICS

The law mandating the destruction of chemical agent and munitions requires that the destruction be executed with maximum protection to workers, the public, and the environment. In the initial years of the stockpile disposal program, reports by NRC's Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program repeatedly encouraged the Army and its contractors to pay increased attention to safety and to engage in processes aimed at continuous improvement with respect to safety.[3] More recently that committee's successor committee, the standing Committee on Chemical Stockpile Demilitarization, and numerous ad hoc NRC committees concerned with chemical demilitarization have continued to emphasize safety.

The Army and its contractors have responded so effectively that the remaining operating facilities have attained Occupational Safety and Health Administration (OSHA) recordable injury rates of less than one injury per 200,000 hours worked. Even so, in the interest of continuous improvement, in 2007 the Army expressed a desire and intent to achieve safety performance that is equal to, or better than, that of the best industrial companies, which are consistently near an OSHA recordable injury rate of 0.5. To assist in achieving this goal, the NRC was asked to review existing safety and environmental metrics at operating chemical agent disposal facilities and to recommend additional metrics and/or program modifications, if necessary. The NRC issued its report, *Evaluation of Safety and Environmental Metrics for Potential Application at Chemical Agent Disposal Facilities*, in April 2009.

Having been provided with the 2009 report, and for reasons such as the use of first-of-a-kind equipment and the need to conscientiously adhere to congressional mandates that the destruction of chemical agent and munitions be executed with maximum protection to workers, the public, and the environment, the Program Manager for Assembled Chemical Weapons Alternatives (PMACWA) determined that it would be useful for the NRC to conduct a study on process safety metrics to guide it in formulating a process safety plan for PCAPP and BGCAPP. Accordingly, PMACWA asked the NRC to undertake a study that would guide its development and application of process safety metrics. Since the PCAPP and BGCAPP sites are presently under construction, PMACWA has a timely opportunity to develop process safety metrics to measure and monitor process safety performance.

Because process safety metrics can measure the effectiveness of process safety program management, they are increasingly being used by industry. An independent investigation following an industrial accident at the BP refinery at Texas City, Texas, on March 23, 2005, underscored the inadequacy of injury rates alone to measure process safety performance and called attention to the value of process safety metrics. Specifically, the ensuing report by the BP Independent Refiners Safety Review Panel (the Baker panel report) stated:

> BP primarily used injury rates to measure process safety performance at its U.S. refineries before the Texas City accident. Although BP was not alone in this practice, BP's reliance on injury rates significantly hindered its perception of process risk. BP tracked some metrics relevant to process safety at its U.S. refineries. Apparently, however, BP did not understand or accept what this data indicated about the risk of a major accident or the overall performance of its process safety management systems. As a result, BP's corporate safety management system for its U.S. refineries does not effectively measure and monitor process safety performance (Chemical Safety Board, 2007, p. xiv)

[2]Information about the history of the Assembled Chemical Weapons Alternatives (ACWA) program may be found at http://www.pmacwa.army.mil/index.html, including http://www.pmacwa.army.mil/info/dl/acwa_brochure_121310.pdf and http://www.pmacwa.army.mil/info/dl/ACWA_Overview_Fact_Sheet_FINAL_2010.pdf.

[3]The Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program interacted with the Program Manager for Chemical Demilitarization and the CMA.

STATEMENT OF TASK

The statement of task for the Committee to Assess Process Safety Metrics for the Blue Grass and Pueblo Chemical Agent Destruction Pilot Plants is the following:

> The National Research Council will establish an ad hoc committee to:
>
> - Review and evaluate plans for the use of process safety metrics to be employed at the two Assembled Chemical Weapons Alternatives (ACWA) pilot plant facilities,
> - Examine and assess the process safety metrics used in commercial and industrial operations for potentially applicable process safety metrics, and
> - Assess new initiatives at national organizations (i.e., American Institute of Chemical Engineers, etc.) that could be used by ACWA.

PROCESS SAFETY MANAGEMENT

This report is focused on metrics to manage operations from the process safety perspective. As will be discussed more fully below, process safety is a disciplined framework for managing the integrity of operating systems, processes and personnel handling hazardous substances, and operations by applying good design principles, engineering, and operating practices. At PCAPP and BGCAPP, process safety encompasses all aspects of the process from the delivery of the chemical weapons from storage, to shipping solid and liquid waste streams for final disposal. Process safety includes keeping materials inside their primary containment, preventing the unintended release of chemical agent, and safely handling all materials and chemicals related to the process. Historically, the CMA has focused its safety program on the prevention of agent releases, the safe handling of energetics, and the safe closure of chemical agent disposal facilities that have completed operations.

The systematic application of process safety principles encompasses the various controls and monitoring of the operations, the data on process compliance, and the effectiveness of these systems. The focus is on performance—that is, on operating excellence that goes beyond strict compliance with regulations or procedures. The mindset of the organization and its ability to focus on and devote time to process safety is essential. The site management must be fully involved in a manner that fosters continuous improvements—for example, by tracking performance through periodic measurements.

A basic principle of a good safety culture is that safety cannot be delegated and is the responsibility of both line management and operations personnel. Line management must take an active leadership role to ensure the effectiveness of a process safety management system. Metrics for monitoring the effectiveness of key process safety programs can be used by management for accomplishing continuous improvement. A focused effort on both leading and lagging metrics is needed.[4] Developing and implementing leading metrics is more complex and challenging than developing and implementing lagging metrics, but the former have been shown to provide better overall awareness and serve as an early warning of potential process safety incidents, allowing for preventative actions. Similarly, well-designed lagging metrics also provide valuable information about the process, which, if trends are measured, could serve as an indicator of continuous improvement.

The primary mission for chemical demilitarization operations is to destroy the agent and dispose of the associated munitions safely. Well-designed leading process safety metrics can provide an early warning of potential process safety incidents.

An effective process safety program, as outlined above, requires a strong commitment to the shared values and behaviors of a work culture that is pursuing safe operating excellence. Such efforts explicitly require (1) a willingness to devote time and resources to the safety system; (2) constant, focused management involvement; and (3) the active participation of all employees. Successful process safety operations must continuously assess the effectiveness of the process safety management program and the organization's ability to focus on safety, including but not limited to operational discipline and adherence to standards and performance metrics. Actions to remediate nonconformances must be clearly spelled out along with responsibility for implementing them and time lines for completing them. The success of a safety program will rest on an organization's ability to maintain operational excellence through demonstrated operational discipline at the management, supervisory, and process levels (operators, maintenance, etc.). Some key operational discipline elements include personal responsibility for understanding risks and the purpose of controls;

[4] "Leading metric" and "lagging metric" are defined in Appendix A.

teamwork; active communication with other employees involved in the process; use of updated procedures; and training to ensure operators have the knowledge and skills necessary to safely operate the process. Such discipline is based on the deeply rooted dedication and commitment of every member of the organization to carry out each task the right way each time.

PROCESS SAFETY MANAGEMENT AT PCAPP AND BGCAPP

During site visits to Pueblo, Colorado, and Richmond, Kentucky, to meet with staff supporting PCAPP and BGCAPP, the committee learned that process safety management considerations have been incorporated. The intent at both sites is to operate under the principles and guidelines set forth in OSHA's Process Safety Management (PSM) of Highly Hazardous Chemicals, which is located in 29 CFR 1910.119. The sites' process safety management practices include, but are not limited to, the following:

- Technical risk reduction tests and studies;
- First-of-a-kind process equipment evaluations;
- Application of lessons learned from the Aberdeen and Newport neutralization sites[5] and the baseline incineration design and operations;
- Design criteria that meet national codes and local regulations;
- Hazard and operability analysis to assess equipment and process hazards;
- Internal design reviews to ensure that plant design minimizes adverse safety impacts that would affect the ability to start up, operate, and maintain the sites;
- Use of management of change;[6]
- Process control systems designed to ensure overall operational control and coordination from the control room, and monitoring of critical safety-related systems and agent-monitoring systems;[7]
- Well-defined operating boundaries using critical operating parameters;
- A formal certification program to ensure employees are trained in and knowledgeable about their respective job duties; and
- Detailed material balances and throughput analyses.

Site plans at PCAPP and BGCAPP include the development of process safety management systems that will address OSHA PSM system requirements. Although the mustard agent to be processed at PCAPP is not covered by the OSHA PSM standard, PCAPP plans to establish a process safety management system to meet the intent of the OSHA PSM regulations. During its visits to PCAPP and BGCAPP, the committee saw that both sites recognized the need for process safety metrics and that they are in the initial stages of developing and implementing such metrics. Both sites had developed metrics to measure the effectiveness of several of the OSHA PSM required elements and are looking for additional guidance from this committee.

COMMITTEE MAKEUP AND MEETING SCHEDULE AND REPORT SCOPE AND APPROACH

As is suggested by the statement of task, a committee with very specific expertise was required to undertake the task (see Appendix B).

Four meetings were held, and individual committee members interacted extensively between meetings. The first meeting focused on gathering information and developing an understanding of the processes to be employed at PCAPP and BGCAPP. Between the first and second meetings, the committee requested and received a considerable amount of information on the two sites.

Two members of the committee conducted a site visit to CMA at the Aberdeen Proving Ground in Maryland, where they evaluated process safety-related incidents at CMA sites since 1990 that were relevant to the work of the committee.

The purpose of the second meeting of the committee, held one day in Pueblo, Colorado, and a second day in Richmond, Kentucky, was to interact directly with ACWA project management personnel to gain an understanding of the operating processes at PCAPP and BGCAPP.

At the third meeting, the committee focused on the results of the process safety incident analyses and data

[5]The Aberdeen and Newport sites, like PCAPP and BGCAPP, used neutralization (hydrolysis) instead of incineration as the primary process for agent destruction.

[6]This is a process to analyze and manage the results of any change to the physical plant, process, or people with the potential to introduce health, safety, security, environmental, or operational hazards, whether on a permanent, temporary, or emergency basis.

[7]An example of a critical safety-related system would be a computer, software, or mechanical system the failure of which could result in death, serious injury, or environmental damage.

gathered on process hazards and on assessing how well the draft report met the statement of task.

At the fourth and final meeting, the committee reviewed the report draft, discussed and agreed on findings and recommendations, and set the stage for achieving concurrence soon after via virtual meetings and teleconferences.

Numerous teleconferences and virtual meetings were also conducted between committee meetings; these involved committee members, NRC staff, the Army representatives, and PCAPP and BGCAPP personnel.

This report assesses initiatives undertaken by other process safety-related organizations, such as the American Institute of Chemical Engineers (specifically, its Center for Chemical Process Safety), the American Petroleum Institute, and the United Kingdom Health and Safety Executive, and discusses the applicability of chemical and petroleum industry metrics to PCAPP and BGCAPP.

The committee reviewed process safety-related incidents at CMA facilities since 1990 and their associated key causal factors and suggested metrics based on those factors. The committee also drew on its discussions with project and operations management staff at PCAPP and BGCAPP to aid in the identification of specific process operations that would benefit from the application of process safety metrics.

Using this information, the committee prepared a list of process safety metrics it believes should be adopted at the sites (Recommendation 4-3) and suggested other possible metrics and approaches to generating metrics for consideration and use at the sites (Chapter 4). Additionally, two of the processing steps that will be used, hydrolysate handling and the energetics batch hydrolysis, were selected by the committee to provide guidance on identifying process safety metrics. These examples should help to clarify the process for developing process safety metrics. It is the committee's expectation that site operations management will conduct thorough reviews of the process at both PCAPP and BGCAPP to identify the leading and lagging process indicators necessary for the effective management of process safety.

This study did not include an independent evaluation of the agent destruction processes planned for use at the two sites. The committee used the sites' process designs as the basis for its work on metrics and focused on the processes that fall under PMACWA's management: receipt of munitions for processing, removal of agent and energetics, treatment of recovered agent and energetics, treatment of empty munition bodies, destruction of agent, and secondary processing prior to release of the waste for disposal. Munitions storage is not managed by PMACWA and so is beyond the scope of this report. Also, since the use of explosive destruction technologies for destroying munitions containing agent has been studied extensively by other NRC committees, the committee did not include an assessment of this in this report.

The committee was somewhat constrained by the fact that with planned start-up dates of 2014 and 2018 at PCAPP and BGCAPP, respectively, many operational aspects of the plants are still being defined. As a result, specifying metrics would be premature, so the committee's recommendations could not be overly specific and are instead more aligned with the members' experience in other chemical operations. The committee, therefore, has mainly provided guidelines and suggestions for selecting and developing process safety metrics.

OVERVIEW OF REPORT

This report highlights the use of process safety metrics to provide timely feedback to operations management on the effectiveness of their process safety management system. Chapter 1 describes the U.S. chemical weapons stockpile stored in military depots in the United States. It includes a brief overview of the chemical weapons disposal program developed in response to congressional mandate. The congressional mandate (P.L. 102-484) includes a requirement to provide maximum protection to workers, the public, and the environment. It also provides background information on the role that the NRC has played in assisting the Army to conduct chemical agent disposal operations safely, the origin of the present report and the purpose to be served by it, and the activities to be undertaken by the committee in fulfillment of its statement of task. It also discusses what process safety management and its associated metrics encompass and why they are an important part of a high-functioning worksite safety culture.

Chapter 2 presents a high-level review of the process trains for chemical demilitarization at PCAPP and BGCAPP. Although both facilities will use neutralization processes to dispose of chemical agent, further processing of the resulting hydrolysate to ensure destruction of agent will be accomplished using biotreatment technology at PCAPP and supercritical water oxidation at BGCAPP. Process flow diagrams for the two plants are provided. First-of-a-kind equipment and operations are also reviewed for the additional risk first-of-a-kind equipment can present.

In Chapter 3, a review of the process safety events that occurred at the CMA neutralization and incineration sites illustrates some causes of process safety incidents that might also occur at PCAPP and BGCAPP. There are also valuable lessons to be learned from experiences with those parts of the disposal process used at the CMA neutralization and incineration sites that are similar to the processes planned for use at PCAPP and BGCAPP.

In Chapter 4, the committee reviews the process safety metrics applied in industry, as well as those established by national and professional organizations, such as the American Institute of Chemical Engineers' Center for Chemical Process Safety, the American Petroleum Institute, and the United Kingdom Health and Safety Executive. The committee then provides guidance to PMACWA to help in the selection of process safety metrics and related methodologies for PCAPP and BGCAPP.

REFERENCE

Chemical Safety Board. 2007. The Report of the BP US Refiners Independent Safety Review Panel. Available online at http://www.csb.gov/assets/document/Baker_panel_report1.pdf. Last accessed on October 28, 2010.

2

Overview of Agent Destruction Processes at Pueblo Chemical Agent Destruction Pilot Plant and Blue Grass Chemical Agent Destruction Pilot Plant

The Pueblo and Blue Grass Chemical Agent Destruction Pilot Plants (PCAPP and BGCAPP) will use neutralization technology instead of the incineration processes used at five other storage sites to destroy chemical munitions. Two other sites, Aberdeen, Maryland, and Newport, Indiana, at which chemical agents were stored only in bulk ton containers, used neutralization technology developed by the Army and have since completed destruction operations and been closed. In view of this, and in recognition of local public opposition to the use of incineration, Congress mandated that nonincineration technologies also be used to destroy the assembled chemical weapons stored at the Pueblo and Blue Grass sites (Public Laws 104-201 and 104-208). Neutralization involves the hydrolysis of chemical agent and energetics using hot water for mustard agent and alkali for nerve agents and energetics. BGCAPP will use neutralization followed by the treatment of the resultant hydrolysis products with supercritical water oxidation (SCWO). PCAPP plans to ship the energetics removed from the munitions for disposal offsite; it will use neutralization to destroy the mustard agent followed by biotreatment of the hydrolysate. These plants will be operated 24 hours a day, 7 days a week.

The processes planned for use at PCAPP and BGCAPP are described briefly below. These overview descriptions are not intended to delineate all of the waste streams and final products of the destruction processes. For example, most of the processes are batch operated and have sufficient buffer storage between unit operations. Rather, only those processes that will be discussed later in this report are described here, including those that will be used to exemplify aspects of process safety management. A more extensive description of the unit operations can be found in earlier National Research Council reports and on the Assembled Chemical Weapons Alternatives (ACWA) Web site.[1] Tables 2-1 and 2-2 give the physical properties of the chemical agents that will be processed at PCAPP and BGCAPP. The munitions to be destroyed are depicted in Figures 2-1 through 2-5.

PCAPP PROCESS OVERVIEW

Unless otherwise noted, the material in this section is based on a presentation to the committee.[2] The chemical munitions stockpile stored at the Pueblo Chemical Depot (PCD) consists only of artillery projectiles and 4.2-inch mortars containing mustard agent. The stockpile contents are shown in Table 2-3. The process flow chart for PCAPP is shown in Figure 2-6.

Pallets containing projectiles will be transported from the depot's storage igloos to the munitions storage magazine (MSM) at PCAPP (first box in Figure 2-6). Because munitions can be transported only during daylight hours and in good weather, the accumulation

[1]See, for example, *Interim Design Assessment for the Blue Grass Chemical Agent Destruction Pilot Plant* (2005) and *Interim Design Assessment for the Pueblo Chemical Agent Destruction Pilot Plant* (2005) at http://www.nap.edu/. The Assembled Chemical Weapons Alternatives Web site is at http://www.pmacwa.army.mil/.

[2]Joe Novad, Deputy Program Manager, U.S. Army Element, ACWA, "PCAPP Overview," presentation to the committee on June 14, 2010.

TABLE 2-1 Physical Properties of Nerve Agents

Agent Characteristic	GB	VX
Chemical formula	$C_4H_{10}FO_2P$	$C_{11}H_{26}NO_2PS$
Molecular weight	140.10	267.38
Boiling point (°C)	150 (extrapolated)	292 (extrapolated)
Freezing point (°C)	−56	≤51
Vapor pressure at 25°C (mm Hg)	2.48	0.000878
Volatility at 25°C (mg/m^3)	18,700	12.6
Surface tension at 20°C (dynes/cm)	26.5	32.0
Kinematic viscosity (cSt)	1.28 at 25°C	12.26 at 20°C
Liquid density at 25°C (g/cm^3)	1.0887	1.0083
Solubility (g/100 g of distilled water)	100; soluble in organic solvents	5 at 25°C; best solvents are dilute mineral acids
Heat of vaporization (cal/g)	82.9	71.8
Heat of combustion (cal/g)	5,600	8,300

SOURCE: NRC, 2005; Abercrombie, 2003.

TABLE 2-2 Physical Properties of Mustard Agents[a]

Agent Characteristic	HD	HT[b]
Chemical name	Bis (2-chloroethyl) sulfide or 2,2'-dichlorodiethyl sulfide	Same as HD with 20 to 40 wt% agent T, bis[2(2-chlorethylthio) ethyl] ether
Chemical formula	$C_4H_8Cl_2S$	Not applicable
Molecular weight	159.07	188.96 (based on 60/40 wt%)
Vapor density (relative to air)	5.5 (calculated)	6.5 (calculated based on 60/40 wt%)
Boiling point (°C)	218 (extrapolated)	No constant boiling point
Decomposition temperature (°C)	180	165 to 180
Freezing point (°C)	14.45	1.3 (measured as melting point)
Vapor pressure at 25°C (mm Hg)	0.106	7.7×10^{-2} (calculated based on Raoult's law equation)
Volatility at 25°C (mg/m^3)	9.06×10^2 (calculated from vapor pressure)	7.83×10^2 (calculated from vapor pressure)
Diffusion coefficient for vapor in air (cm^2/sec)	0.060 at 20°C (68°F)	0.05 at 25°C (77°F)
Flash point (°C)	105	Flash point range 109 to 115
Surface tension (dynes/cm)	43.2 at 20°C (68°F)	44 at 25°C (77°F)
Viscosity at 20°C (cSt)	3.52	6.05
Liquid density at 25°C (g/cm^3)	1.2685	1.263
Solubility (g/100 g of distilled water)	0.092 at 22°C (72°F); soluble in acetone, carbon tetrachloride, chloroform, tetrachloroethane, ethyl benzoate, ether	Slightly soluble in water; soluble in most organic solvents
Heat of vaporization		Not available
(Btu/lb)	190	
(J/g)	82	
Heat of combustion		Not available
(Btu/lb)	8,100	
(J/g)	3,482	

[a]Mustard agents are labeled H, HD, and HT. The active ingredient in all these blister agents is bis(2-chloroethyl) sulfide, or $(ClCH_2CH_2)_2S$. HD, called the distilled mustard, is nominally pure mustard agent. H, often called Levinstein mustard, was approximately 70% pure mustard agent and 30% impurities at the time of manufacture. However, the stored H mustard agent has deteriorated over time and its physical properties are highly variable. H is the only form of mustard agent stored at Blue Grass Army Depot.

[b]Overall proportional composition of the mixture. HT is prepared by a chemical process that synthesizes the HT directly in such a way that it contains both the HD and T constituents without further formulation.

SOURCES: Adapted from U.S. Army, 1988; Abercrombie, 2003; BPT, 2004.

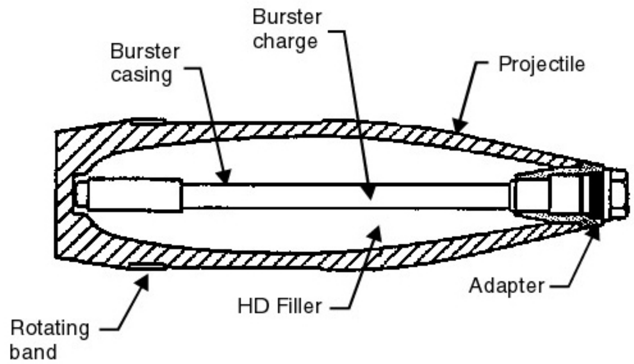


FIGURE 2-1 A 105-mm howitzer projectile. Some cartridges have been reconfigured and therefore will not have propellant in the box with the projectile. For those that still have propellant, there will be propelling charges in the box. SOURCE: Adapted from U.S. Army, 1977.

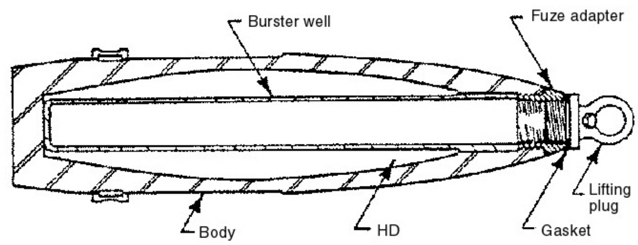


FIGURE 2-2 A 155-mm howitzer projectile. These projectiles have been separated from their propellant and stored. SOURCE: Adapted from U.S. Army, 1977.

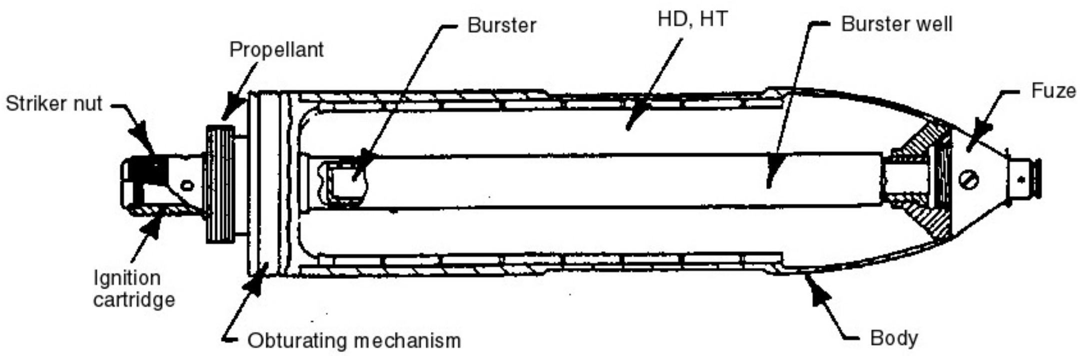


FIGURE 2-3 A 4.2-inch mortar cartridge. The 4.2-inch mortar cartridges will be reconfigured as will be the projectiles. Most 4.2-inch cartridges will also be defuzed. SOURCE: Adapted from U.S. Army, 1977.

of munitions in the MSM allows for round-the-clock operation at PCAPP. From the MSM, munitions will be moved to the unpack area in the enhanced reconfiguration building (second box in Figure 2-6). If the projectiles contain bursters,[3] they will be moved to the reconfiguration room, where the bursters will be removed by the linear projectile and mortar disassembly (LPMD) machine (described later in this chapter) without disturbing the burster well that seals in the chemical agent. Uncontaminated energetics will be sent offsite for processing. Leaker and reject projectiles will be disposed of using an explosive destruction technology, without disassembling the munition (fifth box in Figure 2-6).[4] The reconfigured projectiles (that is, those whose bursters have been removed) will then be transported robotically along a long corridor to the agent processing building in munition transfer carts.

[3]A burster is an explosive charge, the purpose of which is to burst the munition casing and disperse the chemical agent within.

[4]A leaker is a munition that has leaked. A reject is a munition that for any reason cannot be disassembled. These munitions will be destroyed by an explosive destruction technology without removing them from their outer protective overpack, reducing the risk of exposing personnel or the environment to agent. For more information on explosive destruction technology, see the NRC reports *Review of International Technologies for Destruction of Recovered Chemical Warfare Materiel* (2006) and *Assessment of Explosive Destruction Technologies for Specific Munitions at the Blue Grass and Pueblo Chemical Agent Destruction Pilot Plants* (2009). Both are available at http://www.nap.edu.

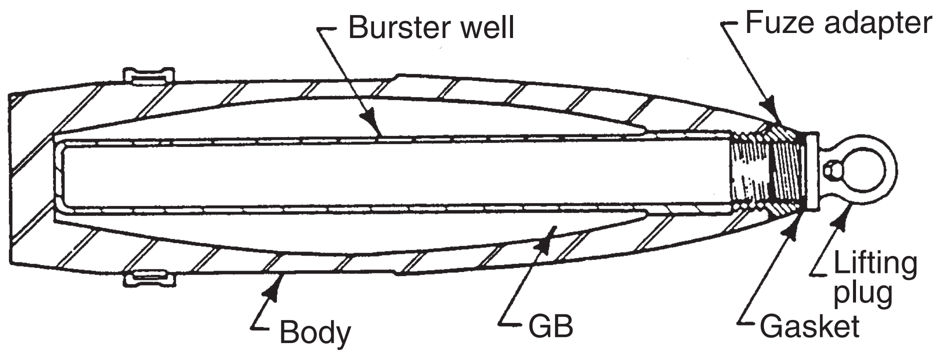


FIGURE 2-4 An 8-inch projectile. The 8-inch projectiles at BGAD do not contain any energetic materials. SOURCE: U.S. Army, 1983.

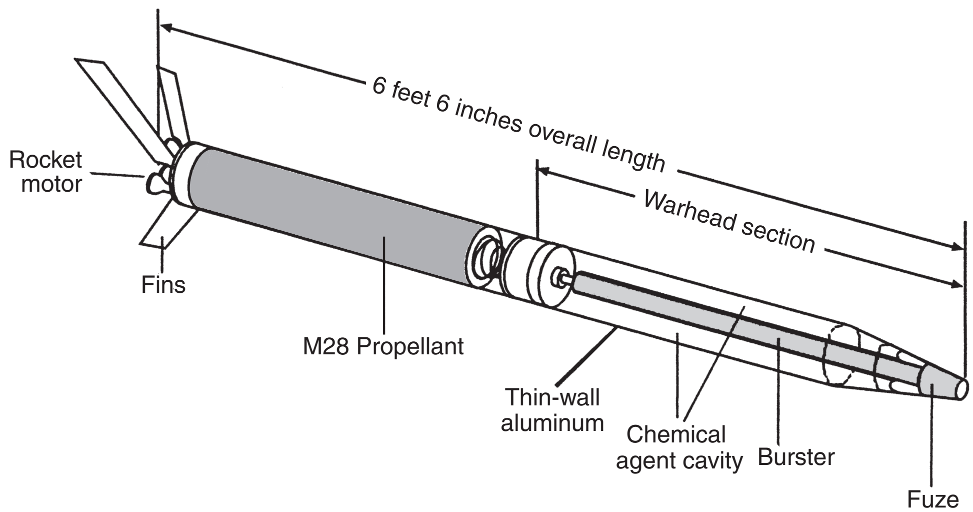


FIGURE 2-5 An M55 rocket. SOURCE: Beth Feinberg, Office of the Program Manager for Alternative Technologies and Approaches, presentation to the Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program, March 28, 2001.

In the agent processing building, the shells, still containing the burster well, will be moved on trays to the munition washout system (MWS) (second box in Figure 2-6). A robot will take a projectile from a tray and place that projectile into a cavity access machine in an inverted position. In the cavity access machine, an arm will dislodge the burster well by ramming it into the shell to expose the agent. The agent will then be drained and the interior of the shell washed using a high-pressure water wand. The chemical agent removed from the munition will then be transferred to the agent neutralization system, where it will be neutralized (third box in Figure 2-6). (Agent neutralization is described after the BGCAPP process description later in this chapter.) Hydrolysate will not be transferred from the agent neutralization system until it has been analyzed and verified that agent destruction is complete. The hydrolysate produced from the neutralization of mustard agent contains mostly thiodiglycol, which is biodegradable. The hydrolysate will thus be transferred to and treated in immobilized-cell bioreactors, where bacteria will feed on the thiodiglycol that is the prime

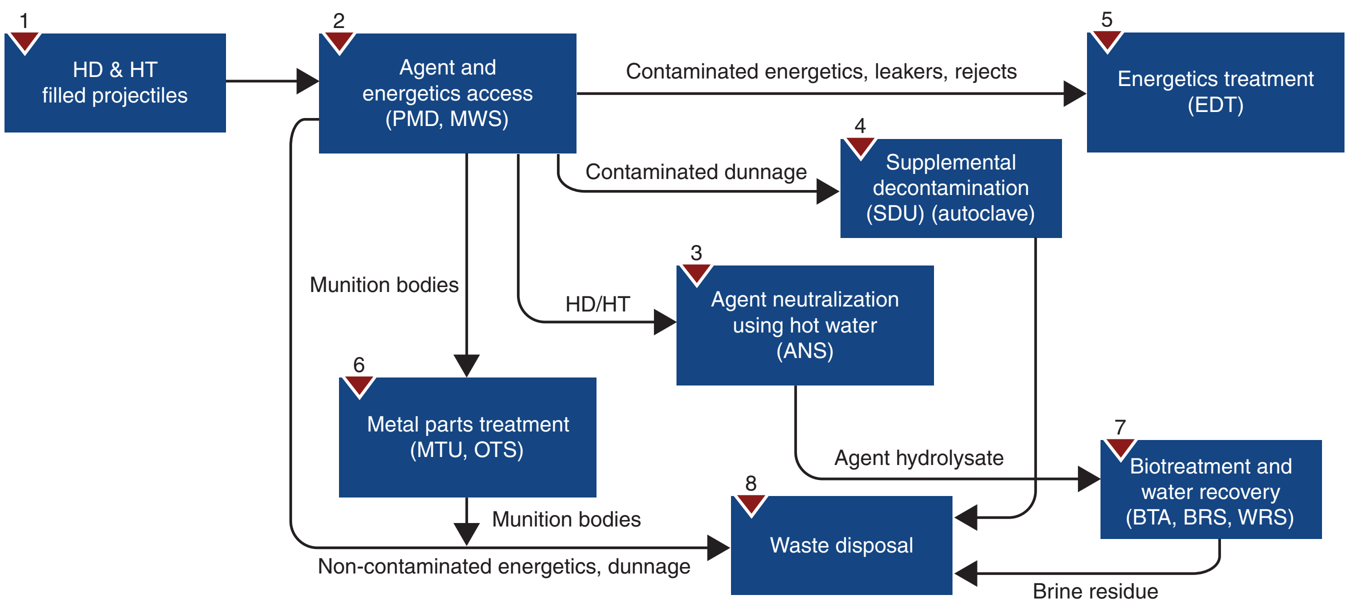
TABLE 2-3 Chemical Weapons Stockpile Stored at PCD

Munition	Agent Fill	Quantity
155-mm projectiles M110	HD	266,492
155-mm projectiles M104	HD	33,062
105-mm cartridge M60	HD	383,418
4.2-inch mortar M2A1	HD	76,722
4.2-inch mortar M2	HT	20,384

SOURCE: NRC, 2001.

constituent of the mustard hydrolysate and convert the hydrolysate compounds to water, carbon dioxide, and sludge that will contain compounds of chlorine and sulfur originating from the mustard (seventh box in Figure 2-6). It is also anticipated that this sludge will contain mercury owing to previous experience with the contamination of mustard agent with mercury at other stockpile sites that contained mustard agent. The Program Manager for Assembled Weapons Alternatives (PMACWA) is working on procedures to address the anticipated presence of mercury.

The projectile bodies are meanwhile placed in other trays and moved to the munitions treatment unit (sixth box in Figure 2-6), where they will be decontaminated at 1000°F for over 15 minutes before being released. The munitions treatment unit is a long muffle furnace with a conveyor that will slowly move projectile bodies from one end to the other as they are heated.



PMD	Projectile mortar disassembly
MWS	Munitions washout system
ANS	Agent neutralization system
EDT	Energetics destruction technology
SDU	Supplemental decontamination unit

MTU	Munitions treatment unit
OTS	Offgas treatment system
BRS	Brine reduction system
WRS	Water recovery system
BTA	Biotreatment area

FIGURE 2-6 PCAPP process flow chart. SOURCE: Joe Novad, Deputy Program Manager, U.S. Army Element, Program Manager for ACWA, "PCAPP Overview," presentation to the committee on June 14, 2010.

TABLE 2-4 Chemical Weapons Stockpile Stored at BGAD

Munition	Agent Fill	Quantity
115-mm rockets M55	GB	51,716
115-mm rockets M55	VX	17,733
115-mm rocket warheads M56	GB	24
115-mm rocket warheads M56	VX	6
155-mm projectiles M121/A1	VX	12,816
155-mm projectiles M110	H	15,492
8-inch projectiles	GB	3,977

SOURCE: NRC, 2005.

BGCAPP PROCESS OVERVIEW

Unless otherwise noted, the material in this section is based on a presentation to the committee.[5] The chemical munitions stockpile stored at the Blue Grass Army Depot (BGAD) is smaller but far more diverse than that at PCD. It contains both rockets and projectiles and the chemical agents H (mustard), GB (sarin), and VX. Consequently, the process for destroying the munitions in the BGAD inventory is more complex than that for the munitions at PCD. The contents of the stockpile stored at the BGAD are shown in Table 2-4, and the flow chart for the destruction process is shown in Figure 2-7.

Rocket Processing

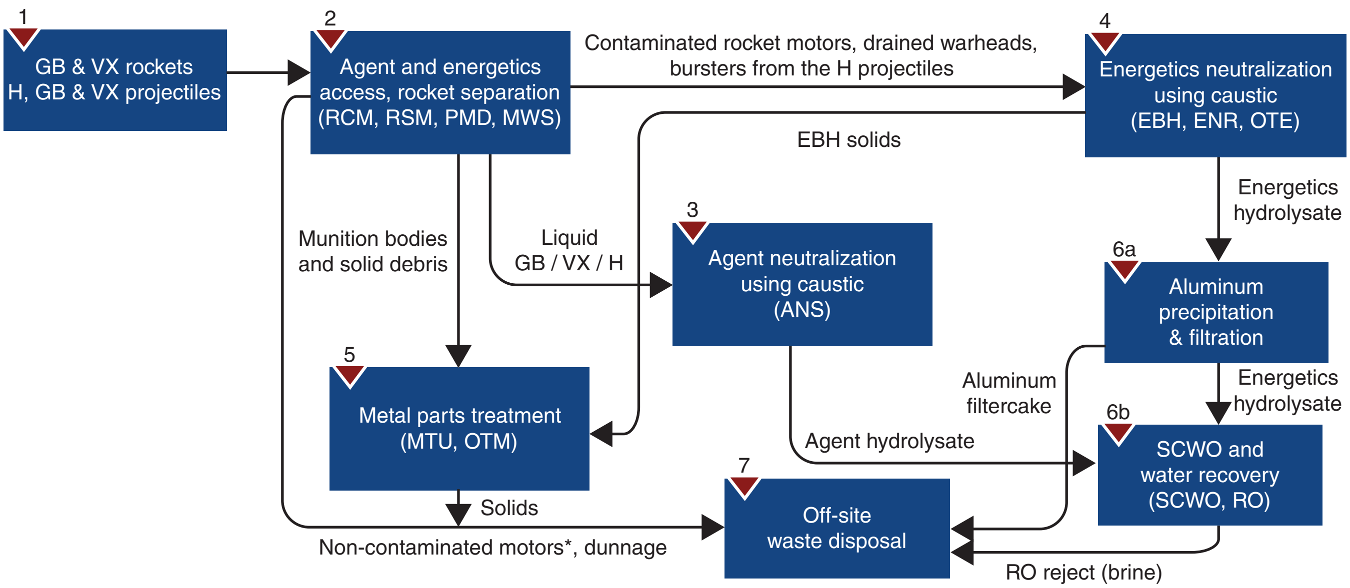
Because the M55 rockets, which contain about 19 pounds of a two-base propellant and 10 pounds of nerve agent, pose the highest storage and processing risks, they will be destroyed first. The rockets will be transported from the igloos into the unpack area, where personnel will remove them from the pallets (first box in Figure 2-7). If agent is detected outside the shipping and firing tube, the rocket is returned to storage until it and other leaking rockets are disposed of. After being removed from their pallets, the rockets, still contained in their fiberglass shipping and firing tubes (SFTs), will be placed on a conveyor and moved to the explosion containment vestibule and onto the rocket cutting machine (second box in Figure 2-7). First, the propellant motor section at the back end will be separated from the rocket warhead in two stages by cutting through the SFT and rocket body with a pipe cutter-like device. The first cut is only deep enough to cut open the SFT so that it can be removed. The second cut will be deep enough to breach the outer body of the rocket, allowing the warhead and motor sections to be separated. Uncontaminated propellant sections and the warhead's SFT sections will be shipped offsite for disposal. Contaminated propellant sections and SFT sections will be sent to the energetics neutralization process for treatment (fourth box in Figure 2-7).

After separation, the rocket warhead will be transferred to the rocket shear machine in the explosive containment room (second box in Figure 2-7). The warhead will be punched on its top and bottom and the agent drained out. The warhead cavity will then be washed out with a high-pressure water system to remove residual agent as well as any gelled or crystallized material that may have formed during storage. The drained warhead will then be sheared into segments in the rocket shear machine. If the rocket warhead cannot be separated from its SFT, it will be processed while it is still in the SFT. Any rockets where agent is detected before punching and draining are returned to storage to await the disposal of leaking rockets.

The chemical agent drained from the warhead will be sent to the agent collection system and put into holding tanks until processed. The wash water from rinsing the warhead will be sent to another holding tank that is used for spent decontamination solution. From the holding tanks, the chemical agent and wash water are sent to an agent neutralization reactor (ANR), where the chemical agent will be neutralized (third box in Figure 2-7). The resulting hydrolysate will then be sent through the SCWO units for further treatment, reducing the products to water, carbon dioxide, and salts, before being released for disposal (box 6b in Figure 2-7). The neutralization process is described in more detail below.

Each rocket segment that was cut in the rocket shear machine will be dropped into a bucket as it is sheared. These parts will include the burster and the fuze. The buckets will then be transported to the energetics batch hydrolyzer (EBH) room (fourth box in Figure 2-7) (BPBGT, 2009a). The three EBHs are large rotating vessels that have discontinuous helical flights that are used to mix the components as the EBH rotates. Indeed, an EBH can be thought of as the drum on a cement mixer. Once in the EBH room, a robot will pick each bucket up and raise it to a platform near the top of the EBHs. A second robot will then move the bucket from

[5]Joe Novad, Deputy Program Manager, U.S. Army Element, ACWA,"BGAPP Overview," presentation to the committee on June 14, 2010.



RCM	Rocket cutter machine
RSM	Rocket shear machine
PMD	Projectile mortar disassembly
MWS	Munitions washout system
EBH	Energetics batch hydrolyzer
ENR	Energetics neutralization reactor
ANS	Agent neutralization system

MPT	Metal parts treater
MTU	Munitions treatment unit
OTM	Offgas treatment system for MPT
OTE	Offgas treatment system for EBH
SCWO	Supercritical water oxidation
RO	Reverse osmosis
*	Non-contaminated rocket motor disposition still under review

FIGURE 2-7 BGCAPP process flow chart. SOURCE: Joe Novad, Deputy Program Manager, U.S. Army Element, Program Manager for ACWA, "BGCAPP Overview," presentation to the committee on June 14, 2010.

the platform to an EBH, into which the contents are dumped.

Prior to the addition of metal parts and energetics, the EBHs will be filled first with water and next with 50 percent caustic, to reach a concentration of 39.5 percent caustic, and will then be heated. After processing the metal parts and energetics for the specified time, the direction of rotation of the EBH drum will be reversed, lifting the metal parts out of the EBH and dropping them onto the vibrating screen belt of a horizontal conveyor. Any liquid passes through the screen and is collected. When this operation is completed, the rotation speed of the vessel will be increased, allowing the liquid to be removed from the EBH through a wire screen that catches any remaining solids.

The metal parts from the EBH will then be sent to the metal parts treater, where they will be decontaminated by heating them to over 1000°F for more than 15 minutes (fifth box in Figure 2-7). The metal parts can then be sent offsite for recycling or to a landfill (seventh box in Figure 2-7). The hydrolysate from the EBHs will be sent to the three energetics neutralization reactors, where it will be analyzed for presence of agent and energetic material (fourth box in Figure 2-7). The contents will remain in the energetics neutralization reactors until it has been verified that any energetics and agent have been neutralized. The hydrolysate from the EBHs will then be sent to the three SCWO units to reduce it to water, carbon dioxide, and salts (box 6b in Figure 2-7) (BPBGT, 2009b). It is anticipated that the solid wastes resulting from mustard hydrolysis will contain mercury owing to previous experience with the contamination of mustard agent with mercury at other stockpile sites that contained mustard agent. PMACWA is working on procedures to address the anticipated presence of mercury.

Projectile Processing

Projectiles will be processed differently from rockets. They will be unpacked manually and conveyed into an explosive containment room where the bursters will be removed by the two LPMD machines (second box in Figure 2-7). The munition bodies, still containing their burster wells, will then be moved to the munitions washout station. The process from this point on will be identical to the process at PCAPP, described above, except that the hydrolysate will be sent to the SCWO units instead of bioreactors for treatment.

NEUTRALIZATION OF CHEMICAL AGENT

The chemical agent at both sites will be treated by chemical neutralization. The agent will first be collected in the agent collection system, where it will be stored in holding tanks until it is moved to an agent neutralization reactor (ANR). The ANR will be a continuously stirred vessel where the hydrolysis reaction will be taken to completion.

For mustard neutralization, hot water will be used. Caustic will be added to neutralize the HCl that forms and to maintain the pH at 10.5 until the hydrolysis is completed (BPT, 2010). Caustic will be used to neutralize GB and VX agent. First, water is added to the ANR. Then the prescribed amount of 50 percent caustic is added. The final caustic concentration will be different for GB and VX. Finally, agent from the holding tanks will slowly be added to the ANR (BPBGT, 2009c). The contents will be both continuously stirred and recirculated to ensure good mixing and a complete reaction.

FIRST-OF-A-KIND PROCESS EQUIPMENT

Since the processes for chemical agent and munitions destruction to be used at PCAPP and BGCAPP are new, several pieces of process equipment that have never been used before have been included in the design of these two pilot plants. These pieces of process equipment are referred to as first of a kind (FOAK). The pieces of FOAK equipment the committee believes are the most likely to pose challenges to operations at PCAPP and BGCAPP are briefly described in Table 2-5. Because they embody new technologies or novel applications of existing technologies these FOAK items are at greater risk of having problems with respect to functionality, reliability, availability, and maintainability and may therefore require adjustments ranging from procedural modifications to varying degrees of redesign as they are developed, tested, and integrated into actual agent processing operations.

The LPMD is one of the pieces of FOAK equipment to be used at both PCAPP and BGCAPP. While it had previously undergone testing on simulated equipment test hardware (SETH) munitions, it had not been tested on actual chemical munitions.

Because the remaining stockpile being destroyed at the Anniston Chemical Agent Disposal Facility (ANCDF) contains mustard agent and projectiles, as does the stockpile to be destroyed at PCAPP, and similar issues relating to age of munitions can therefore be expected at both sites, PCAPP established a test project at ANCDF to evaluate the reliability, operational efficiency, and safety of the LPMD.

To date, LPMD testing at ANCDF has revealed a number of design and operational problems that would have considerably impacted systemization at PCAPP. For example, the munitions reject rate of the process was found to be significantly higher than had been anticipated (1.3 percent actual versus 0.01 percent expected). Thus far, 164 specific LPMD operating criteria have been reviewed, and 20 documented lessons learned will be applied to the design and operation of the system at PCAPP. Additionally, more than 110 significant code changes have been identified during testing at ANCDF.[6] The committee believes that based on the LPMD experience, similar difficulties can be expected with other FOAK equipment as systemization progresses.

SYSTEMIZATION

PCAPP and BGCAPP will both undergo preoperational systemization prior to starting actual agent disposal operations. Both facilities will follow a progression of steps that consist of the installation of process equipment, integration of process equipment, and demonstration of overall plant operation using surrogates instead of actual chemical agent. During this phase of the project, the systems used to operate the plant will be tested and configured. Systemization involves progressive testing, from a component basis to a subsystem basis to a system demonstration on surrogate munitions to bring each system to its fully

[6] Joe Novad, Deputy Program Manager, U.S. Army Element, ACWA, "Anniston LPMD," presentation to the committee on June 14, 2010.

TABLE 2-5 First-of-a-Kind Equipment and Processes That Could Pose Significant Challenges for PCAPP and BGCAPP

FOAK Equipment	Site(s)	Function	Notes
Rocket cutting machine (RCM)	BGCAPP	To separate rocket motors from the warhead.	This is an entirely new piece of equipment.
Linear projectile mortar disassembly (LMPD) machine	BGCAPP PCAPP	To disassemble projectiles and mortars and remove their bursters.	This is a new unit that replaces the PMD machine used at the baseline incineration sites operated by CMA.
Munitions washout station (MWS)	BGCAPP PCAPP	To remove the burster well from projectiles, drain the chemical agent, and wash out any agent residues.	This is an entirely new piece of equipment. It replaces the PMD machine used at the baseline incineration sites operated by CMA.
Energetics batch hydrolyser (EBH)	BGCAPP	To neutralize energetics and any chemical agent in the metal parts of the rockets and fuzes from projectiles.	This is an entirely new piece of equipment.
Metal parts treater (MPT)	BGCAPP	To decontaminate projectile bodies and secondary waste by heating to over 1000°F for more than 15 minutes.	This is an entirely new piece of equipment.
Munitions treatment unit (MTU)	PCAPP	To decontaminate projectile bodies and secondary waste by heating to over 1000°F for more than 15 minutes.	This is an entirely new piece of equipment.
Supercritical water oxidation (SCWO)	BGCAPP	To treat agent and energetics hydrolysates before releasing them for final disposal.	This is an entirely new piece of equipment and process.
Immobilized-cell bioreactors (ICBs)	PCAPP	To treat mustard hydrolysate before releasing it for final disposal.	This is an entirely new piece of equipment and process.

operational design function. Systemization provides an opportunity to train operators and to integrate plant systems and processes with a trained workforce and appropriate documentation. This ensures that each of the systems functions properly before a Declaration of Readiness is issued, Army endorsement is obtained, and governmental approval to begin agent operations is granted. The steps in systemization, along with the staffing levels, are shown in Figure 2-8.

Finding 2-1. Because of the unique nature of the processes at the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant and the extensive use of first-of-a-kind equipment, the use of both leading and lagging process safety metrics will be important in achieving the congressional mandate to safely destroy the chemical weapons stockpiles at the respective sites. Systemization affords an excellent opportunity to implement and evaluate leading and lagging process safety metrics.

Recommendation 2-1. During systemization, the Program Manager for Assembled Chemical Weapons Alternatives should develop and implement extensive process safety metrics that can be evaluated for relevance and utility. Metrics that are found to be meaningful should be carried forward to operations. While

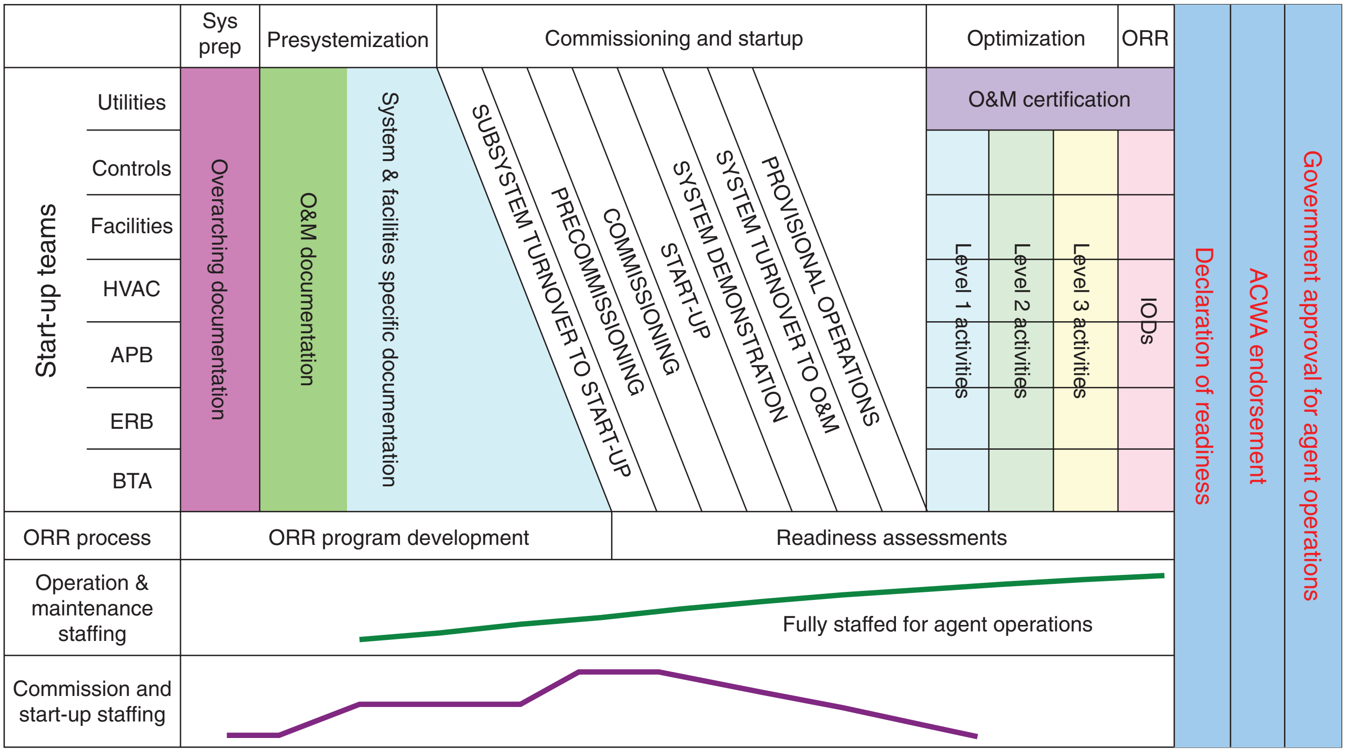


FIGURE 2-8 Overview of the systemization process. SOURCE: Joe Novad, Deputy Program Manager, U.S. Army Element, Program Manager for ACWA, "PCAPP Overview," presentation to the committee on June 14, 2010.

both leading and lagging metrics should be developed and implemented to the extent possible, both the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant should emphasize developing leading metrics to guide them in process safety management.

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3

Review and Assessment of Process Safety Incidents at Other Chemical Demilitarization Sites

Although the processes to be employed for disposal of chemical munitions at the Pueblo and Blue Grass Chemical Agent Destruction Pilot Plants (PCAPP and BGCAPP) are fundamentally different from those used at earlier chemical agent disposal facilities and vary somewhat among themselves, many similarities exist within and among the processes employed at all of the disposal facility sites. Prominent examples of similarities shared by the incineration sites and PCAPP and BGCAPP include the use of rocket shear machines (at sites where M55 rockets have been stored), thermal decontamination of metal parts, and methods used for waste treatment. The committee believed that evaluating documentation from those other sites concerning process incidents, any process safety metrics used, and process hazards could prove useful and would offer guidance on what process safety metrics might be useful for PCAPP and BGCAPP. Although none of the other chemical agent disposal facilities employed formal process safety metrics, the committee believed that an analysis of chemical events that occurred at those sites could provide insights into those process steps that are most subject to failure and might identify opportunities where the use of leading and lagging metrics could help to prevent failures.[1] Thus, there are aspects of the operations of even the baseline incineration facilities that could be useful for deriving process safety metrics for use at PCAPP and BGCAPP.

The National Research Council Committee on Evaluation of Chemical Events at Army Chemical Agent Disposal Facilities (the chemical events committee) reviewed all of the chemical events that had occurred since the commencement of destruction operations through the end of 2001, totaling 81 process and non-process-related incidents at that time. The chemical events committee issued its report, *Evaluation of Chemical Events at Army Chemical Agent Disposal Facilities*, in 2002. This committee reviewed that report to identify which of the events could be classified as process incidents.[2] Interestingly, the chemical events committee found that the causal factors underlying those events were not process related but were independent of any specific process. The chemical events committee's analysis of causal factors is summarized in Table 3-1.

The following definitions extracted from the report on chemical events apply to the terms used in the tables in this chapter:

- *Standard operating procedure (SOP) deficiencies* refer to nonexistent SOPs, inadequate SOPs, or SOPs being circumvented or ignored as a routine operating practice.
- *Equipment malfunction* refers to the failure of equipment to function as designed but does not include design deficiencies. Such failures range from the simple tearing of waste bags to breakdowns of critical instrumentation such as flowmeters and sensors.

[1]"Leading metric" and "lagging metric" are defined in Appendix A.

[2]An "event" is any off-normal occurrence. A "process safety incident" is defined in Appendix A.

- *Design deficiency* applies to equipment or facilities found to perform their operating functions inadequately as a result of poor design.
- *Unexplained human error* refers to human actions that were wrong for no reason recorded in the investigation reports or for which there is no apparent explanation. One example is when an operator assembled a piece of equipment incorrectly.
- *Mindset* refers to the mental attitude people have about the process of disposal and the state of the system during processing. One example is when a person assumes an agent alarm is false because of a historical pattern of frequent false alarms.
- *Improper technique* refers to a manner of performing tasks that causes either a hazard or a malfunction. An example is using equipment for purposes other than those dictated by design.
- *Failures of communication* refer to failure to communicate essential information, failure to heed communicated information, and inadequate communications systems.

This committee requested an update on process-related chemical events from all operating sites and the two sites that completed destruction since the end of 2001. In all, 147 events were reported to the committee,[3] of which 26 were reviewed by the chemical events committee in 2002. This committee evaluated the remaining 121 incidents for frequency of event type, process activity involved (e.g., maintenance, waste handling, weapons transfer, and agent transfer), consequence, and causal factors. The frequencies of incident types, activities, and causal factors mirror those that were noted in the 2002 Chemical Events Report. A summary of the causal factors for these 121 events is presented in Table 3-2.

"SOP deficiencies" was the most frequent causal factor, followed by "equipment malfunction" and "human error." Significantly, almost all of the events were noted to have had multiple causal factors, as is evidenced by the fact that 215 causal factors were identified for 147 events (also see notes to tables).

The activities that had the most incidents and events were maintenance and waste handling. Thirty-one events happened during waste handling, including hydrolysate transfers and spills. Twenty-two events happened during maintenance activities. Only two incidents happened during munitions transfer and two during agent transfer; however, not all agent transfer incidents were tabulated. Twenty-five incidents occurred in the rocket shear machine, but the causes of 21 of these were not, or could not be, assigned.

In summary, it appears that the frequency, types, and causal factors of process safety events in chemical agent disposal facilities could not be correlated with the type of facility (neutralization or incineration), type of chemical weapon (blister agent or nerve agent), or how

[3]Personal communication between Carl Anderson, ACWA, and James Myska, BAST Senior Research Associate, on July 20, 2010.

TABLE 3-1 Frequency of Causal Factors in the 81 Chemical Events Reviewed by the Chemical Events Committee in 2002

Causal Factor	Number of Times a Causal Factor Was Identified	Percentage of Instances of Causal Factors
SOP deficiencies	30	29.4
Equipment malfunction	12	11.8
Human error	7	6.8
Design deficiency	16	15.7
Mindset	15	14.7
Improper technique	12	11.8
Failure of communication	10	9.8
	102	100.0

NOTE: There is not a 1:1 correspondence between chemical events and instances of causal factors. Most events involved more than one causal factor, and for some events, it was not possible to determine causal factors.

TABLE 3-2 Frequency of Causal Factors in the 121 Events at Chemical Agent Disposal Facilities Since 2001

Causal Factor	Number of Time a Causal Factor Was Identified	Percentage of Instances of Causal Factors
SOP deficiencies	31	27.4
Equipment malfunction	29	25.7
Human error	29	25.7
Design deficiency	6	5.3
Mindset	6	5.3
Improper technique	7	6.2
Failure of communication	5	4.4
	113	100.0

NOTE: There is not a 1:1 correspondence between chemical events and instances of causal factors. Most events involved more than one causal factor, and for some events, it was not possible to determine causal factors.

the agent is stored (in assembled munitions or bulk storage). Consequently, PCAPP and BGCAPP can reasonably expect to experience the same types of events with similar causal factors. Because of the unique nature of the processes to be employed at PCAPP and BGCAPP, however, and the extensive use of first-of-a-kind equipment, it may be reasonable to expect more events in the early part of operations and, based on the data in Tables 3-1 and 3-2, a shift in the relative proportion of causal factors. For example, design deficiencies might be more prevalent in new facilities than in older or second-generation facilities.

Finding 3-1. The causal factors involved in past events at chemical agent disposal facilities are not process specific. Consequently, the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant can reasonably be expected to experience the same types of events having causal factors similar to those experienced at the Chemical Materials Agency sites. Also, there may be an increase in the frequency of events and a shift in the relative frequency of causal factors.

Causal factors for process safety events are discussed further in Chapter 4.

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4

Identification and Use of Process Safety Metrics

INTRODUCTION

This chapter describes recent efforts by the chemical and petroleum industries to define process safety metrics suited to the needs of their enterprises. It then discusses how such concepts can be leveraged and applied at the Pueblo Chemical Agent Destruction Pilot Plant (PCAPP) and the Blue Grass Chemical Agent Destruction Pilot Plant (BGCAPP).

Leading and lagging process safety metrics have been of great interest for at least the last 5 years. Process safety and the metrics for such safety have been of concern especially in the chemical and petroleum industries, because it is those sectors that handle or produce toxic and flammable materials, which if released into the environment have the potential to cause multiple fatalities or injuries and significant environmental damage. Since the mid-1990s, these industries have used major unplanned releases of chemicals or energy as a primary process safety metric. Trade associations, including the American Chemistry Council and the American Petroleum Institute (API), have developed and implemented a common definition of a process safety incident (PSI) and have used the PSI to measure the relative performance of the companies that are members of those associations. The definition developed in the mid-1990s included any unintended releases of hazardous chemicals that exceeded the threshold quantity given in 40 CFR 302.4, a listing of designated CERCLA[1] hazardous substances, or events that resulted in serious injury or damages in excess of $25,000.

Although the PSI was used, as defined, for more than 15 years by many U.S. chemical and petroleum companies as a performance metric, it never achieved sufficient acceptance and utilization as a benchmark owing to the lack of broad consensus that it was a good indicator of performance. This was in part because the table of threshold quantities given in 40 CFR 302.4 was not itself viewed as a good indicator of equivalent risks of the chemicals listed nor did it include all chemicals. International acceptance was also hampered by the metric's association with a U.S. regulation.

PROCESS SAFETY METRICS FROM INDUSTRY AND ORGANIZATIONS

American Institute of Chemical Engineers' Center for Chemical Process Safety Metrics

In 2006, the Center for Chemical Process Safety (CCPS) launched a project to develop better leading and lagging process safety metrics.[2] The aim of the CCPS Metrics Project was to establish definitions of lagging metrics that would be broadly accepted internationally and be useful for benchmarking relative performance and parallel the Occupational Safety and Health

[1]CERCLA is the Comprehensive Environmental Response, Compensation, and Liability Act, commonly known as the Superfund. This document lists dangerous chemicals and gives threshold quantities for the purpose of defining a process safety incident.

[2]"Leading metric" and "lagging metric" are defined in Appendix A.

Administration's (OSHA's) injury/illness metric, which has been utilized broadly to benchmark worker safety performance. Another aim of the project was to identify leading metrics that would monitor management systems or other early indicators of necessary actions that had to be taken to avoid process safety incidents, especially catastrophic incidents such as those at Union Carbide in Bhopal, India; BP in Texas City, Texas; and Phillips in Pasadena, California.

Industry interest and participation in the CCPS Metrics Project grew with the release of *The Report of the BP U.S. Refineries Independent Safety Review Panel* (also known as the Baker panel) and the U.S. Chemical Safety Board's (CSB's) *Investigation Report: Refinery Explosion and Fire,* Report No. 2005-04-I-TX, following the incident at the BP Texas City refinery in 2005. Both reports called upon industry to develop and implement better leading and lagging metrics. The CCPS Metrics Project resulted in two publications, a process safety metric pamphlet in December 2007 that recommended specific metrics for industry benchmarking[3] and a book in 2009 titled *Guidelines for Process Safety Metrics*. The latter document recommended a process for companies to adhere to in selecting and implementing other metrics appropriate for their facilities.[4] The metrics in the CCPS publications were embraced by many U.S. and international trade associations and became the basis for metrics collected by those organizations. These publications also describe a hierarchy of metrics, both lagging and leading. Lagging metrics relate to events that actually occurred (e.g., unintended releases of chemicals). Leading metrics may include near-miss events that did not result in an unintended release, management system failures (e.g., missed or overdue inspections), activation of safety systems, or other events that might indicate areas requiring attention to reduce the likelihood of a significant event. The hierarchy is illustrated as a pyramid in Figure 4-1. There are typically more minor events than major events, more near misses than actual releases, and more management system defects or other early indicators than near misses.

The CCPS *Guidelines for Process Safety Metrics* expanded the discussion of metrics by describing the processes that a company or organization should use to select metrics that are specific or applicable to that organization. It also included an appendix document containing several hundred potential metric options that an organization should consider, depending upon the areas of performance that are most important or in need of strengthening for that organization.

The relationship of the hierarchy of incident categories to the James Reason barrier model is shown in Figure 4-1. The latter model illustrates independent layers of protection, which can alternatively be illustrated by the "Swiss cheese" model that is shown in Figure 4-2. As explained in the two previously noted CCPS documents, there are typically multiple independent layers, or barriers, that prevent an incident from occurring or that limit the severity of an incident. When all process safety barriers are in place, a single barrier can typically fail without significant consequences. However, when multiple barriers fail, the probability that an incident can occur is increased. Individual barrier failures may often occur without being noticed until a second or third barrier has failed. For this reason, metrics are needed to ensure the integrity of all barriers.

American Petroleum Institute Metrics

Following the completion of the CCPS Metrics Project, the CSB still desired that an American National Standards Institute (ANSI) standard be developed to codify the recommendations on process safety metrics. It hoped in this way to ensure that all relevant companies and stakeholders would support a common set of metrics. CSB requested that API work with the United Steelworkers' Union to sponsor an ANSI standard project. A committee was organized, and an ANSI standard, *Process Safety Performance Indicators for the Refining and Petrochemical Industries* (ANSI/API RP 754), was created. The vast majority of definitions and concepts developed by the CCPS Metrics Project were retained in the ANSI/API RP 754 document.[5] Since this document was developed shortly after issuance of the original CCPS metric definitions, the API committee used the opportunity to make minor modifications to metric definitions based upon lessons learned from early implementation by users of the original CCPS metrics. See Box 4-1 for definitions of Tier 1-4 process safety events from API RP 754.

[3] Available at http://www.aiche.org/uploadedFiles/CCPS/Metrics/CCPS_metrics%205.16.08.pdf.

[4] Available at http://www.wiley.com/WileyCDA/WileyTitle/productCd-0470572124.html.

[5] See http://www.api.org/Standards/new/api-rp-754.cfm.

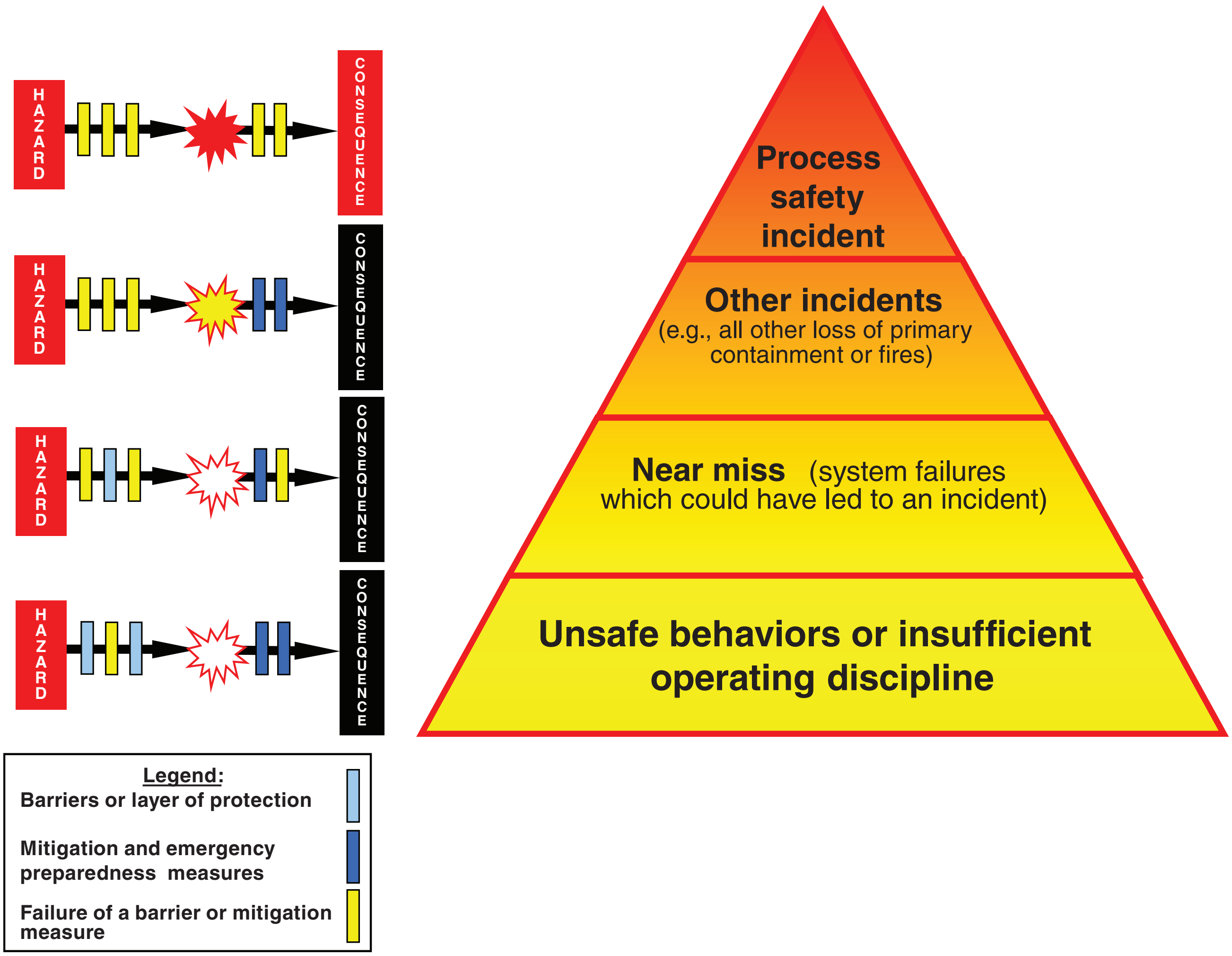

FIGURE 4-1 Hierarchy of leading and lagging metrics illustrated by the James Reason barrier model (left) and the Pyramid model of incident categories (right). SOURCE: CCPS, 2008. Used with permission.

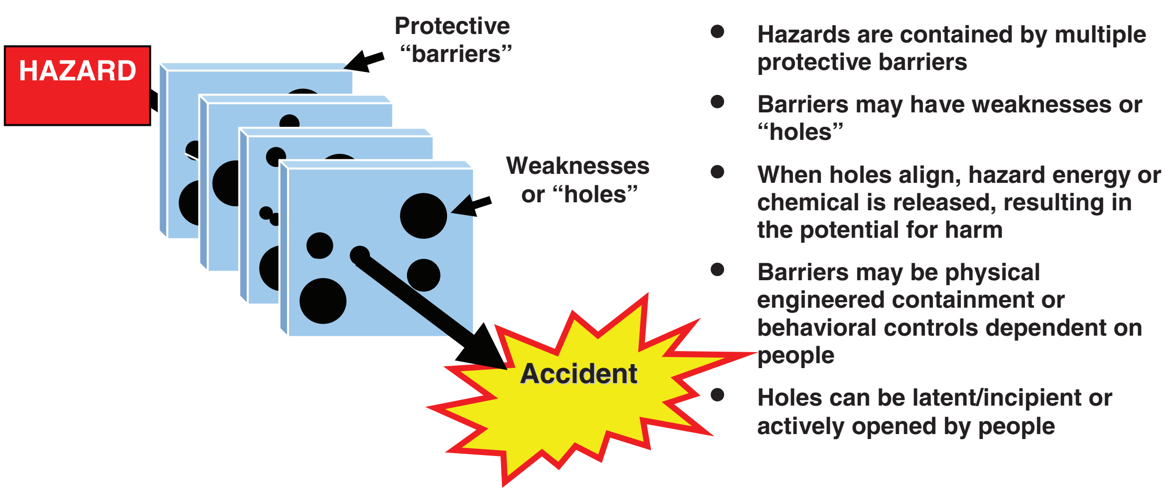

FIGURE 4-2 Illustration of the Swiss cheese model. SOURCE: CCPS, 2008. Used with permission.

BOX 4-1
Definitions of Tier 1-4 Process Safety Events from API Recommended Practice (RP) 754

A Tier 1 Process Safety Event (T-1 PSE) is a loss of primary containment (LOPC) with the greatest consequence as defined by this RP.

A Tier 2 Process Safety Event (T-2 PSE) is an LOPC with lesser consequence. A T-2 PSE is an unplanned or uncontrolled release of any material, including non-toxic and non-flammable materials (e.g., steam, hot condensate, nitrogen, compressed CO_2 or compressed air), from a process that results in one or more of the consequences listed below and is not reported in Tier 1:

- An employee, contractor or subcontractor recordable injury;
- A fire or explosion resulting in greater than or equal to $2,500 of direct cost to the Company;
- A pressure relief device (PRD) discharge to atmosphere whether directly or via a downstream destructive device that results in one or more of the following four consequences:
  —Liquid carryover;
  —Discharge to a potentially unsafe location;
  —An on-site shelter-in-place;
  —Public protective measures (e.g. road closure);
  —And a PRD discharge quantity greater than the threshold quantity in Table 2 in any one-hour period; or
- A release of material greater than the threshold quantities described in Table 2 in any one-hour period.

A Tier 3 PSE typically represents a challenge to the barrier system that progressed along the path to harm, but is stopped short of a Tier 1 or Tier 2 LOPC consequence. Indicators at this level provide an additional opportunity to identify and correct weaknesses within the barrier system.

Tier 4 indicators typically represent performance of individual components of the barrier system and are comprised of operating discipline and management system performance. Indicators at this level provide an opportunity to identify and correct isolated system weaknesses. Tier 4 indicators are indicative of process safety system weaknesses that may contribute to future Tier 1 or Tier 2 PSEs. In that sense, Tier 4 indicators may identify opportunities for both learning and systems improvement. Tier 4 indicators are intended for internal Company use and for local (site) reporting.

SOURCE: API (2010).
Note: Table number refers to table in API RP 754, not this report.

United Kingdom Health and Safety Executive Metrics

In 2006, the United Kingdom Health and Safety Executive (HSE) published a methodology for establishing metrics, *Developing Process Safety Indicators: A Step-by-Step Guide for Chemical and Major Hazards Industries* (HSG 254), based on specific processes.[6] This document recommended that facilities examine their specific process details or their particular process unit and develop leading metrics that are specific to that process and that could be monitored to prevent and mitigate the occurrence of a major accident. For example, if the most significant hazard in a plant is the overflow or overpressurization of a specific vessel, the HSG 254 approach to metrics might call for specific lagging metrics that serve as a track record for keeping that vessel within safe operating limits, or leading metrics that serve as an track record for maintenance of the vessel's instrumentation that measures the content's level or pressure.

[6]HSE HSG 254 is available from HSE at http://books.hse.gov.uk/hse/public/home.jsf and is also included on a CD included with the CCPS book *Guidelines for Process Safety Metrics*.

APPLICABILITY OF PUBLISHED CHEMICAL AND PETROLEUM INDUSTRY METRICS TO PCAPP AND BGCAPP

Elements in each of the CCPS, API, and HSE metrics publications could be appropriate for the Assembled Chemical Weapons Alternatives (ACWA) program to consider using at PCAPP and BGCAPP. An example would be for the Program Manager for Assembled Chemical Weapons Alternatives (PMACWA) to define what is meant by a "process safety incident." This definition would be used in developing metrics to measure the frequency and severity of process safety incidents.

There are established chemical release thresholds and associated metrics for common industrial chemicals such as caustic and nitric acid that could be directly applied to process safety at ACWA sites.[7] However, the physical properties of chemical warfare agents may not align well with the release threshold quantities used in the API or CCPS definitions. Perceptions of the toxicity of chemical warfare agents require that the Army treat any unintended release of agent as a process safety incident.[8]

Finding 4-1. At the present time, there is no definition of a process safety incident other than "release of agent" within the Assembled Chemical Weapons Alternatives program. Establishing or adopting a common definition for process safety incidents would improve consistency of reporting and sharing of lessons learned within the program.

Recommendation 4-1. The Program Manager for Assembled Chemical Weapons Alternatives should adopt the definitions of Tier 1-4 process safety events in Recommended Practice 754, *Process Safety Performance Indicators for the Refining and Petrochemical Industries,* a joint recommendation of the American National Standards Institute and the American Petroleum Institute, with the exception that the reporting threshold for chemical agents should be defined as any unintended release.

PROCESS SAFETY METRICS DERIVED FROM PRIOR OPERATING EXPERIENCE AT CHEMICAL AGENT DISPOSAL FACILITIES

As was noted in Chapter 3, causal factors for process safety events at other chemical demilitarization facilities were not directly related to the specific process used for agent destruction, so it is reasonable to expect that the same types of causal factors will be associated with any events and incidents that may occur at ACWA demilitarization facilities. The causal factors identified in Chapter 3 provide an excellent basis for the ACWA sites to develop process safety metrics that relate directly to chemical weapons destruction experiences.

At 28.4 percent of the total, standard operating procedure (SOP) deficiencies was the most prevalent causal factor identified. For PCAPP and BGCAPP, metrics that enable early identification and avoidance of SOP deficiencies should be a priority. Among the parameters that could be considered are these:

- Documenting the percentage or number of process safety operations and maintenance procedures reviewed or revised as scheduled.
- Tracking revisions to SOPs and documenting the communication of those revisions and training on revised SOPs.
- Implementing and documenting job cycle checks[9] to ensure that training in roles and responsibilities is understood and implemented. Such reviews evaluate employees' understanding of SOPs and assess the adequacy of SOPs.

Human factors, which include "human error," "mindset," and "improper technique," altogether accounted for approximately 37 percent of the causal factors. Again, metrics derived from training activities and job cycle checks can be useful in developing actions to mitigate these causal factors and to identify areas where regular annual, or more frequent, training should be improved or changed. Other possible considerations are these:

[7]Such metrics can be found in API and CCPS publications and in DOT 49 CFR 173.2.

[8]There are intended releases of agent as part of the normal demilitarization process, such as when munitions are drained and washed out. Any release that is not part of a planned process is an "unintended release."

[9]Job cycle checks are a formal process whereby a supervisor or his designee assesses an employee's performance in the field in relation to the training he has received on the tasks he will perform during the course of his job. This assessment would include the pertinent operations and maintenance tasks. All written procedures that the employee is asked to follow would also be reviewed.

- Results of periodic employee attitude or perception surveys.
- Frequency with which upper managers visit the worksite, or percentage of scheduled visits that actually take place.
- Number of unresolved recommendations from risk analyses, incident investigations, audits, and safety suggestions.
- Percentage of near misses and incidents identified as being caused by unsafe acts or shortcuts.

Equipment malfunction was the second most prevalent causal factor (19 percent) noted at other chemical demilitarization facilities. While the definition of equipment malfunction did not include design deficiencies, it should be noted that design deficiencies caused some equipment malfunctions and that equipment malfunctions and design deficiencies were present in over 29 percent of the total number of incidents. At the two ACWA facilities, this factor could become even more pronounced because first-of-a-kind equipment that has never been used before will be installed. Conducting design audits and basing metrics on the results could assist in finding design deficiencies before they cause an equipment malfunction or other process incidents or upsets. A system of process-safety-critical equipment inspections is key to minimizing equipment malfunctions. Metrics-based parameters such as the following could be considered:

- Safety-critical equipment inspections could be assessed, for example, by the percentage of these inspections completed on time. This metric relies on the prior identification of equipment deemed to be critical to safety. Such equipment might include pressure vessels, storage tanks, piping systems, pressure relief devices, pumps, instruments, control systems, interlocks and emergency shutdown systems, mitigation systems, and emergency response equipment.
- Scheduled and preventive maintenance activities.
- Equipment repair logs.

Communications deficiencies are not typically documented until after a failure but should be considered as integral to the full complement of process safety metrics. Audits of communications systems (active and passive) and documentation of communications failures might be one metric for communication failures.

Finding 4-2. Developing metrics for the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant based on operating experience at other chemical agent disposal facilities would help to avoid failures that lead to process safety incidents.

Recommendation 4-2. The Program Manager for Assembled Chemical Weapons Alternatives should take into account the causal factors in past process safety incidents at chemical agent disposal facilities when devising process safety metrics for the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant.

OTHER PROCESS SAFETY METRICS THAT MAY BE RELEVANT TO PCAPP AND BGCAPP

Other leading metrics recommended in the CCPS and API documents could also be relevant to PCAPP and BGCAPP. The committee believes that the following metrics could be utilized at ACWA sites.

Process Safety Near-Miss Events

Near-miss events are undesired events that, under slightly different circumstances, could have resulted in harm to people or damage to property, equipment, or the environment. This metric includes the following:

- *Critical operating limit excursions.* This is a process parameter deviation that exceeds the operating limits for critical steps in the process. The operating limits may be different for the same equipment depending on the operating phase. For example, the required temperatures might depend on the pressure. Troubleshooting efforts should end when the established operating limits are exceeded at critical points in the process, and predetermined action should be taken to return the process to a known safe state.
- *Demands on safety systems.* This is a demand on a safety system that is designed to prevent a loss of primary containment (LOPC) or to mitigate the consequences of an LOPC. The safety system being activated may be known as a "safety instrumented system" following the terminology in the International Electrotechnical Commission standard *Functional Safety—Safety Instrumented Systems for the Process Industry Sector* (IEC-61511).

- *Other unanticipated LOPC events.* Recognizing that leaking chemical munitions are a known concern, the sites may wish to have separate metrics for leaks or LOPCs that were known to exist before munition processing begins and those that occur during the processing. This would serve to identify aspects of the overall disposal operation that are increasing risk (CCPS, 2008).

Action Item Closure

This metric looks at the percentage and/or number of process-safety-related actions that remain unresolved past the date by which they were to have been resolved. These might include outstanding action items from hazard evaluations, compliance audits, overdue training, or prior incident investigations or drills (API, 2010).

Completion of Emergency Response Drills

This metric pertains to the number of completed emergency response drills that use a realistic failure scenario, completed written records, and completed identification and closure of identified deficiencies (API, 2010).

Management of Change

In the area of process safety management, management of change (MOC) refers to a specific system that, prior to the implementation of a change, identifies, reviews, and approves any change to (1) equipment, (2) personnel assigned to the area, (3) raw materials, or (4) the process technology or operating conditions. Another aspect of MOC that must be recognized is that some changes are subtle. A subtle change might be one involving the supplier of a raw material or a chemical or the rerouting of a pipeline to a different elevation. As an example of the former, a new material might meet basic technical specifications but contain a contaminant that has not been reported to the purchaser but might cause a reaction in the process, with undesirable results. These "subtle" changes are often labeled as "not replacement in kind."

Each change should be reviewed and assessed for its impact on operations and on safety, health, and the environment. The review should be documented and approved by management and should include any actions needed to move forward, specify responsible parties, and set closing dates for action items. MOC actions would be sampled quarterly or biannually, and the percent of sampled MOC actions that met all requirements and quality standards would be determined (CCPS, 2008; API, 2010).

Understanding and using MOC leading indicators requires that the staff operating a facility understand its current operations: the technology, the operational knowledge possessed by personnel, and the physical specifications of equipment. Implementing a system to manage change must be preceded by a program to train a facility's staff in MOC. There must also be a strong process safety culture for MOC to be effective. Particularly in the area of subtle change, the people best positioned to recognize the impacts of any proposed changes are those directly involved in operating a facility.

Metrics Related to Other Management Systems

CCPS's book *Risk-Based Process Safety* contains a number of process safety best practices. It also lists potential metrics for the implementation status of those practices. PCAPP and BGCAPP managers could work to identify common process safety management system elements that may not be well implemented yet are important to the safe and reliable operation of the facilities. In light of what they learn, they could review the extensive listing of CCPS metrics to find metrics that could be used at their facilities.[10] While PCAPP and BGCAPP might not adopt many of these metrics, a number of them could be beneficial to their process safety efforts.

Finding 4-3. Many process safety metrics that could be used by the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant are available to the public, including those in the list of metrics in the Center for Chemical Process Safety publication *Guidelines for Process Safety Metrics*. These metrics could complement process-specific metrics developed at the respective sites.

Recommendation 4-3. The Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant should adopt the metrics listed below and develop process-specific leading and lagging metrics. The ACWA program should also

[10] The CCPS metrics are listed in Appendix I of *Guidelines for Process Safety Metrics* (CCPS, 2009).

consider a metric associated with emergency planning and response as well as published lists of process safety metrics and should adopt those that appear to be of value to these sites.

- Count of process safety near-miss events.
- Training records such as validation of job cycle checks and completion of training, including refresher training.
- Job procedures:
  —Statistics on whether a procedure was used and, if it was, was the procedure the correct one?
  —Validation that procedures are current and accurate.
- Statistics on the closure of action items.
- Percent of inspections of safety-critical equipment completed on time.
- Percent of sampled management of change instances that met all requirements and quality standards.

EXAMPLES OF ACWA PROCESS-SPECIFIC METRICS

The United Kingdom HSE's publication HSG 254, *Developing Process Safety Indicators: A Step-by-Step Guide for Chemical and Major Hazard Industries*, could be readily applied to PCAPP and BGCAPP processes and operations. For example, one hazard at PCAPP would be the premature release of contents from the agent neutralization system before complete neutralization (see Figure 4-3). This could be caused by the incorrect sequencing of the neutralization steps

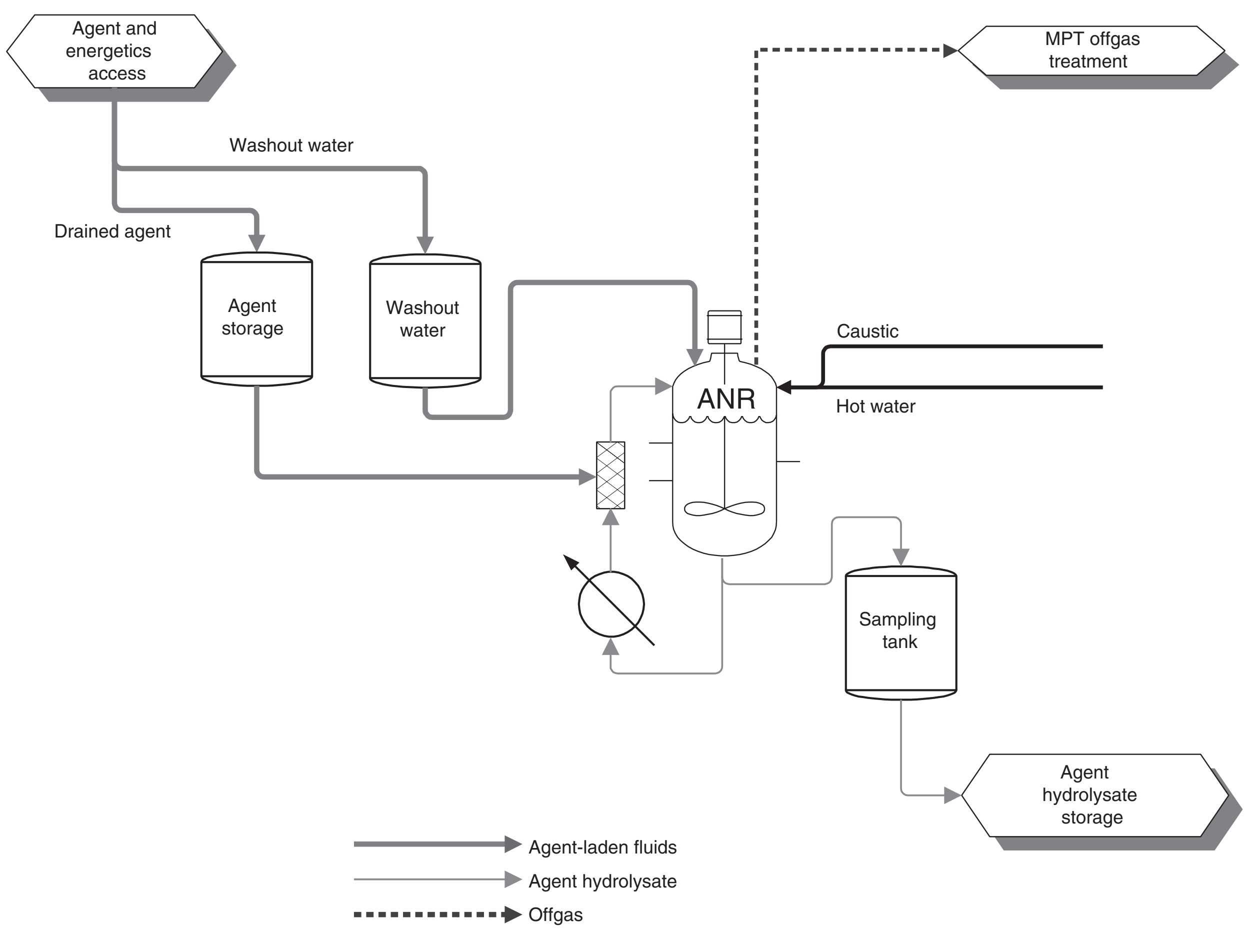

FIGURE 4-3 Process flow diagram for agent neutralization. SOURCE: Chris Haynes, Blue Grass Design Build Manager, Bechtel Parsons, "BGCAPP MDB intermediate design," presentation to the BGCAPP intermediate design review executive overview, February 15, 2005.

or inaccurate readings from instruments, among other things.

Process-specific leading metrics for this portion of the process could therefore include the following:

- Calibration records for analysis equipment associated with the agent neutralization system, including any performance deviations or drift in calibration;
- Maintenance records associated with the agent neutralization reactor agitator, including any changes in vibration or current; and
- Training validation and job cycle checks (see above) for all operators involved in the operation of the agent neutralization system.

Lagging metrics for this portion of the process could include records of any near-miss events or process safety incident associated with the agent neutralization system before complete neutralization—for example, the premature opening of valves, faulty instruments, or the failure of caustic valves to open.

Another example of a possible equipment-specific process safety event is failure of one of the energetics batch hydrolyzers (EBHs) that are to be used at BGCAPP (see Figure 4-4). The committee has identified the sudden failure of the drive train, bearings, or any other aspect of the rotating drum either when filled with energetics that have not been neutralized, or after neutralization when there are still metal parts that need to be removed, as a process safety risk associated with

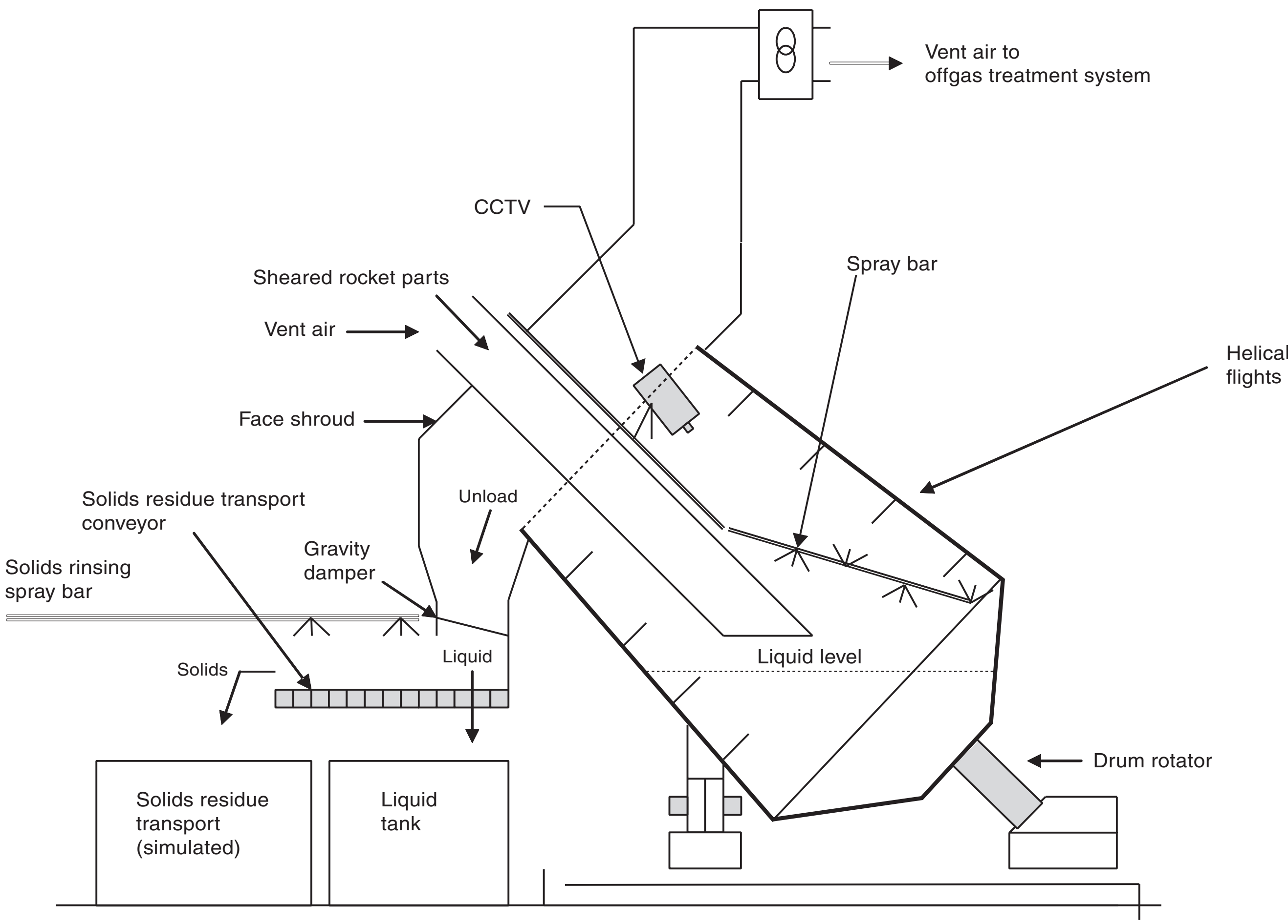

FIGURE 4-4 Diagram of EBH. SOURCE: John Ursillo, Bechtel, "Process design overview (Blue Grass)," presentation to the Committee to Assess Designs for the Pueblo and Blue Grass Chemical Agent Destruction Pilot Plants, September 22, 2004.

this piece of equipment. Specific leading metrics for this portion of the process could include the following:

- Maintenance records associated with the rotating drum, including any changes in vibration readings for the main bearing or in vibration or current readings for the drive train motor(s);
- Training validation and job cycle checks (see above) for all technicians involved in the maintenance of this equipment; and
- Having an SOP for emptying the EBH if the unit does not function or turn or tip to be emptied.

Lagging metrics for this portion of the process could include records for any near-miss events or process safety incident associated with the EBH—for instance, bearing failures, motor failures, or drum leaks.

These two examples illustrate the concept of developing process-specific leading and lagging process safety metrics. PCAPP and BGCAPP could utilize a similar approach to develop such metrics for other equipment that poses the greatest potential for process safety events.

Finding 4-4. The United Kingdom Health and Safety Executive's Health and Safety Guidance 254 (UK HSE HSG 254) provides a methodology to develop process-specific leading and lagging metrics.

Recommendation 4-4. Given that the two facilities are pilot facilities and make extensive use of first-of-a-kind equipment, the Pueblo Chemical Agent Destruction Pilot Plant and the Blue Grass Chemical Agent Destruction Pilot Plant should review their hazard assessment documents to identify and consider implementing leading or lagging metrics specific to each piece of equipment or area of the plant. These efforts should follow the approach outlined in the United Kingdom's Health and Safety Executive Health and Safety Guidance 254 (UK HSE HSG 254), *Developing Process Safety Indicators: A Step-by-Step Guide for Chemical and Major Hazard Industries*.

MANAGEMENT OF BEST PRACTICES OF PROCESS SAFETY METRICS IN INDUSTRY

Managerial leadership encompasses responsibility for setting the tone and performance expectations in an organization. When process safety metrics are set for an organization, the operation's line leadership must set performance milestones and must review the operation's performance against those milestones with the organization's top managers at least quarterly. If performance does not meet expectations or the goals that have been set, the organization must develop an action plan to rectify the situation so that goals can be achieved. Such performance reviews may suggest that additional or different metrics are needed to help the organization strive for and achieve continuous improvement and operational excellence. Reviews of operations should be conducted not only at the site leadership level but also above the plant level, including reviews by ACWA off-site leadership.

Finding 4-5. A formalized mechanism for a periodic review of process safety metrics by management is an established best practice in industry to verify that management is involved and can drive continuous improvement.

Recommendation 4-5. The Program Manager for Assembled Chemical Weapons Alternatives and site management should perform periodic reviews of process safety metrics utilized at PCAPP and BGCAPP and implement action plans as appropriate to drive continuous improvements.

PROCESS SAFETY COMPETENCY

The chemical, petroleum, and related industries have learned that maintaining a staff of trained process safety professionals is vital to the avoidance of process incidents. The focus on this area started in the mid-1950s, when the chemical industry experienced a number of process safety incidents. Following the serious incidents at Bhopal and elsewhere, the chemical industry invested heavily in developing process safety expertise in its companies. Following the BP Texas City incident in 2005, a second wave of hiring safety experts and building safety competency occurred in many petroleum and chemical companies.

Such process safety professionals, partnering with senior management, can educate staff and track the performance of key process safety programs such as management of change, the generation and use of good SOPs, incident investigations and corrective actions, reporting of near misses and incidents, and process safety training programs for operators. They review all these findings with management and propose and develop programs as required to address issues. Partnership with and support from higher levels of management is essential for the success of these professionals. Examples of metrics for process safety competency are available from CCPS and can be tracked. In addition to tracking the proportion of positions key to process safety that are currently staffed, other metrics, such as completed process safety training and the enhancement of process safety competence for relevant personnel, such as managers, supervisors, and technical staff, can be utilized as well.

Although the practice of having safety professionals is not as widespread outside the chemical and petroleum industries, several other industries (nuclear power is one) and government facilities engaged in hazardous processes have also been hiring full-time staff members to develop and monitor their process safety programs. These individuals often participate in industry conferences in order to learn about the best practices being implemented by other companies, with the aim of sharing them with their own facilities and possibly implementing them there.

Process safety technology conferences such as the American Institute of Chemical Engineers' annual Global Congress of Process Safety and other meetings hosted by organizations such as the CCPS and the Mary Kay O'Connor Process Safety Center provide ongoing programming on process safety and the identification of best practices. The CCPS, the API, and the U.K. HSE documents discussed above would also provide a starting point for learning about industry best practices for process safety.

Finding 4-6. The chemical and petroleum industries have found it very beneficial to have employees on staff with process safety expertise. These individuals partner with senior management and are accountable for monitoring industry best practices in process safety and for implementing those that are applicable within their facilities. These individuals are also tasked with assisting in embedding process safety into the organization's culture by organizing and leading grassroots process safety teams while reviewing outcomes and metrics with management.

Recommendation 4-6. The Program Manager for Assembled Chemical Weapons Alternatives should maintain process safety expertise at the programmatic level to ensure effective implementation of process safety metrics. To be successful, process safety experts must partner with and be supported by management.

Finding 4-7. There are a number of resources that the Program Manager for Assembled Chemical Weapons Alternatives can use to learn about best practices for process safety management in the chemical and petroleum industries. Process safety technology conferences such as the American Institute of Chemical Engineers' annual Global Congress of Process Safety and others hosted by organizations such as the Center for Chemical Process Safety and the Mary Kay O'Connor Process Safety Center provide ongoing programming on process safety and the identification of best practices.

Recommendation 4-7. The Program Manager for Assembled Chemical Weapons Alternatives should undertake a review of best practices in process safety management, especially in the chemical and petroleum industries. These practices are described in the Center for Chemical Process Safety book *Guidelines for Risk Based Process Safety.* Those that are applicable should be incorporated into the Pueblo and Blue Grass Chemical Agent Destruction Pilot Plants.

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Appendixes

Appendix A

Glossary

This short glossary presents some terms the committee believes should be clearly defined for the reader. They are drawn from a National Research Council report, *Safety and Environmental Metrics for Potential Application at Chemical Agent Disposal Facilities*, and a document published by the American Institute of Chemical Engineers' Center for Chemical Process Safety, *Guidelines for Process Safety Metrics*.

Injury Physical trauma to a body part that requires treatment in some form (NRC, 2009).

Lagging indicator/metric A retrospective set of metrics that are based on incidents that meet an established threshold of severity (CCPS, 2009).

Leading indicator/metric A forward-looking set of metrics that indicates the performance of the key work processes, operating discipline, or layers of protection that prevent incidents. It may include measures of safe practices such as training and completion of safety meetings, as well as distractions in the workplace (CCPS, 2009).

Metric A standard of measurement or indicator of process safety management efficiency or performance (CCPS, 2009).

Near miss An undesired event that, under slightly different circumstances, could have resulted in harm to people or damage to property, equipment, or the environment (NRC, 2009).

Process safety incident An unusual or unexpected event that either resulted in, or had the potential to result in, serious injury to personnel, significant damage to property, adverse environmental impact, or a major interruption of process operations (CCPS, 2009).

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NRC (National Research Council). 2009. Safety and Environmental Metrics for Potential Application at Chemical Agent Disposal Facilities. Washington, D.C.: The National Academies Press.

Appendix B

Committee Meetings and Activities

FIRST COMMITTEE MEETING
JUNE 14-16, 2010
WASHINGTON, D.C.

Objective: To introduce required administrative procedures set forth by the National Research Council, conduct the composition and balance discussion, discuss the committee statement of task and background review with committee sponsor, receive chemical demilitarization and process and equipment briefing presentations, review the preliminary report outline and report-writing process, flesh out the report outline into a concept draft, confirm committee writing assignments, and discuss next steps and future meeting dates. The briefings covered the following topics:

Overview of ACWA and Chemical Demilitarization, Joe Novad, Deputy Operations and Engineering Manager, Program Manager for Assembled Chemical Weapons Alternatives.

BGCAPP Process Overview, Joe Novad, Deputy Operations and Engineering Manager, Program Manager for Assembled Chemical Weapons Alternatives.

PCAPP Process Overview, Joe Novad, Deputy Operations and Engineering Manager, Program Manager for Assembled Chemical Weapons Alternatives.

LPMD at Anniston, Joe Novad, Deputy Operations and Engineering Manager, Program Manager for Assembled Chemical Weapons Alternatives.

Explosive Destruction Technologies, Joe Novad, Deputy Operations and Engineering Manager, Program Manager for Assembled Chemical Weapons Alternatives.

WHOLE COMMITTEE TELECONFERENCE
JULY 9, 2010

Objective: To discuss data gathering and report development.

VIRTUAL MEETING
JULY 23, 2010

Objective: To conduct committee discussions, discuss report development, and discuss the upcoming meeting in Pueblo, Colorado, and Richmond, Kentucky.

SITE VISIT
JULY 29, 2010
ABERDEEN PROVING GROUND, MARYLAND

Objective: To conduct data gathering on Chemical Materials Agency process safety incidents to identify what lessons could be learned that would benefit the Program Manager for Assembled Chemical Weapons Alternatives.

SECOND COMMITTEE MEETING AUGUST 3-5, 2010 PUEBLO, COLORADO, AND RICHMOND, KENTUCKY

Objective: To conduct fact-finding at the contractors' offices for the Pueblo Chemical Agent Destruction Pilot Plant (PCAPP) and the Blue Grass Chemical Agent Destruction Pilot Plant (BGCAPP).

August 3, 2010, Pueblo, Colorado

Safety Share, Terry Wells, Safety Manager, Bechtel Pueblo Team.

Plant Overview Video, Scott Susman, Site Project Manager, Program Manager for Assembled Chemical Weapons Alternatives.

Management Overview, Kevin Chalmers, Deputy Project Manager, Bechtel Pueblo Team.

Engineering Overview, George Fry, Bechtel Pueblo Team.

Operations Overview, Jerry Tiller, Plant Manager, Bechtel Pueblo Team.

Process Safety Management, Rob Jensen, Bechtel Pueblo Team.

August 5, 2010, Richmond, Kentucky

Project Management, Jeff Brubaker, Site Project Manager, Program Manager for Assembled Chemical Weapons Alternatives, and Mark Seely, Project Manager, Bechtel.

Process Overview, Ron Hawley, Plant General Manager, URS.

Safety Overview, Jeffrey Weldon, Safety, Health, and Emergency Response Manager, Bechtel.

First-of-a-Kind (FOAK) Equipment, Mark Johnson, Assistant Project Manager, Bechtel.

Design Process, Neil Frenzl, Resident Engineering Manager, Bechtel.

Operations Management, Ron Hawley, Plant General Manager, URS.

Lessons Learned, Ron Hawley, Plant General Manager, URS.

System Safety, Jeffrey Weldon, Safety, Health, and Emergency Response Manager, Bechtel.

Training Overview, John Gaffney, Training Manager, General Physics.

VIRTUAL MEETING AUGUST 17, 2010

Objective: To discuss data gathering and report development.

VIRTUAL MEETING AUGUST 20, 2010

Objective: To discuss report development.

THIRD COMMITTEE MEETING SEPTEMBER 1-3, 2010 WASHINGTON, D.C.

Objective: To discuss the adequacy of data gathering to date and identify any gaps and how to address those gaps, conduct writing sessions and achieve a first full-message draft, and make work assignments.

VIRTUAL MEETING SEPTEMBER 15, 2010

Objective: To discuss report development.

FOURTH COMMITTEE MEETING OCTOBER 13-15, 2010 WASHINGTON, D.C.

Objective: To discuss the report draft, conduct writing sessions, and achieve a concurrence draft.

VIRTUAL MEETING OCTOBER 20, 2010

Objective: To discuss the report draft and development and achieve a concurrence draft.

Appendix C

Biographical Sketches of Committee Members

Otis A. Shelton, *Chair*, is director for Safety and Environmental Services Compliance and Operational Assessments Program for Praxair, Inc., a position he has held since 1992. In this position, Mr. Shelton is responsible for managing Praxair's assessment program that focuses on environmental, process safety, personnel safety, industrial hygiene, emergency planning, distribution, and medical gases programs. Previously, Mr. Shelton worked for Union Carbide Corporation (UCC) for 25 years in a variety of assignments, including production, distribution, financial analysis, and safety. Starting in 1986, he managed UCC's Regional Corporate Health, Safety, and Environmental Protection Audit Program. This program reviewed UCC's health, safety, and environmental compliance in all UCC's operations, worldwide. He holds an M.S. in chemical engineering from the University of Houston. He is a fellow of the American Institute of Chemical Engineers (AICHE) and has served on its board of directors. He has also served on the National Society of Black Engineers' National Advisory Board for 20 years. He was elected as secretary of the American Institute of Chemical Engineers in 2004. Mr. Shelton was a member of the NRC Committee on Chemical Demilitarization and has served as vice-chair on the NRC Committee to Review Secondary Waste Disposal and Regulatory Requirements for the Assembled Chemical Weapons Alternatives Program. He was also a member of the NRC Committee to Evaluate the Safety and Environmental Metrics for Potential Application at Chemical Agent Disposal Facilities.

Robert A. Beaudet is retired from the faculty of the University of Southern California, where he served continuously in the Department of Chemistry since 1962. He received his Ph.D. in physical chemistry from Harvard University in 1962. In 1961 and 1962, he was a U.S. Army officer and served at the Jet Propulsion Laboratory as a research scientist. He also has served on Department of Defense committees that have addressed both offensive and defensive considerations surrounding chemical warfare agents. He was chair of an Army Science Board committee that addressed chemical detection and trace gas analysis. He also was the chair of an Air Force technical conference on chemical warfare decontamination and protection. He has participated in numerous NRC studies relating to chemical demilitarization. Most of his career has been devoted to research in molecular structure and molecular spectroscopy. Previously, Dr. Beaudet served as a member of the Board on Army Science and Technology (BAST), as a member of the NRC Committee on Review of the Non-Stockpile Chemical Materiel Disposal Program, and as a BAST liaison to the NRC Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program (the Stockpile Committee). He was a member of the NRC Committee to Examine the Disposal of Activated Carbon from the Heating, Ventilation and Air Conditioning Systems at Chemical Agent Disposal Facilities; the NRC Committee to Review and Assess Developmental Issues Concerning the Metal Parts Treater Design for the Blue Grass Chemical Agent Destruction Pilot Plant; and the NRC Committee on the Review of the Design of the

Dynasafe Static Detonation Chamber (SDC) System for the Anniston Chemical Agent Disposal Facility (Anniston). He was also a member of the standing NRC Committee on Chemical Demilitarization.

Mauricio Futran, NAE, is currently an independent consultant. Previously, he was vice president for Process Research and Development at Bristol-Myers Squibb Company, where he was responsible for leading process development. He was responsible as well for small molecule and semibiologic API development from its interface with discovery to manufacturing validation. Prior to joining Bristol-Myers Squibb, Dr. Futran held positions with Merck Research Labs and Maquinaria Plastica, Morderna, in Mexico. He has published in journals such as the *Journal of Chemical Physics*, made invited presentations at national scientific meetings, and lectured at universities such as Harvard and North Carolina State. He holds two patents, "Crystallization method to improve crystal structure and size" and "Process for producing N-amino-1hydroxyalkylidene-1, 1-bisphosphonic acids." He is a member of the National Academy of Engineering, the American Institute of Chemical Engineers, and the American Chemical Society. Dr. Futran formerly served on the Board on Chemical Sciences and Technology. In addition, he serves as chair of the chemical engineering advisory board at Princeton. He received the B.S. and M.S. in chemical engineering from Rice University and a Ph.D. in chemical engineering from Princeton.

J. Robert Gibson retired as a director in DuPont's Crop Protection Products Division in Wilmington, Delaware, in 2001. During his 30-year career with DuPont, Dr. Gibson held positions in R&D, chemical plant management, and corporate administration, as corporate director of safety and health. He was also assistant director of DuPont's Haskell Laboratory for Toxicology and Industrial Medicine. He was board-certified in toxicology by the American Board of Toxicology from 1980 until 2005 and is currently a consultant in toxicology and occupational safety and health. Dr. Gibson graduated from Mississippi State University with a Ph.D. in physiology. He holds a master's degree in zoology and a B.S. in general science from that same institution. He has chaired the standing NRC Committee on Chemical Demilitarization and served on its predecessor, the Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program (the Stockpile Committee), because of his more than 25 years of experience in toxicology and occupational safety and health. Dr. Gibson was appointed as the U.S. representative to the Scientific Advisory Board of the Organisation for the Prohibition of Chemical Weapons in October 2003. He has served on a variety of chemical demilitarization ad hoc committees, including as chair of the NRC Committee to Review and Assess Industrial Hygiene Standards and Practices at Tooele Chemical Agent Disposal Facility (TOCDF).

Randal J. Keller is currently a professor in the Department of Occupational Safety and Health at Murray State University. He received a B.A. in chemistry from Eisenhower College in 1979; an M.S. in toxicology from Utah State University in 1984, and a Ph.D., also in toxicology, from Utah State University in 1988. He is certified in the comprehensive practice of industrial hygiene by the American Board of Industrial Hygiene, the comprehensive practice of safety by the Board of Certified Safety Professionals, and in the general practice of toxicology by the American Board of Toxicology. Dr. Keller is widely published and maintains an independent consulting practice related to toxicology, industrial hygiene, and safety. He served on the NRC's Committee to Review and Assess Industrial Hygiene Standards and Practices at Tooele Chemical Agent Disposal Facility (TOCDF) and on its Committee on Evaluation of Safety and Environmental Metrics for Potential Application at Chemical Agent Disposal Facilities.

Tim Overton is president of TOPS Consulting. Before this, he was the group head for process safety at BP. His expertise is in development and implementation of process safety standards and management systems and of corporate process safety metrics and incident reduction and risk reduction programs. Prior to joining BP, Mr. Overton was chief process safety engineer at the Dow Chemical Company, where he had oversight of process safety practices and standards. He holds a B.S. in chemical engineering from the University of Texas. Mr. Overton serves as chair of the Center for Chemical Process Safety's Committee on Process Safety Metrics. He is also a member of the standing NRC Committee on Chemical Demilitarization.

Carol A. Palmiotto is the global safety health and environmental manager for the agriculture, nutrition, and applied biosciences businesses at E.I. du Pont de

Nemours. During her 30 years there she has worked for a variety of businesses and at several manufacturing sites, including the Department of Energy's Savannah River Plant in Aiken, South Carolina. In the 10 years Ms. Palmiotto spent at the Savannah River plant she was responsible for safety, health, and environment at the Savannah River laboratories, P-reactor area and F area separation facilities, which included the naval fuels operations. She has served as a panel member on the National Safety Council's Off the Job and Community Safety programs. From 1997 through 2005 she served on the International Institute of Synthetic Rubber Producers Environmental Health Committee. Currently she is a member of the European Crop Protection Association Manufacturing and Supply Chain EHS committee. Ms. Palmiotto graduated magna cum laude with a B.S. degree in biology from Tufts University. In 1978 she received an M.S. in environmental health/engineering and air pollution, with recognition in radiation control and industrial hygiene, from the Harvard University Graduate School of Public Health. She is a certified industrial hygienist.

Styron N. Powers is currently vice president, environmental, health, safety and security, at U.S. Foodservice. Before that, he was the director for health, safety, security and the environment (HSSE) at BP Refining and Marketing, Global Fuels Value Chain. Prior to that, Mr. Powers held senior HSSE positions for Invensys, RR Donnelly, and Lockheed Martin. He is a member of the board of directors of the Virginia Tech Department of Industrial and Systems Engineering. Mr. Powers was educated at Harvard's Advanced Management Program (2002); he holds an M.B.A. from Rutgers University and B.S. degrees in chemical engineering and biological life sciences from North Carolina State University. He is a certified safety engineer and certified hazardous materials manager.