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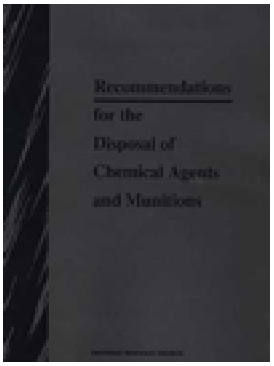

Recommendations for the Disposal of Chemical Agents and Munitions

Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Recommendations for the Disposal of Chemical Agents and Munitions

COMMITTEE ON REVIEW AND EVALUATION OF THE
ARMY CHEMICAL STOCKPILE DISPOSAL PROGRAM
BOARD ON ARMY SCIENCE AND TECHNOLOGY
COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS
NATIONAL RESEARCH COUNCIL

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

The United States has maintained a stockpile of highly toxic chemical agents and munitions for more than half a century. In 1985, Congress, in Public Law 99-145, directed the Department of Defense to destroy at least 90 percent of the unitary chemical agent and munitions stockpile, with particular attention to M55 rockets, which were deteriorating and becoming increasingly hazardous. The program has expanded to treat the entire unitary stockpile, and after setting several intermediate goals and dates, Congress, in the National Defense Authorization Act for Fiscal Year 1993, dated October 28, 1992, directed the Army to dispose of the entire unitary chemical warfare agent and munitions stockpile by December 31, 2004.

The Army had commissioned studies of different disposal technologies and tested several in the 1970s. In 1982, incineration was selected as the method to dispose of agents and associated propellants and explosives, and to thermally decontaminate metal parts. In 1984, the National Research Council (NRC) Committee on Demilitarizing Chemical Munitions and Agents reviewed a range of disposal technologies and endorsed the Army's selection of incineration.

Incineration technology is embodied in today's "baseline" disposal system, developed largely at the Chemical Agent Munitions Disposal System (CAMDS) experimental facility at Tooele Army Depot, Utah. The first full-scale operational plant is now in service at the Johnston Atoll Chemical Agent Disposal System (JACADS) on Johnston Atoll in the Pacific Ocean, southwest of Hawaii. The second operational plant has just been completed at Tooele and is undergoing "systemization" testing, which uses surrogates for agent to verify that all components of the system work as designed. Similar facilities are planned for the remaining seven continental agent and munitions storage sites.

The Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program (Stockpile Committee) was formed in 1987 at the request of the Undersecretary of the Army to monitor the disposal program and to review and comment on relevant technical issues. The Stockpile Committee is a standing committee, to remain in service with rotating personnel until completion of the disposal program. The Stockpile Committee has monitored the development and implementation of the baseline system; has visited CAMDS numerous times, JACADS three times, and the new facility at Tooele twice; and has issued numerous reports on various aspects of the disposal program.

There is public concern with the selection of incineration as the process for destruction of chemical agents. In March 1991, the Stockpile Committee suggested, and the Army agreed, that a new study of alternatives to incineration be undertaken. Accordingly, the Committee on Alternative Chemical Demilitarization Technologies (Alternatives Committee) was established in January 1992 to develop a comprehensive list of alternative technologies and to review their capabilities and potential as agent and munitions disposal technologies. That committee's report, *Alternative Technologies for the Destruction of Chemical Agents and Munitions* , was issued in June 1993. The Alternatives Committee report serves as a reference document but does not make recommendations. It was planned in 1991 that the Stockpile Committee, working with the report of the Alternatives Committee and with its own knowledge of the baseline system and disposal requirements, would formulate recommendations regarding the pursuit of potential alternatives to incineration. In the course of formulating its recommendations, the Stockpile Committee and the Alternatives Committee held a public forum in June 1993 to learn more about the public's concerns with the planned disposal operations.

The Defense Authorization Act of 1992 also directed the Army to submit to Congress, not later than December 31, 1993 (extended to 60 days following delivery of this report), a report on potential alternatives to the baseline system. That report is to contain an analysis of the Alternatives Committee report and "any recommendations that the National Academy of Sciences makes to the Army ...". This report provides those recommendations to the Army.

This report has been a true committee effort, with major contributions from practically each and every member to the discussions, deliberations, and writing. The committee is particularly pleased with the unstinting support from NRC staff members Margo Francesco, Robert Katt, Donald Siebenaler, and Tracy Wilson.

Carl R. Peterson, *Chairman*
Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program

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Abbreviations and Acronyms

ACAMS	Automated Continuous Agent Monitoring System
AChE	Acetylcholinesterase
APE	Ammunition Peculiar Equipment
ARPA	Advanced Research Projects Agency
ATSDR	Agency for Toxic Substances and Disease Registry
BRA	Brine Reduction Area
CAMDS	Chemical Agent Munitions Disposal System
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CSDP	Chemical Stockpile Disposal Program
DAAMS	Depot Area Air Monitoring System
DMMP	Dimethoxy Methyl Phosphate
DOD	Department of Defense
DPE	Demilitarization Protective Ensemble
DRE	Destruction Removal Efficiency
DUN	Dunnage Furnace
EEG	Electroencephalograph
EMPA	Ethylmethylphosphoric Acid
EPA	Environmental Protection Agency
ERDEC	Edgewood Research, Development and Engineering Center
GA	Tabun
GB	Sarin
GD	Soman

H, HD, HT	Blister or Mustard Agents
HEPA	High-Efficiency Particulate Air
IBP	Kitazin P
ID	Induced Draft
in.	Inch
JACADS	Johnston Atoll Chemical Agent Disposal System
JSLRMDP	Joint Services Large Rocket Motor Disposal Program
lb	Pound
LIC	Liquid Incinerator
m^3	Cubic Meter
mg	Milligram
min	Minute
mm	Millimeter
mM	Millimolar
µm	Micromole
MPF	Metal Parts Furnace
NDPA	2-Nitrodiphenylamine
NOEL	No-Observed-Effect-Level
NO_x	Nitrogen Oxides
NPDES	National Pollution Discharge Elimination System
NRC	National Research Council
OPH	Organophosphorus Hydrolase
OTA	Office of Technology Assessment
OVT	Operational Verification Testing
PCB	Polychlorinated Biphenyl
PEIS	Programmatic Environmental Impact Statement
PIC	Product of Incomplete Combustion
POHC	Principal Organic Hazardous Constituent
ppm	Parts per Million
psi	Pounds per Square Inch
RCRA	Resource Conservation and Recovery Act
SAIC	Science Applications International Corporation
SCWO	Supercritical Water Oxidation

TDG	Thiodiglycol
TSCA	Toxic Substances Control Act
USATHAMA	U.S. Army Toxic and Hazardous Materials Agency
VOC	Volatile Organic Compound
VX	Organophosphate Nerve Agent
WAO	Wet Air Oxidation

Executive Summary

The U.S. unitary chemical agent and munitions stockpile that has been maintained for more than 50 years is now obsolete and scheduled for disposal. The Congress directed the Department of the Army to accomplish this task, resulting in the present Chemical Stockpile Disposal Program. Further, congressional direction, reflecting international efforts, now requires disposal by the year 2004.

Historically, chemical munitions have been disposed of by land burial, open burning, and ocean dumping. In 1969, the National Research Council (NRC) recommended that ocean dumping be discontinued. The Army undertook a study of disposal technologies in the 1970s, including assessment of incineration and chemical neutralization methods. In 1982, that study culminated in the selection of incineration technology, now incorporated in what is known as the "baseline" system. In 1984, another NRC committee reviewed the chemical stockpile program and possible disposal technologies, and endorsed incineration as the method of choice. Construction of the Johnston Atoll Chemical Agent Disposal System (JACADS), a full-scale prototype facility using the baseline system, began in 1985, with Operational Verification Testing (OVT) being conducted in 1990-1993. The present Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program (Stockpile Committee) has monitored these developments. During this period, several other nations have employed chemical neutralization and incineration with flue gas scrubbing, or various combinations thereof.

To address growing public concern over incineration, Congress, in 1992, directed the Army to evaluate alternative disposal approaches that might be "significantly safer" and more cost effective than the baseline and that could complete disposal operations in time to meet a 2004 treaty requirement. The Army was asked to report to Congress on potential alternative technologies by the end of 1993 (extended to 60 days following delivery of this report) and to include in that report, "any recommendations that the National Academy of Sciences makes...". This Stockpile Committee report provides that advice. The committee drew upon its own expertise and long experience with the disposal program and upon the report of the Committee on Alternative Chemical Demilitarization Technologies (Alternatives Committee) in the preparation of these recommendations. This report compares alternatives to the baseline system and makes recommendations for the best approach to stockpile disposal. The Office of Technology Assessment has investigated the subject, and the General Accounting Office is also assessing alternatives.

In deriving its recommendations, the Stockpile Committee has been concerned primarily with the technical aspects of safe disposal operations. However, the committee recognizes that other issues will influence the selection of disposal technologies, not least of which are the concerns of citizens who might be affected by these operations. There is concern for the environment as well as for both long- and short-term health risks related to release of agent and other pollutants, either accidental or from routine storage and disposal operations. There is also a desire for more effective participation in program planning and decision processes. To learn more of these concerns, the Stockpile Committee and the Alternatives Committee held a public forum in June 1993 to listen to the public and to discuss the committee's criteria for evaluating alternative technologies.

This report is arranged to progress from the general to the specific, from historic information to recommendations for future operations. The findings and recommendations of the report are included in this Executive Summary.

THE UNITARY CHEMICAL AGENT AND MUNITIONS STOCKPILE

There are two basic types of chemical agents in the unitary stockpile: nerve (GB, VX) and blister (mustard) agents. These are contained in a variety of bulk containers and munitions. Munitions such as M55 rockets and various projectiles have associated explosives and propellants (so-called energetics) that also must be disposed of. The stockpile is stored at eight continental U.S. sites and at Johnston Atoll in the Pacific Ocean, about 700 miles southwest of Hawaii. Each site differs in the amount and types of agents, energetic materials, and associated metal containers stored there.

The condition of the stockpile is a factor in the decision to eliminate these materials and in how disposal will be accomplished. Of particular concern are the declining levels of stabilizer in M55 rocket propellants that may eventually lead to autoignition of the propellant. This hazard was addressed in the 1984 NRC study, as well as in a number of studies by the Army and its contractors beginning in 1985. Of two recent studies, one estimates that critical propellant stabilizer levels may be reached in 2019, whereas a second estimates 2002. Examination of these reports indicates considerable uncertainty in all analyses. The Stockpile Committee believes that this potentially serious hazard should be reexamined promptly, since it may influence the disposal schedule.

Both degradation of the materials and external threats to the stockpile will continue until disposal is completed. Other forms of degradation of both munitions and agent during storage amplify the storage risks and make disposal more difficult and risky. Gelled mustard prevents drainage and impedes agent destruction by any technology.

FUNDAMENTALS OF DISPOSAL

Disposal of chemical agent and munitions means release of all unitary stockpile materials from Army control in an altered form that satisfies both international treaty requirements and domestic environmental requirements. Waste streams from disposal processes may be gaseous, liquid, or solid, and although the ultimate chemical products are usually similar, the selection of technologies and disposal strategies can alter the condition, timing, and perhaps location of the final products. A fully oxidized or "mineralized" end state is the most stable of discharge conditions, but other end states will meet both treaty and environmental requirements.

A number of federal and state environmental regulations govern continental U.S. disposal operations, including the Resource Conservation and Recovery Act; Toxic Substances Control Act; Clean Air Act; Clean Water Act; and the Hazardous Materials Transportation Act. Each of these requirements must be met by any disposal method selected.

The performance and safety of candidate disposal methods is greatly increased by separation of the stockpile feed material into distinct streams of agent, energetic materials, metal parts, and dunnage (packing and other miscellaneous material) prior to disposal or destruction. The stockpile disposal program, and any stockpile disposal technology selected, should handle each of these materials separately.

HEALTH, SAFETY, AND RISK CONSIDERATIONS

The health and safety of the public and the protection of the environment are leading citizens' concerns. *In view of the overriding public and committee concern for health and safety, the committee selected as its primary criterion, in formulating its recommendations, the minimization of the cumulative adverse consequences from all relevant risks over the full duration of the disposal program.* This total risk criterion extends to protection of the environment and relates to the risk from agent and other pollutants released as a consequence of either accidents or routine operations, including both acute and latent health effects.

Economic considerations may also be of concern, but they do not appear to be a major factor at this time. Economic data on the use of alternative technologies are virtually nonexistent, but the committee believes that equipment and operating cost variations among alternatives will be very small in comparison to overall program costs. Consequently, cost is not an effective discriminator among alternatives at this early stage. On the other hand, research and development costs for alternatives, and accompanying increases in storage costs and risks from program delays, suggest that minimum risk and minimum cost may both be associated with an expedited program based upon existing technology.

Total risk is a measure of the likelihood that people or the environment will experience adverse health effects from operations of both storage and disposal facilities. Because chemical munitions and agent inventories vary from site to site, as do storage conditions and surrounding community conditions, implementation of the minimum cumulative total risk strategy should be determined on a site-specific basis.

In addition to this primary total health and safety risk minimization criterion for technology selection, there are technical requirements that all technologies (or combinations of technologies) must meet. Disposal requires an extensive *system* rather than a single technology to dispose of the stockpile. Agent and munitions must be moved from the stockpile to the disposal facility and unpacked; containers must be opened and drained to gain access to the agent; the four (preferably separated) materials—agent, energetics, metal parts, and dunnage—must be destroyed or treated; and waste products must be treated for acceptable discharge. Most alternative technology discussions have addressed only agent destruction, but there are five important technology selection criteria that must be addressed for any potential alternative technology system:

1. Can the technology contribute to a program of disposal and associated storage that is safer than that of the baseline program?
2. Can the technology treat agent, energetics, metal parts, and dunnage?
3. Can the technology destroy all agents?
4. Do waste products meet environmental disposal requirements?
5. Can the technology achieve treaty requirements for irreversible agent destruction?

The primary criterion, safety, involves a number of issues including basic chemistry and the composition and quantity of waste streams, system complexity, and time to completion of the disposal program. Selection among the alternatives with regard to these safety issues requires careful risk analyses. A great deal of progress has been made in recent years in designing safety into industrial facilities by considering safety like any other performance factor. One way to do this is by conducting a risk assessment that calculates the frequency of events that lead to consequences of various severity. Two major risks are important in the Chemical Stockpile Disposal Program: acute, high-level agent exposures (which may or may not be fatal) from accidents in storage or processing; and chronic, long-term, low-level exposure to agent or disposal products from routine storage or disposal operations.

Most chemical disposal risk assessments to date have focused primarily on high-level exposures, but the public is increasingly concerned about the long-term effects of chronic, low-level exposure to agent or disposal products. Long-term effects are those that might occur during the lifetime of a person exposed to low-level emissions from continuing storage or to any emissions that might result from several years of disposal operations. Attempts to assess the latter effects suffer from a lack of preexposure population data, and the use of self-reported, nonrandom data. A recent U.S. Environmental Protection Agency study has shown that, in general, normal hazardous waste incinerator operations produce stack emissions comparable to "clean" boiler systems and common household emission sources, suggesting that they should have relatively little public health effect. Latent risks could include potential carcinogenic, mutagenic, and teratogenic risks associated with sublethal agent releases and releases of products from stockpile destruction. Off-normal operation is not monitored by the Environmental Protection Agency, but disposal facility operating permits will require cessation of agent feed if furnace conditions are outside normal operating limits. The issue of the health impact of incineration is a significant one, such that a separate National Research Council committee has been established to address the nature and probability of health effects associated with incineration.

The Army has performed a quantitative risk assessment for acute or high-level agent exposure from storage and processing accidents using the baseline system. The risks assessed include continued storage versus disposal, on-site versus regional versus national disposal sites, and the reliability of individual unit operations. Although the risks for the entire program were estimated to be very low (less than a mean of 0.02 fatality per year), it was concluded that acute risks from storage were greater than those from disposal using the baseline system (with the exception of Blue Grass Army Depot, in Kentucky, where the two are about equal). At the peak of the disposal effort, the risk of disposal will be approximately 0.0004 fatality per year, by which time the storage risk will have decreased to approximately 0.012 fatality per year as the material in storage is diminished. The committee has already recommended the development of updated, site-specific risk assessments to clarify these findings, but it believes that new studies will likely draw the same conclusion: that the storage risks significantly outweigh disposal risks.

Aside from these acute, high-level risks from accidents, either low-level agent releases from routine storage operations or low-level agent and other pollutant releases from routine disposal operations may also pose chronic health risks if not controlled. Records indicate that leaking munitions are discovered regularly (averaging more than 130 per year, largely from GB-filled M55 rockets).[1] In September 1993 at Tooele Army Depot, Utah, there was a mustard leak of approximately 100 gallons from a ton container. This had a maximum distance of adverse medical effects estimated at more than 900 meters. There were no apparent exposures or casualties.

The selection of an alternative technology would affect only a fraction of the releases from disposal operations (except, of course, that the risk of releases from storage would accumulate over time if an alternative technology delayed disposal). Chronic health risks from disposal operations are not well understood. However, they are believed to be low for all technologies under consideration, providing that the reaction products, which vary among the technologies, are disposed of in accordance with relevant regulations and standards.

In the baseline system risk analyses, the greatest disposal risk was found to stem from transportation of materials (and associated handling) from storage areas to the disposal facility located at the site. All alternative disposal technologies will share these same activities. They also will share many other common operations, such as gaining access to the agent stored in various munitions and containers, and the disposal of energetic materials. Thus, differences in the actual agent disposal process will likely produce the only difference in overall risk.

The long-term and short-term risks of the baseline system have been identified, whereas the risks of alternative technologies are largely unknown and the technical feasibility of most alternatives is unproven. However, the committee believes that all technically feasible technologies can be engineered to similar levels of safety, given sufficient time and money.

Minimization of cumulative total health and safety risk may affect the disposal schedule in ways that the committee considers more important than treaty or other political considerations. Because disposal risks are generally lower than storage risks, and because agent destruction (the objective of alternative technologies) is but a fraction of disposal risk, delaying the disposal program to await the development of a safer alternative agent destruction technology (or delaying for any reason) will result in a higher overall risk. Today's evidence suggests that any reduction in disposal risk

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[1] The leakage rate is not high—only 0.017 percent per year for M55 rockets loaded with GB.

afforded by an alternative technology will be more than offset by the larger cumulative risk from extended storage. It is probable that this conclusion will be verified by new, site-specific risk analyses designed to clearly define the lowest risk. Given this evidence, the disposal program should not be delayed pending development of detailed information on alternative technologies.

The committee recognizes that other issues affect the selection process including social, political, economic, and even emotional issues. It will be necessary, therefore, to ensure effective public involvement in the decision-making process. For example, the construction, use, and decommissioning of disposal facilities will influence local jobs, transportation, infrastructure, and property values. There is also public concern that the facility might continue to be used as a hazardous waste facility, resulting in a continuing hazard to the local community.

The committee has attempted to take these issues into account in the report that follows. All reasonable technologies have been reviewed, including an enhanced baseline system. Those technologies that are the most promising alternatives to components of the baseline system have been identified. Overall safety, as well as public participation, are emphasized as essential to the Army program.

THE PRESENT BASELINE SYSTEM

The baseline system is currently undergoing systemization at the first continental U.S. site, the Tooele Army Depot in Utah. This facility represents a baseline system improved as a result of the Operational Verification Testing program of the Johnston Atoll Chemical Agent Disposal System.

In the baseline system, agent is removed from munitions and containers by two methods. Most are simply punched and drained, whereas artillery projectiles are mechanically disassembled to be drained. These processes yield three material streams: agents, energetic materials, and metal pans. All streams may be contaminated by agent, though the vast majority of agent is in the agent stream. This material separation is a major safety feature of the baseline system, allowing the design and operation of disposal components properly matched to the widely differing materials.

Agents are pumped to, and destroyed in, a specially designed liquid incinerator. The liquid incinerator consists of primary and secondary combustion chambers and a pollution abatement system. Agent flow is stopped if the combustion chamber temperature drops below that required for agent destruction. Associated energetic materials are burned in a rotary kiln deactivation furnace system, with exhaust gases sent to an afterburner, followed by a pollution abatement system. Metal parts are decontaminated by heating them to 1000ºF for a minimum of 15 minutes in a metal parts furnace.

Residual agent is vaporized from the metal parts and burned within the furnace. Exhaust gases are sent to an afterburner followed by a pollution abatement system that removes gaseous pollutants and particulates. Acidic gases are scrubbed from the discharge stream with alkali solutions to form salts. The brine reduction area dries collected brines from the pollution abatement system, producing dry salts for later disposal in hazardous waste landfills.[2]

The dunnage furnace burns contaminated or noncontaminated packing materials and miscellaneous waste or "dunnage." Exhaust gases are discharged through a separate stack without scrubbing to remove acid gases.

Two auxiliary material streams, decontamination fluids used throughout the facility and ventilation air, are also processed.

Except for the destruction of agent by incineration, none of these disposal operations would be eliminated by the employment of an alternative technology for agent destruction.

The baseline monitoring system is used to detect agent releases and to check adherence to all environmental requirements. The system consists of a combination of the Automated Continuous Agent Monitoring System (ACAMS), which is used to provide rapid detection of immediate threats (3 to 8 minutes response time at 20 percent of permissible 8-hour exposure level for workers) and the Depot Area Air Monitoring System (DAAMS), which has a slower response time in order to achieve a much more selective laboratory analysis. ACAMS alarms require immediate agent feed shutoff. DAAMS analyses are used to confirm ACAMS alarms and to document environmental compliance.

Operational Verification Testing was undertaken to gain experience with and demonstrate the baseline system at JACADS. Four testing campaigns, with representative munitions and agents, were conducted. The committee reviewed the performance of the baseline system during the testing and concluded that the system is capable of safe disposal of the stockpile. It also identified areas for improvement that should be implemented at Tooele before agent operations commence there. These included the following: upgrade of the monitoring system, demonstration of the dunnage furnace and brine reduction area or suitable alternatives, development of an abatement system for nitrogen oxides for agent disposal at continental U.S. sites if required, development and demonstration of a slag removal system for the liquid incinerator, improved control of feed materials for the deactivation furnace system and metal parts furnace, and solution of the problems of gelled agents.

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[2] Neither the dunnage furnace nor the brine reduction process has been proven in operations at Johnston Island. These operations (or alternative systems) must be proven before agents can be processed at Tooele.

COMPARISON OF THE BASELINE SYSTEM AND ALTERNATIVE TECHNOLOGIES

The selection of the best stockpile disposal technology should minimize the risks of agent release during both storage and disposal operations, as well as the public health and environmental risks from other process effluents. Two major routes for doing so have been considered:

- use of the baseline system with the improvements suggested for demonstration at Tooele or use of an enhanced baseline system with added charcoal filters; and
- use of completely different technologies, called alternative technologies, for destruction of one or more of the four process streams involved.

Many of the candidate technologies are, or can be, developed for safe disposal of a variety of hazardous materials. However, it was necessary for the committee to use engineering judgment in developing its recommendations for promising alternatives for the very special requirements of this disposal program. In addition to the necessary fundamental process capabilities, and in keeping with the committee's desire to minimize cumulative total risk, technology readiness becomes an important selection criterion.

Candidate alternatives are examined at two levels: a first screening is used to eliminate unattractive candidates, whereas the more attractive alternatives are examined in greater detail. The five major criteria, presented earlier were used in the screening. No single technology, including incineration, can satisfy all five requirements with a single process, but there are reasonable combinations that are satisfactory.

The committee recommends further study of an enhanced baseline system and of four alternative technology combinations for agent destruction, all based upon neutralization (chemical hydrolysis or solvolysis) of the agent as a first step. The four alternatives are

1. neutralization followed by incineration of the hydrolysis products, either on-site or transported to another liquid incinerator-equipped site;
2. neutralization followed by wet air oxidation, followed by biological oxidation;
3. neutralization followed by supercritical water oxidation; and
4. neutralization followed by biological treatment.

Neutralization is an attractive approach because it operates at low temperature and at atmospheric pressure in conventional chemical reactors. The most commonly used neutralization (or hydrolysis) reagents have been bases, such as sodium hydroxide, potassium hydroxide, calcium hydroxide, and ethanolamine, and oxidizers such as sodium hypochlorite. Neutralization of GB has been carried out on a large scale, but neutralization of VX and HD has been held up by the low water solubility of these agents and low reaction rates. Encouraging research results have been obtained, and research is continuing in the belief that solutions to these problems are possible.

Neutralization alone may not satisfy the Chemical Weapons Convention of 1993 requirement for irreversible destruction of the agent—hence the need for a follow-up oxidation process. Wet air oxidation and supercritical water oxidation are both capable of destroying neat agent, but high operating pressures (e.g. 2,000 to 4,000 pounds per square inch) cause some safety concerns with such lethal materials. The combination of neutralization with either of these processes is synergistic: prior neutralization eliminates the extreme toxicity of the feed material to the high-pressure system, and at the same time, excess base introduced to drive the hydrolysis reaction will neutralize extremely corrosive acids formed in the subsequent oxidation step. Wet air oxidation is a proven industrial process. However, since it discharges a high percentage of organic materials, it must be followed by a subsequent oxidation process such as biological oxidation. Supercritical water oxidation may be capable of complete destruction of neutralized agents, but it is not a proven process and its application is dependent upon successful outcomes from current research programs. Biological treatment of neutralized agents will require modified neutralization processes and identification of organisms or enzymes adapted for use with each material.

Neutralization followed by a second process raises the possibility of neutralization at one site followed by transport of the material off-site for subsequent treatment. Properly neutralized materials can be transported under Army control, but this option is dependent upon finding acceptable transport routes, as well as receiver sites willing and able to treat the material. This option would be particularly attractive for those sites that store only bulk agents.

The committee found no feasible alternatives to incineration for energetics or for high-temperature detoxification of metal parts. Thus, even a successful alternative technology would affect only agent disposal operations and the associated potential release of either agent or other pollutants.

The committee believes that alternative technologies for the liquid incinerator could be ready for full-scale pilot testing in three to seven years with a well-funded, well-staffed program, although delays in obtaining required permits for testing and for disposal operations might significantly delay implementation. In considering alternatives to the baseline system, any potential decrease in disposal risk needs to be balanced against the increase in accumulated storage risk that would result from any associated schedule delay.

Incinerator operations at Johnston Atoll have more than satisfied all requirements for control of agent and toxics discharge concentrations, but accidents or upsets could, in principle, produce unacceptable performance until detected and corrected or operations cease. An enhanced baseline system would use charcoal scrubbing of all gaseous discharges to remove virtually all residual agent, as well as trace organics such as dioxins and other high molecular weight compounds (e.g., chlorinated compounds). This enhancement would also be effective in controlling emissions during process transient and upset conditions (e.g., loss of combustion air or sudden variations in agent feed rate). Charcoal scrubbing of the ventilation air discharge at Johnston Atoll has been highly successful. It is a proven technology at typical ambient temperatures, but some development work would be necessary for anticipated flue gas temperatures. In addition, upstream cooling and dewatering of the flue gas would be necessary to avoid condensation within the charcoal bed.

FINDINGS AND RECOMMENDATIONS

The committee has completed its review of the available technologies for disposal of the chemical agent and munitions stockpile. The baseline system has been demonstrated as a safe and effective disposal process for the stockpile. The current status of alternative technologies ranges from some that are in commercial use for other applications, to those that are based only on preliminary laboratory experiments. The development of a successful alternative technology for agent destruction may produce some reduction in the risks associated with that portion of disposal operations. However, all other acute and chronic risks from the other disposal operations at the six sites storing more than bulk liquid agents, and acute and chronic risks from storage at all sites, will be unaffected. Furthermore, delays in disposal operations can only increase the already much larger cumulative risk of accidental release from storage; they will extend the chronic risk from storage; and they can add to the risks of disposal as agents and munitions continue to deteriorate. Since the baseline system has already been proven, and because delays will increase cumulative total risk, the committee believes that the disposal program should proceed expeditiously at a pace in keeping with reasonable and safe facility construction and operating schedules. The only promising alternative technologies for agent disposal that have been identified involve neutralization followed by secondary treatment options. These options should be evaluated and developed at an accelerated pace so that they might potentially be available within a safe disposal schedule.

The findings and recommendations are organized in seven categories: expeditious progress, risk analyses, public concerns, current systems, alternatives, stockpile safety, and staffing needs.

Expeditious Progress

Finding 1. The storage risk will persist until disposal of all stockpile materials is complete. Both storage risk and disposal risk will increase with time as the stockpile deteriorates further. Existing analyses indicate that the annual storage risk to the public at each site is the same as or greater than the annual risk due to disposal. Thus, total risk to the public will be reduced by prompt disposal of the stockpile.

> **Recommendation 1.** *The Chemical Stockpile Disposal Program should proceed expeditiously and with technology that will minimize total risk to the public at each site.*

Risk Analyses

Finding 2. Existing risk analyses did not evaluate the latent health hazards associated with storage, handling, and disposal activities. These latent risks represent one of the major concerns voiced by the public.

> **Recommendation 2.** *The committee expects the latent risks from storage, handling; and disposal activities to be low. However, new risk analyses should be conducted that explicitly account for latent health risks from storage, handling, and disposal*

Finding 3. The finding that total risk will be reduced by prompt disposal, although apparently reasonable, is based upon earlier analyses that do not reflect current risk assessment methods and knowledge about the storage, handling, and disposal activities.

> **Recommendation 3.** *Updated analyses of the relative risk of storage, handling; and disposal activities should be completed as soon as possible*.

Finding 4. The Stockpile Committee is confident that site-specific risk analyses will confirm the wisdom of proceeding promptly. Further, the schedule of the disposal program should not be delayed pending completion of the updated analyses, because they can be conducted concurrently with other activities within the overall construction and operations schedule. Both storage risk and processing risk differ from site to site. Storage risks differ greatly depending on storage configuration, types and mix of munitions, and the potential for external events, as well as nearby community conditions.

Recommendation 4A. *New risk analyses should be site specific, using the latest available information and methods of analysis. At this time, since there is insufficient knowledge of potential alternative technologies, a first-cut series of analyses should compare the relative risks of continued storage and disposal by the baseline system. Analyses should identify the major contributors to total risk including storage. The analyses will confirm or refute the present belief that maximum safety dictates prompt disposal.*

Recommendation 4B. *As new, site-specific risk analyses become available, the Army should reconsider the schedule of construction and operation of disposal facilities and, if indicated, reorder the remaining sequence so as to minimize any subsequent cumulative total risk: The Army should also consider reconfiguring each high-risk stockpile to a safer condition prior to disposal if this will significantly decrease cumulative total risk*:

Finding 5. The committee does not foresee that any alternative agent destruction technology will substantially reduce the total agent processing risk. Site-specific risk analyses will identify the potential to improve safety over the baseline system and thus serve as a check on this belief.

Recommendation 5. *As research progresses on potential alternative technologies and as their potential for improved safety becomes apparent, site-specific risk analyses should be reexamined, with the potential alternative substituted in the baseline system, to estimate overall system performance. In view of the limited potential for overall safety improvement, however, the disposal program should not be delayed pending completion of such research.*

Public Concerns

Finding 6. The members of the public in communities near the chemical stockpile sites have voiced diverse views and opinions regarding the stockpile disposal program, and their desire to have greater access and input into decisions concerning that program. The committee's public forum, as well as correspondence and telephone calls to the committee, indicate that the Army is not as well informed of public sentiment as desirable. The public wants a larger role in the selection of disposal technology, the monitoring of operations that ensure its own safety, and determining the fate of the facility after completion of disposal efforts.

> **Recommendation 6.** *The Army should develop a program of increased scope aimed at improving communication with the public at the storage sites. In addition, the Army should proactively seek out greater community involvement in decisions regarding the technology selection process, oversight of operations, and plans for decommissioning facilities. Finally, the Army should work closely with the Chemical Demilitarization Advisory Citizen's Commissions, which have been (or will be) established in affected states. There must be a firmer and more visible commitment to engaging the public and addressing its concerns in the program.*

Current System

Finding 7. Chemical agents and munitions materials have been successfully divided into four distinct process streams having widely differing properties. Separation of these materials for processing in distinct, well-engineered systems provides a safer and more reliable operation than would processing of a mixed stream in a single process.

> **Recommendation 7.** *All disposal systems should be designed to separately process agent, energetics and associated small metal components, large metal parts, and dunnage streams.*

Finding 8. The committee found no acceptable alternative to mechanical methods to gain access to agent in munitions and to separate agent, energetics, and associated small metal components, and large metal parts.

> **Recommendation 8.** *The Army should continue with mechanical methods to gain access to agent and to separate material streams. Alternative mechanical systems should be pursued if simpler, more durable concepts, which also permit separation of the streams, are discovered.*

Finding 9. Gelled agent, particularly mustard, is difficult to separate from its container and will hamper any agent destruction or neutralization process or any attempt to decontaminate containers.

> **Recommendation 9.** *Research to develop means to extract, handle, and process gelled agents should be accelerated, to sustain the advantages of handling separate streams and to facilitate the use of alternative technologies.*

Finding 10. The committee found no readily applicable alternative to incineration of energetic components. Energetics are solid materials, cast in place in metal containers. In this form they are not compatible with alternative oxidation technologies that require liquid or finely divided feed materials. Extraction of energetics and reduction to suitable slurry form would be difficult and hazardous.

> **Recommendation 10.** *Dispose of energetic materials by incineration.*

Finding 11. The committee found no alternative to high-temperature treatment for reliable decontamination of metal parts to a level suitable for release to the public.

> **Recommendation 11.** *Use of the baseline metal parts furnace or other high-temperature treatment is recommended.*

Finding 12. The Johnston Atoll Chemical Agent Disposal System (JACADS) Operational Verification Testing (OVT) provided additional assurance that the baseline system is capable of the safe disposal of the Army's chemical stockpile. However, the committee found that OVT identified opportunities for improvements in operations, management practices, and training with regard to safety, environmental performance, and plant efficiency. The committee has recommended that systemization be used to implement these improvements prior to the initiation of the destruction of agent and munitions at Tooele.

> **Recommendation 12.** *The Chemical Stockpile Disposal Program should continue on schedule with implementation of the baseline system, unless and until alternatives are developed and proven to offer safer, less costly, or more rapidly implementable technologies (without sacrifice in any of these areas). Baseline system improvements should be implemented as identified and successfully demonstrated.*

Finding 13. The Stockpile Committee finds the baseline system to be adequate for disposal of the stockpile. Addition of activated carbon filter beds to treat all exhaust gases would add further protection against agent and trace organic emissions, even in the unlikely event of a substantial system upset. If the beds are designed with sufficient capacity to adsorb the largest amount of agent that might be released during processing, addition of these beds could provide further protection against inadvertent release of agent.

> **Recommendation 13.** *The application of activated charcoal filter beds to the discharge from baseline system incinerators should be evaluated in detail, including estimations of the magnitude and consequences of upsets, and site-specific estimates of benefits and risks. If warranted, in terms of site-specific advantages, such equipment should be installed.*

Alternatives

Finding 14. After examination of all the technologies brought to the attention of the Stockpile Committee by the Alternatives Committee and others, the Stockpile Committee has determined that four neutralization-based systems offer the most promise for agent destruction. Neutralization has been demonstrated to be effective for GB but is not yet proven for mustard and VX. Utilizing lower temperatures and pressures and ordinary chemical processing equipment, neutralization is simpler than incineration, and it may be lower in cost for some sites. Recent laboratory studies have reported encouraging results for the neutralization of neat VX and mustard (see Appendix E), though questions remain for neutralizing impure and gelled materials. Reaction products from neutralization processes will require further treatment prior to disposal. Potentially applicable processes for further treatment of these reaction products are incineration, wet air oxidation, supercritical water oxidation, and biological treatment. All of these combinations will require further research and demonstration to ensure that the combination of these processes treats agent to levels consistent with treaty and environmental requirements.

In view of the increasing total risk associated with disposal program delays, and recognizing that public opposition might delay the program for a number of reasons, including opposition to incineration, it is imperative that alternative technologies be developed promptly.

> **Recommendation 14A.** *Neutralization research should be substantially accelerated and expanded to include field-grade and gelled material as appropriate and the neutralization of drained containers.*
>
> **Recommendation 14B.** *Neutralization research should be accompanied by preliminary analyses of integrated systems capable of reducing agents all the way to materials acceptable for transport or disposal*
>
> **Recommendation 14C.** *These analyses and research should be conducted in parallel to lead to the selection of a single system for further development.*

Finding 15. There has been continued development of various research programs involving potential alternatives since the National Research Council report *Alternative Technologies for the Destruction of Chemical Agents and Munitions* was issued.

> **Recommendation 15.** *The Army should continue to monitor research developments in pertinent areas.*

Finding 16. Neutralization of agent and decontamination of containers, followed by transport of both to another facility for final treatment, offer an attractive alternative to the baseline liquid incinerator, especially for sites with no stored energetics. Receiving sites might be another chemical agent disposal site or commercial hazardous waste incineration facilities (if possible). This option could be viable at Newport Army Ammunition Plant and at Aberdeen Proving Ground, provided complications with gelled mustards do not arise.

> **Recommendation 16.** *Neutralization followed by transport for final treatment should be examined as an alternative, at the Aberdeen and Newport sites. This examination should include location of acceptable receiver sites and transport routes, and a comparison of costs and schedules relative to on-site baseline treatment. If favorable results are indicated, the examination should be expanded as an option to eliminate the liquid incinerator at other sites. At those locations, on-site incineration of energetics and associated metal parts is still recommended.*

Finding 17. The current chemical stockpile disposal schedule may provide time for site-specific substitution or integration of proven alternative agent disposal processes at selected sites if research and development efforts are accelerated and results are favorable.

> **Recommendation 17.** *Proven alternative technologies, if available without increasing risk; should be considered for application on the basis of site-specific assessments.*

Finding 18. Future developments for the baseline system as well as for a number of alternative technologies will require a flexible, agent-qualified experimental facility.

> **Recommendation 18.** *The facility and staff at the Chemical Agent Munitions Disposal System (CAMDS) facility should be maintained at an effective operating level for the foreseeable future. However, agent stocks should not be deliberately retained at Tooele in order to feed an alternative technology demonstration.*

Finding 19. Application of all known alternative agent disposal systems will require research and development, and demonstrated safe operation (operational verification testing) with chemical agents.

Recommendation 19. *Application of an alternative technology at any site should be preceded by demonstration of safe, pilot operation (operational verification testing) at the Chemical Agent Munitions Disposal System facility. These operations should not be carried out on a trial basis at storage sites.*

Stockpile Safety

Finding 20. A recent MITRE Corporation evaluation of stockpile condition with respect to propellant stabilization in M55 rockets suggests that the stockpile is safe until 2007 or later, whereas a similar Army report suggests 2002. The MITRE report notes that stockpile surveillance may be reduced in the belief that the stockpile will be disposed of by 2004. The committee is concerned that there is considerable uncertainty in all of the attempts to estimate safe storage life of the M55 rocket propellant. Degradation is not well understood. If surveillance is reduced, it would leave the stockpile subject to dangerous uncertainty. Further, other signs of degradation—gelled mustard, foaming mustard artillery shells, leaking and corroded ton containers—suggest that stockpile degradation can adversely affect disposal processes. Finally, realistic estimates of the duration of the disposal effort will extend well beyond 2004, particularly if alternative technologies are to be used.

Recommendation 20. *Further research into the nature and sequence of propellant stabilizer degradation should be undertaken promptly. The present condition of the stockpile should be evaluated with sufficient new field sampling of propellant grains, including grains from representative leakers that have been overpacked. Stockpile surveillance should be increased rather than decreased, particularly for M55 rockets.*

Staffing Needs

Finding 21. The Army faces significant challenges in executing the Chemical Stockpile Disposal Program. As more sites begin development, important engineering and technical issues will be faced. These will cover a large spectrum over the life of this program, and will include, for example, development and maturation of alternative technologies, as well as development of a method for extracting and disposing of gelled mustard. These challenges will create more demand for planning, management, and supervision than the office of the Program Manager for Chemical Demilitarization will be capable of providing without augmentation. A shortage of skilled staff could have safety implications for the program, as well as its more obvious implications for program slowdown with attendant increased risk.

> **Recommendation 21.** *The Army should establish a program to incrementally hire (or assign military) personnel to ensure that staff growth is consistent with the workload and with technical and operational challenges. These additional personnel must be assigned and trained before the project office gets deeply involved in addressing each challenge*.

The emphasis on cumulative total risk reduction in the selection of technologies for the disposal of the chemical agent and munitions stockpile leads to a strategy that also happens to have favorable cost and schedule consequences. This follows from the unusual circumstance that time and money spent in search of a better technology are likely to result in program delays and an increase in cumulative total risk, whatever the characteristics of any new technology. Although this conclusion remains to be confirmed with updated risk analyses, the existing evidence is strong enough to recommend that the disposal program proceed in parallel with the analyses and without deliberate delay. It is also clear that the updating of risk analyses should be undertaken promptly.

Through Operational Verification Testing, the baseline system has a demonstrated safety record, and means have been recommended to reinforce that safety. Of the alternatives, neutralization offers the greatest direct experience with agent and, together with a process to dispose of neutralized products, the greatest potential for utilization without a needless increase in overall risk. The Army Chemical Stockpile Disposal Program should not be used as a means for experimental development and demonstration of new waste disposal technologies for other applications.

It should be reemphasized that the Stockpile Committee recommends proceeding expeditiously entirely on the basis of minimizing total cumulative risk. The committee does not endorse programs that would increase risk. Others who may wish to delay the schedule in order to develop and prove alternative technologies, or to delay for any other reason, should proceed in the full knowledge that they do so at the expense of increased risk.

1

Introduction

THE CALL FOR DISPOSAL

The United States has maintained a stockpile of highly toxic chemical agents and munitions for more than half a century. Three unitary[1] agents are stored and disposed largely as liquids: nerve agent VX, a high-boiling point liquid that will adhere to surfaces for days or weeks; nerve agent GB (satin), a volatile liquid that rather quickly evaporates; and mustard, a blister agent that evaporates slowly. These agents are stored in a variety of munitions and standard ton chemical containers.

Lethal chemical agents are extremely hazardous materials. That is why they are used in weapons. That hazard is increased when the materials are contained in explosively configured munitions—again an inherent feature of weapons. The manufacture and stockpiling of these agents and munitions and their subsequent storage were undertaken in the belief that they had value as deterrents to the use of such materials against U.S. forces. That deterrence is no longer necessary and, therefore, does not justify the continuing risk and expense of storage.

Further, in an attempt to avoid the worldwide risk of someone using chemical warfare materials, this nation has entered into agreement with others to rid the world of all such materials. These reasons provide ample incentive for the disposal of U.S. chemical agents and munitions as promptly as safe procedures permit. Congress, in 1992 legislation, mandated that this shall occur before December 31, 2004 (Appendix A).

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[1] The term unitary distinguishes a single chemical loaded in munitions or stored as a lethal material. More recently, binary munitions have been produced in which two relatively safe chemicals are loaded in separate compartments to be mixed to form a lethal agent after the munition is fired or released. The components of binary munitions are stockpiled apart, in separate states. They are not included in the present Chemical Stockpile Disposal Program. However, under the Chemical Weapons Convention of 1993, they are included in the munitions that will be destroyed.

The disposal of these materials is a controversial program, involving social and political as well as technical issues. The public's opinions range widely: from some who would do nothing on the grounds that storage has been safe enough so far, to others who would use this program as a vehicle to develop and test new technologies for the future disposal of unspecified hazardous materials.

In part because of these public concerns, Congress requested the National Research Council Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program (Stockpile Committee) to provide technical advice on the selection of disposal technologies. In that selection, the "do-nothing" extreme is not an option that has been considered. The Stockpile Committee has been asked for advice on how to dispose of the stockpile, not whether to dispose of it. At the other extreme, the committee believes that the development of generic technologies solely or primarily for future applications is not a legitimate option within this program. Chemical agents and munitions are uniquely hazardous materials. The selection of technologies for their disposal should not be compromised to meet future, less critical requirements. The Stockpile Committee has concentrated on the disposal of nerve and blister agents and munitions, with safety as its primary concern.

THE CALL FOR RECOMMENDATIONS

Congress, with its 1985 Public Law 99-145, initiated the Chemical Stockpile Disposal Program to dispose of the unitary chemical stockpile, starting with an "expedited" effort to dispose of M55 rockets, a particularly hazardous munition. The program was expanded to treat the entire stockpile and led to the development of today's baseline system (see Chapters 2 and 5). After setting several intermediate goals and dates, Congress, with its 1992 Public Law 102-484, directed the Army to dispose of the entire unitary chemical warfare agent and munitions stockpile by December 31, 2004 (see Appendix A). That act further directed the Army to submit to Congress, not later than December 31, 1993, "a report on the potential alternatives to the use of the Army's baseline disassembly and incineration system for the disposal of lethal chemical agents and munitions." That report is to include inputs from two National Research Council (NRC) committees: (1) the Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program (Stockpile Committee) and (2) the Committee on Alternative Chemical Demilitarization Technologies (Alternatives Committee). Congress requested that the Army's report include an analysis of the Alternatives Committee report (NRC, 1993a), *Alternative Technologies for the Destruction of Chemical Agents and Munitions* (hereafter *Alternatives* report) and "any recommendations that the National Academy of Sciences makes to the Army regarding the report of that [Alternatives] committee, together with the Secretary's [of the Army] evaluation of those recommendations." At the time of the 1992 Congressional directive, the Alternatives Committee study was well under way and the mechanism was in place for submission of recommendations from the Stockpile Committee in this report.

The Stockpile Committee has worked with the Alternative Committee's extensive report and has drawn on its own technical expertise and knowledge of the baseline system and disposal program requirements. The Stockpile Committee defined selection criteria based on programmatic needs. Alternative technologies were evaluated on the basis of these criteria and were compared to components of the baseline system. This report makes recommendations to the Army for safe, efficient, and timely disposal of the stockpile.

DISPOSAL TECHNOLOGY SELECTION BACKGROUND-THE ROLE OF NATIONAL RESEARCH COUNCIL COMMITTEES

The search for the best agent and munitions disposal system has gone on for some time, with several inputs by committees of the National Research Council. Prior to 1969, disposal was mainly by land burial, open pit burning, and deep ocean dumping.[2] An NRC review committee (NAS, 1969) concluded in 1969 that

> *it should be assumed that all agents and munitions will require eventual disposal and that dumping at sea should be avoided. Therefore, a systematic study of optimal methods of disposal on appropriate military installations, involving no hazards to the general population and no pollution of the environment, should be undertaken.*

The reference to <u>no</u> hazard and <u>no</u> pollution is unfortunate. The stockpile <u>is</u> a hazard, and both storage and disposal entail risk. No activity is entirely without risk. The only way to eliminate the hazard and associated storage risk from these materials is to eliminate the materials themselves.

The Army commissioned studies of different disposal technologies and tested several in the 1970s, including both incineration and chemical neutralization (Moynihan et al., 1983). In 1982 the Army selected component

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[2] Such dumping at sea was later banned by the Marine Protection, Research, and Sanctuaries Act of 1972 (P.L. 92-532).

disassembly and incineration with associated pollution abatement systems, now known as the baseline system, as the preferred disposal system.

The NRC Committee on Demilitarizing Chemical Munitions and Agents was formed in August 1983 to review both the status of the stockpile and the technologies for its disposal. That committee reviewed a range of technologies and, in its final report in 1984, endorsed incineration as an adequate technology for the safe disposal of chemical agents and munitions (NRC, 1984). It also concluded that the stockpile was well maintained and in no imminent danger, but added, "It is not possible to give assurance at this time that an increased rate of deterioration may not occur within the relatively near future." The committee and Army personnel have been and continue to be concerned about depletion of stabilizers in M55 rocket motors. This is discussed in detail in Chapter 2.

Construction of the Johnston Atoll Chemical Agent Disposal System (JACADS), the first facility to bring together and integrate the elements of the baseline system, was begun in 1984. JACADS began operations using agents in 1990 with Operational Verification Testing that concluded in March 1993. The MITRE Corporation was engaged to monitor these tests (MITRE, 1991, 1992, 1993a-c), and the Stockpile Committee issued a preliminary review (NRC, 1993b) and commentary on MITRE's reports, including comments on the implications of JACADS performance for disposal facilities in the continental United States (discussed in Chapter 5). The Stockpile Committee also issued a more detailed review, containing recommendations for improvement of the baseline system (NRC, 1994b).

Public concern with incineration in general prompted the Stockpile Committee to recommend a study of alternatives in March 1991. That concern led independently to the preparation, for Greenpeace International, of an informational document listing a number of potential alternative technologies, published in May of 1991 (Picardi et al., 1991). Public concern has also prompted a number of government activities, including the conduct of an independent study of alternative technology potential by the Office of Technology Assessment (OTA, 1992), the conduct of a similar study by the General Accounting Office, and the congressional request for a report from the Army, initially required by December 31, 1993. From the Army report, the Congress will presumably outline future directions with regard to technology selections.

The actual wording of the congressional request directs a search for an alternative that, without extending the disposal deadline (now 2004), "... is significantly safer and equally or more cost-effective than the use of the baseline disassembly and incineration process, ..." (National Defense Authorization Act, 1992). It is directed only to "low-volume" storage sites (Aberdeen Proving Ground, Maryland; Newport Army Ammunition Plant, Indiana; Blue Grass Army Depot, Kentucky), but development of such an alternative clearly would be of interest for other sites. Taken literally, the congressional constraints on schedule, safety, and cost performance would, in view of realistic estimates of the time necessary for development and proof of alternatives, virtually eliminate from contention any alternative technology that might be developed. The Stockpile and Alternatives Committees have taken a more liberal view of these constraints.

RELATED OPTIONS AND ISSUES

The Chemical Stockpile Disposal Program is influenced or constrained by many nontechnical issues and concerns. The Stockpile Committee has been engaged to make recommendations for this program based primarily upon technical issues. It will do so in what it believes to be the best interests of the health and safety of the public and overall impact on the environment. However, as the committee formulates and evaluates disposal options, it must also consider related issues and concerns, which are discussed in the following sections.

Health and Environmental Impacts

Discharge of waste streams from disposal operations is governed by a host of federal and state regulations. Although the regulations are stated in technical terms, their formulations are not always based upon hard technical data. Thus, the regulations themselves can be a source of controversy. They sometimes change over time, often in the direction of tighter constraints as more sensitive instrumentation is developed. While the committee recognizes that some parties are concerned with the validity of current regulations, it cannot address those concerns as part of its evaluations and recommendations for alternative disposal technologies. Technologies are evaluated in this report with respect to existing regulations and reasonably anticipated trends in regulations.

Schedule

The schedule for disposal of the U.S. stockpile now calls for completion by 2004. This schedule is subject to change as may be dictated by congressional action or treaty developments. Although the committee favors prompt disposal of the stockpile as long as safety is not compromised, it recognizes that the completion date may change, and it assumes that completion can be delayed if there is a valid technical reason to do so.

Transportation

One option favored by many living near an agent storage facility is transport of all materials from that location for disposal at another facility. Congress has prohibited further study of transport of agent and munitions (P.L. 102-172). Independent of that prohibition, public resistance to the transport of such materials either to or through all other states effectively eliminates this option. The committee, therefore, does not consider transport of agent and munitions as an available option.

Transport of properly neutralized materials, on the other hand, is at least legally possible and may present a viable option in some cases. Material can be neutralized so that it can be transported under Army control and treated elsewhere or disposed in a hazardous waste facility. The Army has neutralized GB at Rocky Mountain Arsenal, Colorado and transported the resultant reaction mass to a landfill in Utah. (That material would have required further treatment to meet today's treaty requirements for "irreversible" destruction.) More recently, decontaminated material has been transported from JACADS to landfills in California. Thus, transport of processed agent derivatives, and associated nonenergetic decontaminated materials, is considered a technically viable option by the committee. However, exercise of this transport option is subject to the important conditions that a site can be found that is willing and able to receive and process the material, and that an acceptable transport route can be found.

Community Concerns

One of the paramount issues is the concern of local citizens about the impacts of the demilitarization program on their communities. The Stockpile Committee has acted, and will continue to act, in what it believes to be their best interest in terms of dearly defined technical criteria. Others may disagree with the committee's conclusions or may wish to use other criteria. Those responsible for decisions on disposal strategies should consider the recommendations of local citizens as well as those of this committee.

PUBLIC FORUM

Media coverage, Army reporting on interactions with the public, and letters and calls to the Stockpile and Alternatives Committees make it obvious that the public has many concerns about the stockpile and the plans for its disposal. As part of its deliberations, the Stockpile Committee wanted an opportunity to discuss those concerns directly with the interested parties. One step to enhance the committee's understanding was to hold a public forum.

On June 30, 1993 an alternative technologies forum was held in the main building of the National Academy of Sciences in Washington, D.C. The forum represented a major undertaking by the Alternatives and Stockpile Committees to obtain public input and comment. The morning session summarized and received comment on the *Alternatives* report. The afternoon was devoted to explaining the Stockpile Committee's plans and processes for producing its final report for the Army. Table 1-1 presents a list of technology evaluation considerations discussed at the forum and used in the evaluations summarized in Chapter 6. Prior to the forum, public concerns reaching the committee were summarized, as shown in Table 1-2. Based on the material from Tables 1-1 and 1-2, the public commented on and suggested revisions in some of the committee's plans. Background material for the forum and the list of invitees are provided in Appendix B of this report.

The Stockpile Committee's desire to obtain detailed insight into the public's views and concerns about the chemical demilitarization program is consistent with, but predates, the passage of Public Law 102-484 (Sec. 173) of October 1992. In that law, Congress specifically directed the Army to consider appropriate concerns arising from meetings with the Chemical Demilitarization Advisory Citizen's Commissions, which were to be established in each state having a stockpile storage site and in two bordering states (P.L. 102-484, Sec. 173). Even prior to that law, the Army had been briefing the Stockpile Committee on a regular basis with regard to citizens' concerns. The completion of the *Alternatives* report provided the Stockpile Committee with an opportune point in its deliberations to seek out and to consider the public's reactions and concerns about the disposal program.

Many of these public concerns are reflected in the specific considerations that the Stockpile Committee used for technology selection (see Chapter 4). Five specific types of considerations that the public addressed in the forum axe important to discuss here.

Human Impacts

First, the major issue that emerged concerned the safety of the unitary chemical stockpile and of the technologies being considered for its disposal. One of the concerns was whether enough information was available to assess all potential health effects from short-term or long-term exposure to the agents and their destruction by-products. This concern went beyond the potential for immediate fatalities, to include cancer, nerve damage, genetic effects, etc.

TABLE 1-1 Presentation by Dr. Carl R. Peterson during the June 30, 1993, Public Forum

Technology Evaluation Considerations—Safety, Environment, Performance
Capability to Treat Feed Materials
• Agent (GB/VX/HD) (pure/impure/gelled)
• Energetics
• Metal parts
• Dunnage
• Decontamination fluid
Process Characteristics
• Development status (time to proof)
• Complexity
• Durability of equipment (corrosion, etc.)
• Operational reliability
• Controllability (including rapid shutdown, recovery)
• In-process inventory
Waste Streams
• Quantity (gas, liquid, solid)
• Hazard potential (short and long term)
• Monitoring ease
Treaty/Legislative Matters
• Degree of destruction (irreversibility)
• Schedule compliance
Facility Deactivation Ease
Cost
• Research and development
• Construction
• Operations

The human impacts issue was expressed in several ways by members of the public, including concern about whether all of the potentially relevant alternative technologies had been or would be adequately examined. For example, comments about storage and about the baseline system dealt with both accidental and routine airborne releases and the perception of their potential short-term and long-term risks to the public. The issue of safety also was the basis for lengthy discussion of the potential for detoxifying chemical munitions (using chemical neutralization) and then finishing their destruction for treaty compliance at another site.

TABLE 1-2 Prior Public Concerns About the Disposal Program

Health and Safety

- Destruction effectiveness
- Workers
- Community
    - Risk of catastrophe
    - Long tern health effects

Environmental Impact

Socioeconomic Issues

Process for Public Input to Decision Making

- Mechanics
- Schedule

Other

- Credibility and capability of institutions
- Future use
- Treaty compliance
- Cost
- Schedule

External Driving Factors

A second set of public concerns was related to anxieties that factors external to scientific and technological considerations might drive decisions about disposal technology and the timing of implementation. A persistent concern was that mandated treaty compliance might overshadow local or even national issues. People were concerned that rising costs might lead to shortcuts or less emphasis on safety, and about the increasing congressional pressure on the Army. They also expressed concern that such a large investment would not be dismantled as mandated once a site's chemical agent and munitions stockpile had been disposed, but that the facility would continue to be used for destruction of hazardous wastes from elsewhere. The public perceived all of these external factors as having the potential to compromise safety considerations.

Management Capabilities

A third set of issues raised in the public forum was related to the Army's ability to implement its Chemical Stockpile Disposal Program. Several comments called into question the management efficacy and capacity of those running the program at the various sites. Potential or perceived shortcomings in the Army's ability to manage the recommended solutions have the potential to undercut confidence in program decisions. The overriding anxiety is that mismanagement will result in threats to the safety of the community or of workers at the site.

Site-Specific Impacts

The fourth set of public concerns is that the Army might overlook important differences that should or could lead to different or alternative recommendations for some of the communities. For example, several comments concerned the differences in the nature of the agents and munitions stored at different sites. There may also be different risks from external sources or differing concerns such as nearby population, vulnerable water supply, croplands, etc. These differences might lend themselves to alternative methods of destruction. Hence, there was a strong expression of the importance of both undertaking site-specific risk analyses and examining site-specific solutions. These communities, it was suggested, not only have different types of agents, munitions, and external risks, but also have different experiences in working with the Army. These factors affect their willingness to accept the use of certain potential technologies.

Ecological Impacts

The fifth area of concern was the long-term impacts on the environment. Comments concerned the potential impact on specific ecological niches due to either short-term or long-term chemical exposures from both air emissions and wastewater effluents. People also expressed concern about the adequacy of federal environmental standards, as well as their enforcement, and their relationship to more rigorous state regulations. Some of these comments related to both safety and management concerns.

Perhaps it is best to consider this set of five concerns, not as separate issues, but as strongly interrelated concerns. Each involves the overall issue of safety (especially when there are visual reminders that destruction of the munitions is occurring). Management efficacy and capacity could affect safety as they relate to meeting complex environmental regulations and safely operating technologies that will be implemented. Cost and time constraints are perceived as having the potential to inhibit adequate attention to safety issues. These all manifest themselves in the concern that insufficient consideration will be given to the local differences that exist in both the chemical stockpiles and the proximity of communities to disposal facilities. The public is concerned that potentially safer solutions will not be given adequate attention and that communities will lack voice in the decision about how the stockpile in their own area is to be managed. The committee recognizes the depth of feeling some people hold, and understands how important specific concerns are to various individuals and groups.

Underlying much of the discussion and the expressed concern appears to be a dissatisfaction with the relationship between the Army and the public in the way the program has proceeded to date. There are clear indications that the public has tired of an acquiescent role in the program, and wishes greater attention be paid to its concerns and views. The public forum represented the committee's effort to seek out these concerns so that its recommendations might better reflect and address the public's interests and apprehensions. Yet, it is only the responsible agency, the Army, that can establish a meaningful and efficacious relationship with the public. The committee's report should not be viewed as a decision, but only as a series of recommendations to the Army and ultimately the Congress. It is the responsibility of the Army to successfully implement subsequent decisions and the program. The forum indicated that the public is concerned not only with the safety of the technologies but also with the development of a meaningful public role in these decisions. This can hopefully lead to a better understanding of the technical issues involved and a greater trust in program management as a basis of support for future problem solving.

To the extent feasible, the committee has considered these public concerns. When appropriate, it has taken steps to emphasize these issues in its scientific and technically rooted recommendations. Specifically, the committee has reflected these public concerns in its choice of selection criteria for alternative technologies.

The list of invitees in Appendix B reflects the committee's attempt to ensure wide representation of potentially different viewpoints across various segments of the public. The written and verbal comments largely reinforced what had been gleaned from the media, from the Army's reporting on its contacts with the public, and from calls and letters directly to the committees. At the same time, the Stockpile Committee recognizes that these diverse information sources make it difficult to gauge the strength of specific concerns, even though they stress the variety among those concerns. They also illustrate that some groups support moving ahead with the baseline system, whereas others are vehemently opposed to it.

SCHEDULES

Despite potential flexibility in disposal program completion dates, the committee notes that disposal of the chemical agent and munitions stockpile will be a lengthy process and that time is of some importance in terms of risk to the public. Table 1-3 presents the Army's scheduled program, as of December 1993, giving a perhaps optimistic estimate of the time necessary to design, obtain necessary permits, construct, and test (systemization) each facility. This schedule includes time allotted for the completion of site-specific risk analyses (described in more detail in Chapter 4) at all sites. Slippage in the schedule has already occurred, and more may be expected.

Apart from political deadlines, time is important in at least two ways. It is an economic issue: present stockpile maintenance costs are about $100 million per year. It is a safety issue for two reasons: (1) delays extend the period of storage and thereby increase the risk to the community from the stockpile; and (2) continuing deterioration of the materials adds to both the storage risk and the risks associated with stockpile disposal. Thus, although the committee does not feel bound by political deadlines that may be arbitrary and subject to change, there is every technical reason to expedite the disposal program to the extent that safe disposal practices permit.

TABLE 1-3 Schedule for the Construction and Operation of Chemical Stockpile Disposal Facilities (December 1993)

Installation	Begin Construction[a]	Begin Systemization[b]	Begin Operations
Johnston Atoll (JACADS)	Nov. 1985	Aug. 1988	July 1990-Nov. 1996
Tooele Army Depot (TEAD)	Sept. 1989	Aug. 1993	Feb. 1995-May 2000
Anniston Army Depot	Aug. 1994	June 1997	Dec. 1998-Jan 2002
Umatilla Depot Activity	Mar. 1995	Jan. 1998	July 1999-Feb. 2002
Pine Bluff Arsenal	July 1995	Mar. 1998	Sep. 1999-May 2002
Pueblo Depot Activity	Jan. 1996	Nov. 1998	May 2000-Jan. 2002
Blue Grass Army Depot	Jan. 1997	Nov. 1999	May 2001-Oct. 2002
Aberdeen Proving Ground	Jan. 1998	June 2000	June 2001-June 2002
Newport Army Ammunition Plant	Jan. 1999	June 2001	June 2002-Apr. 2003

[a] Procurement of selected equipment could precede construction up to approximately one year.
[b] Testing the facility before operations begin.
SOURCE: Program Manager for Chemical Demilitarization, U.S. Army, Aberdeen, MD.

2

The Unitary Chemical Agent and Munitions Stockpile

This chapter presents a brief overview of the chemical agents in the U.S. stockpile and their containers and associated munitions. It describes inventories and their locations, and assesses the condition of the stockpile. Comprehensive data on the first two parts can be found in a number of other reports (NRC, 1984; U.S. Army, 1988) including the National Research Council's *Alternatives* report (NRC, 1993a).

AGENTS

The two principal types of agent in the U.S. stockpile are nerve agents (GB[1] and VX[2]) and blister or mustard agents (H, HD, HT). Each is found in a variety of containers and munitions. The structures of these compounds are shown in Chapter 3.

Nerve agents are organophosphonate compounds that contain phosphorus double-bonded to an oxygen atom and single-bonded to a carbon atom. They are highly toxic or lethal in both liquid and vapor forms. In pure form, the nerve agents are practically colorless and odorless. GB evaporates at about the same rate as water and is relatively nonpersistent in the environment. VX evaporates much more slowly and can persist for a long time under average weather conditions.

Bis(2-chloroethyl)sulfide is the principal active ingredient in blister agents or mustard.[3] Mustard has a garlic-like odor. It presents both vapor and

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[1] GB is O-isopropyl methylphosphonofluoridate.

[2] VX is O-ethyl, S[2-(diisopropyl amino)ethyl]rnethylphosphonothiolate.

[3] Names such as mustard gas, sulfur mustard, and yperite have also been applied to this agent. The term mustard "gas" is often used, but the chemical is a liquid at ambient temperature.

contact hazards. Because it is practically insoluble in water, mustard is very persistent in the environment and can contaminate both soils and surfaces for a long time.

CONTAINERS AND MUNITIONS

The stockpile of unitary chemical agents can be found in containers (various bombs stored without explosives, aerial spray tanks, and ton containers) and munitions (land mines, M55 rockets, artillery projectiles, and mortar projectiles) (Figures 2-1, 2-2, and 2-3). Some munitions have no explosives or propellant, whereas others contain some combination of fuse, booster, burster, and propellant (Table 2-1). Generally, these components are referred to collectively as energetics. They incorporate a variety of chemical compounds that must be eliminated as part of the chemical stockpile disposal operation.

The fuse, a small, highly sensitive explosive element, initiates an explosive chain by detonating a booster. The booster is an intermediate charge, sensitive enough to be detonated by the fuse and energetic enough to detonate the much larger burster. The burster, the end of the chain, bursts the munition with sufficient energy to disperse the agent held in the munition. The M55 rocket also contains an integral solid rocket propellant that can be removed only by cutting open the rocket.[4]

GEOGRAPHICAL DISTRIBUTION

The unitary chemical stockpile is located at eight continental U.S. storage sites (Figure 2-4) and at Johnston Atoll in the Pacific Ocean, about 700 miles southwest of Hawaii. The nature of the stockpile at each continental U.S. site, by type of container or munition and by type of agent, is delineated in Table 2-2. Each site differs in the amount of metals, explosives, propellants, and agent stored (Table 2-3).

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[4] Fuses may contain cyclonite, lead styphnate, lead oxide, barium nitrate, antimony sulfide, tetracine, and potassium chlorate. Bursters may have tetryl, tetrytol (tetryl plus trinitrotoluene [TNT]), or Composition B (cyclonite plus TNT). Propellants may include nitrocellulose, dinitrotoluene, lead stearate, triacetin, dibutylphthalate, and diphenylamine.

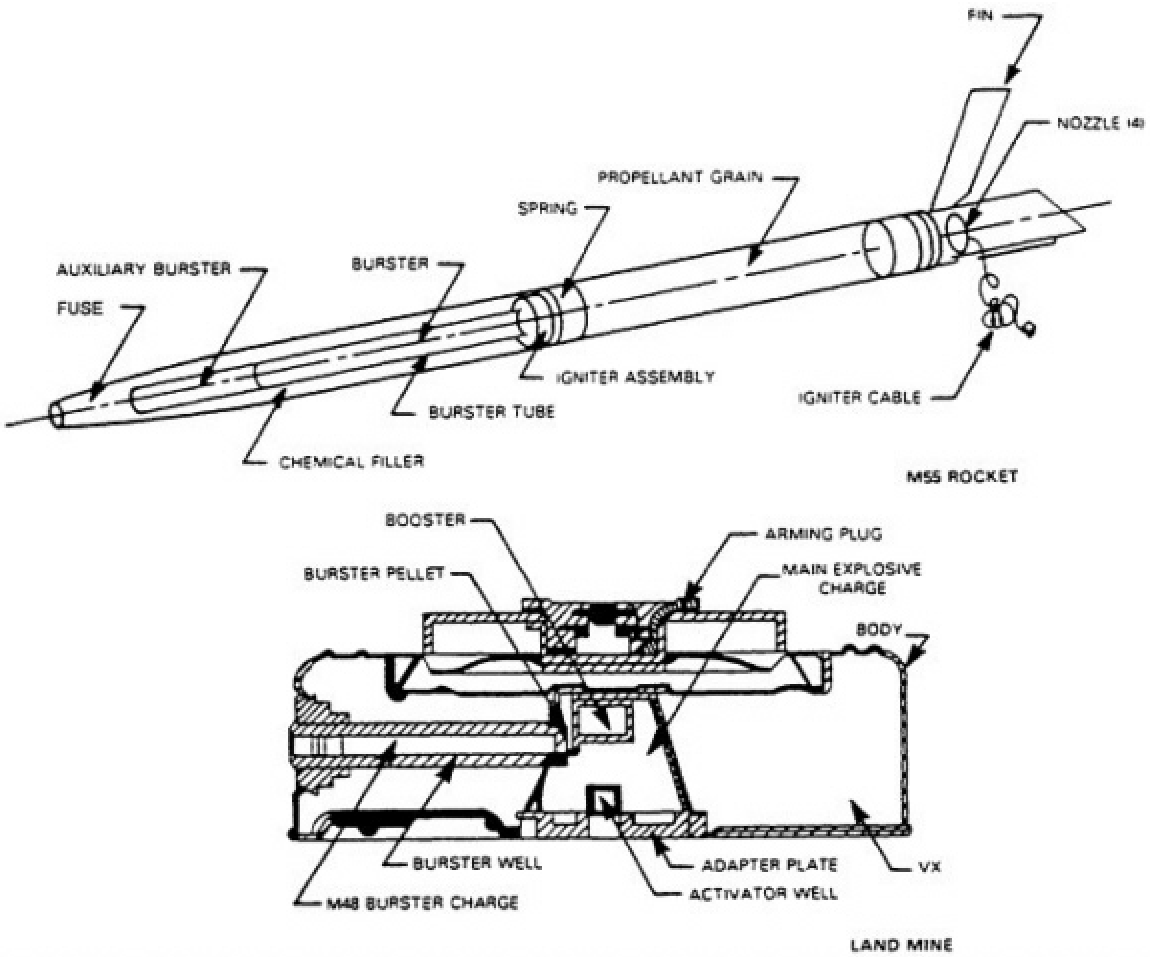

Figure 2-1 M55 rocket and M23 land mine.
Source: USATHAMA, 1982, 1983; NRC, 1993a.

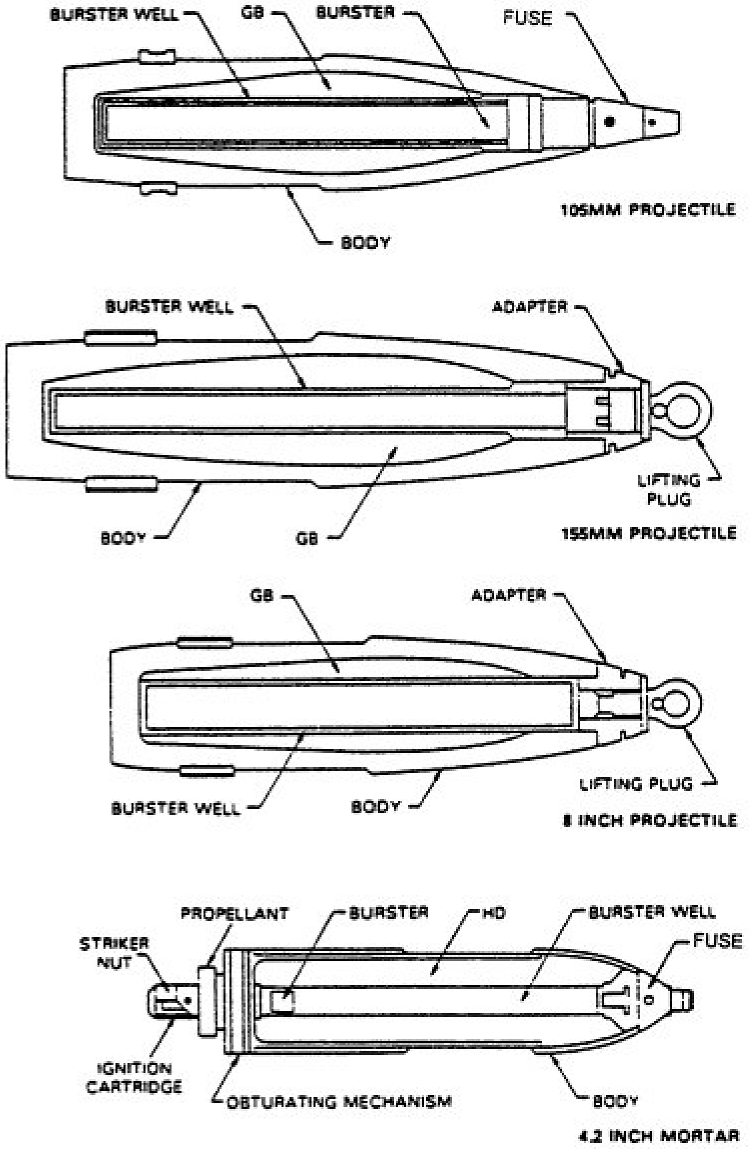

Figure 2-2 105-mm, 155-mm, 8-inch, and 4.2-inch projectiles.
Source: USATHAMA, 1982, 1983; NRC, 1993a.

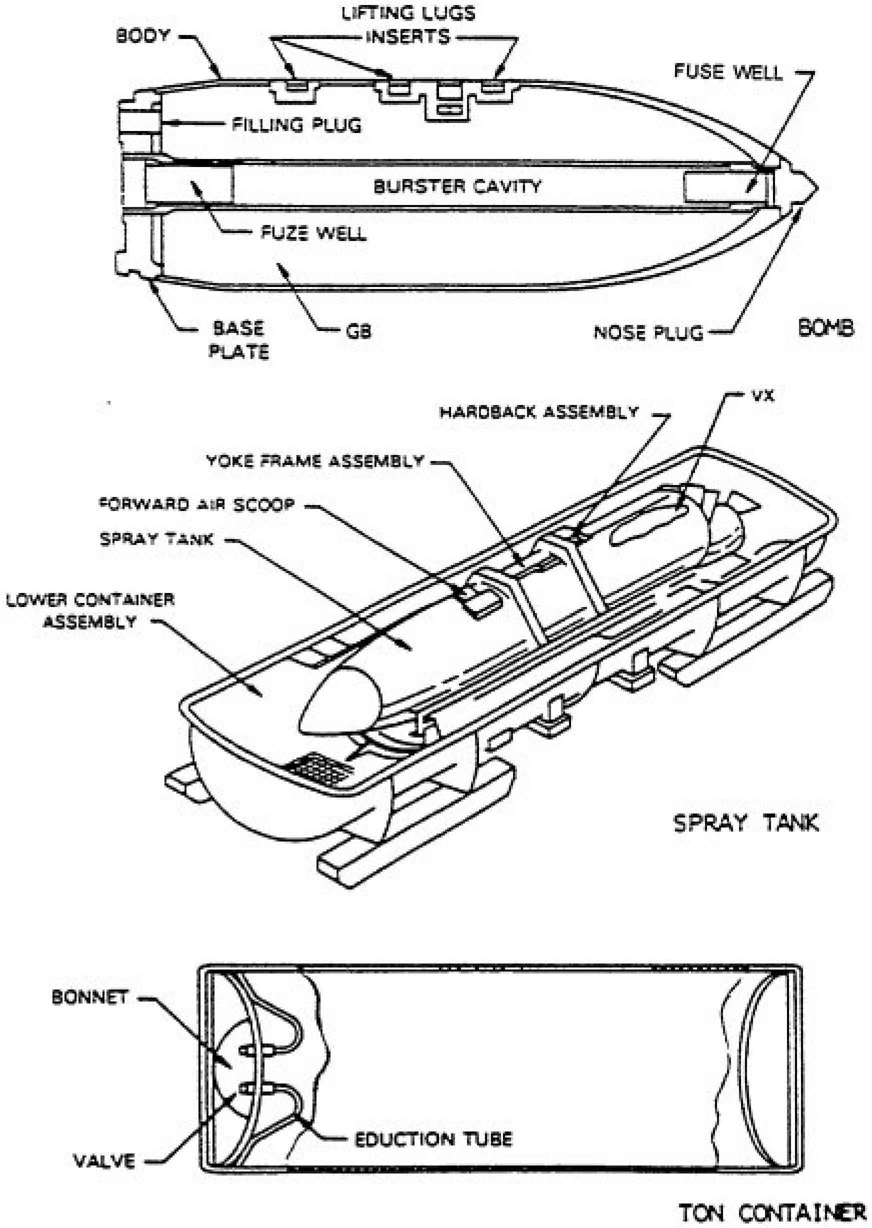

Figure 2-3 Bomb, spray tank, and ton container.
Source: USATHAMA, 1982, 1983; NRC, 1993a.

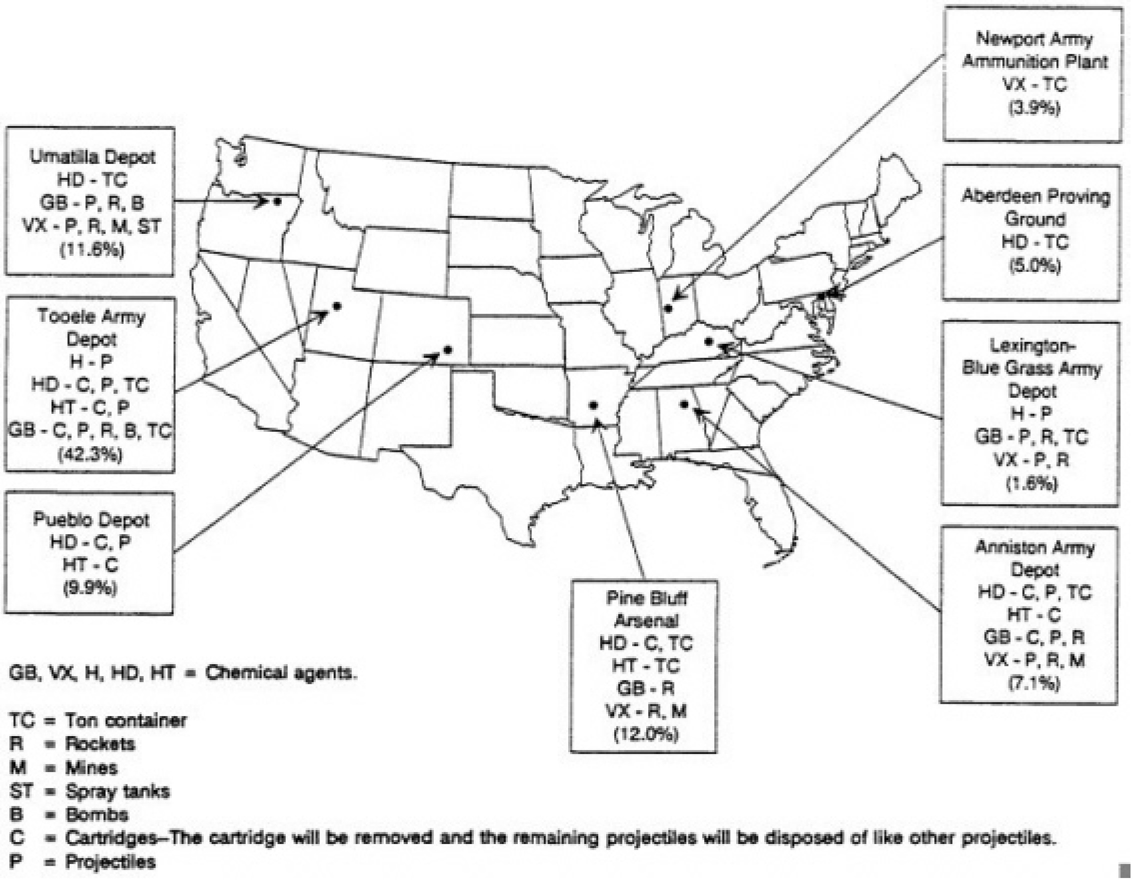

Figure 2-4 Types of agent and munitions, and percentage of total agent stockpile (by weight of agent at each storage site).
Source: OTA, 1992.

TABLE 2-1 Composition of Munitions in the U.S. Chemical Stockpile

Munition Type	Agent	Fuse	Burster	Propellant	Dunnage
M55 115-mm rocket[a]	GB, VX	Yes	Yes	Yes	Yes
M23 land mines	VX	Yes[b]	Yes	No	Yes
4.2-in. mortars	Mustard	Yes	Yes	Yes	Yes
105-mm cartridges	GB, mustard	Yes	Yes	Yes	Yes
105-mm projectiles	GB, mustard	Yes[c]	Yes[c]	No	Yes
155-mm projectiles	GB, VX, mustard	No	Yes[c]	No	Yes
8-in. projectiles	GB, VX	No	Yes[c]	No	Yes
Bombs (500-750 lb)	GB	No	No	No	Yes
Weteye bombs	GB	No	No	No	No
Spray tanks	VX	No	No	No	No
Ton containers	GB, VX, GA[d], mustard, Lewisite[e]	No	No	No	No

[a] M55 rockets are processed in individual fiberglass shipping containers.
[b] Fuse and land mines are stored together but not assembled.
[c] Some projectiles have not been put into explosive configuration.
[d] GA (Tabun), or ethyl-N, N-dimethylphosphoramidocyanidate, is a nerve agent.
[e] Lewisite, or Dichloro(2-chlorovinyl) arsine, is a volatile arsenic-based blister agent.
SOURCE: PEIS, 1988.

TABLE 2-2 Chemical Munitions Stored in the Continental United States

Chemical munitions (agent)	APG	ANAD	BAD	NAAP	PBA	PUDA	TEAD[a]	UMDA
Mustard agent (H, HD, or HT)								
105-mm projectile (HD)		X				X		
155-mm projectile (H, HD)		X	X			X	X	
4.2-in. mortar (HD, HT)		X				X	X	
Ton container (HD)	X	X			X	X[b]	X	X
Ton container (HT)					X			
Agent GB								
105-mm projectile		X					X	
155-mm projectile		X					X	X
8-in. projectile		X	X				X	X
M55 rocket		X	X		X		X	X
500-lb bomb								X
750-1b bomb							X	X
Weteye bomb							X	
Ton container		X[b]	X[b]		X[b]		X	X
Agent VX								
155-mm projectile		X	X				X	X
8-in. projectile							X	X
M55 rocket		X	X		X		X	X
M23 land mine		X			X		X	X
Spray tank							X	X
Ton container				X				

NOTE: APG, Aberdeen Proving Ground, Md.; ANAD, Anniston Army Depot, Ala.; BAD, Blue Grass Army Depot, Ky.; NAAP, Newport Army Ammunition Plant, Ind.; PBA, Pine Bluff Arsenal, Ark.; PUDA, Pueblo Depot Activity, Colo.; TEAD, Tooele Depot, Utah; and UMDA, Umatilla Depot Activity, Ore.

[a] Small quantities of Lewisite and tabun (GA) are stored in ton containers at TEAD.

[b] Small quantities of agent drained as part of the Drill and Transfer System assessment for the M55 rockets.

TABLE 2-3 Approximate Amounts of Metals, Energetics, and Agent Contained in the Chemical Weapons Stockpile (tons), by Site

Site	Ferrous Metal	Aluminum	Explosive	Propellant	Estimated Agent[a]
Tooele	22,000	570	350	175	10,500
Anniston	13,700	1,020	451	757	1,800
Umatilla	7,930	1,380	338	1,030	2,900
Pine Bluff	2,644	1,431	180	1,060	3,000
Lexington	1,631	904	115	670	400
Pueblo	10,910	0	124	0	2,500
Newport	2,455	0	0	0	1,000
Aberdeen	NA[b]	0	0	0	1,300
JACADS	NA	NA	NA	NA	1,700
TOTAL	61,270	5,305	1,558	3,692	24,800

[a] Estimated values, calculated by the Alternatives Committee, based on percentages of the total stockpile at each site, multiplied by 25,000 tons.

[b] NA—not available.

SOURCE: Information supplied by the Program Manager for Chemical Demilitarization at a meeting of the Committee on Alternative Chemical Demilitarization Technologies, March 9-10, 1992, National Academy of Sciences.

The significance of these tables for selecting disposal technologies is that the storage sites are highly varied, in that

- they range in size from Tooele with 42.3 percent of the stockpile to Blue Grass with only 1.6 percent;
- two sites have only liquid agent stored in ton containers—Aberdeen with mustard and Newport with VX;
- Pueblo has only mustard in artillery projectiles; and
- all sites except Aberdeen, Newport, and Pueblo have all three agent types and a variety of munitions.

CONDITION OF THE CHEMICAL STOCKPILE

The condition of the unitary chemical agent and munitions stockpile has been a significant factor in the decisions to effect its elimination, as well as in the decisions on how to eliminate it. In the 1984 National Research Council (NRC) report *Disposal of Chemical Munitions and Agent*, these issues were addressed:

- all chemical agents maintained in the stockpile by the Army were at least 16 years old (now at least 25 years), some more than 40 years old (now more then 49 years); none was manufactured after 1968;
- the stockpile was deteriorating, and some munitions had begun to leak;
- the stockpile was expensive to safeguard and maintain; and
- the timing of the disposal of the unitary chemical stockpile would likely be affected by a treaty then under consideration.

The Committee on Demilitarizing Chemical Munitions and Agents and its associated Stockpile Assessment Panel recommended the following (NRC, 1984)

> *The stockpiles of obsolete or unserviceable toxic chemical agents and munitions, including bulk stocks, should be destroyed as soon as possible. For the present time [1984], however, storage is the only option.*

According to a 1992 Army report, there have been almost 1,500 "leakers" found since 1982 in the stockpile of unitary chemical agents and munitions, a yearly average of somewhat more than 130 containers and munitions as illustrated by Table 2-4 (Evans, 1993). More than two-thirds of these leakers (907) have been M55 rockets.

In September 1993, the Army informed the committee that an estimated 100-gallon spill from a ton container of mustard was discovered at Tooele Army Depot. Subsequently, the committee received a copy of a "Chemical Event Report" (U.S. Army, 1993c), giving some of the details of the event, and the committee discussed the event with Army personnel. The leak occurred around a corroded plug. This plug was at the "8 o'clock" position in the round end of the container, and the container had drained down to that level. (Normally, containers are positioned with plugs between "10 o'clock" and "2 o'clock" to limit liquid leakage). The leak produced a 10-foot by 12-foot pool on the ground, leading to speculation that leakage had been rapid and that the material may have been under pressure, perhaps due to high temperature (a slow leak would probably have seeped into the ground without

TABLE 2-4 Toxic Chemical Munition Leakers

			Number of Leakers by Year											
Nomenclature	Agents	Leakage Rate (%)	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	Jan-Jun 1992	Total
105-mm cartridge	H, GB	0.004		4	1		10	3	2	11	1	1		33
4.2 in. cartridge	HD, HT	0.008		4			8	21	2	1	2	3	4	45
155-mm projectile	H, GB, VX	0.039	40	36	56	3	11	10	11	15	8	16	67	273
8 in. projectile	GB, VX	0.013			6									6
MC-1 bomb	GB	0.67	11	1			9	2	8	6	2	7		46
MK94 bomb	GB	0.384					3					2		5
MK 116 bomb	GB	0.0[a]												0
M55 rocket	GB	0.285	20	12	164	212	99	35	67	125	74	68	31	907
M55 rocket	VX	0.005			2	1				2	4			9
M23 mine	VX	0.087		4			2							6
TMU-28/B spray	VX	0.0												0
Ton container	H, GB, VX		11	1	11	19	15	18	35	10	1	16	4	141
TOTAL			82	62	240	235	157	89	125	170	92	113	106	1,471

[a] None since 1979.

SOURCE: Evans, 1993. Information supplied by M. Evans, Office of the Program Manager for Chemical Demilitarization, Aberdeen, MD.

spreading as far). A subsequent check of all containers at that site found another that showed evidence of small seepage. The containers are in an area that is normally inspected every three months.

The significance of the leak is that it was *large. Leaks* tabulated in Table 2-4 are typically small seepages. The leak was estimated to have had a maximum distance of adverse medical effects of 908 meters (still within chemical storage area boundaries). No agent was detected at the site boundaries, and there were no injuries as a result of the leak. Had the leak been of a volatile nerve agent, the consequences could have been much more serious, and the leak might have triggered an evacuation procedure.

From available information it cannot be said that one large leak portends a significant decrease in stockpile safety. Ton containers have a history of leakages around corroded plugs, with GB the most common offender. There is no direct evidence that the mustard leak was rapid or that the container was pressurized, although this appears to be a plausible explanation. At the time of the writing of this report, there was no further investigation of the incident under way or planned. The Stockpile Committee believes that this incident should be more thoroughly investigated to determine if such leaks are a new phenomenon and if container pressurization is, or will become, an increasing problem. The committee notes that unexpectedly pressurized mustard projectiles were encountered in disposal operation at Johnston Atoll Chemical Agent Disposal System (JACADS).

Although evidence presented in Table 2-4 seems to suggest that the rate of occurrence of leakers does not depend on the duration of storage, age does affect munitions and agents in several ways. Metal corrosion has been observed within burster wells, and resultant metal salts may produce sensitive compounds. Corrosion also inhibits disassembly of artillery projectiles as practiced in the baseline system, and likely to be practiced in any alternative system that processes the liquid agent in a separate stream. GB is known to corrode aluminum, and this has led to the majority of the M55 rocket leakage problems.

Mustard and GB both gel with age, producing a material that can neither be drained from its container nor, if mechanically removed, processed through a facility designed to treat liquids. Disposal operations at JACADS also uncovered some 105-mm mustard projectiles that had developed an increased internal pressure that caused foaming upon extraction of the burster well. The reason for the pressure rise is not understood. Gelled agent and foaming agent, though not direct safety problems, complicate and slow the disposal operations.

M55 PROPELLANT STABILITY

The M55 rocket presents the most serious threat to public safety from an accident initiated by a weapon in storage. The weapon is fused, loaded with agent, has a burster installed to disperse the agent, and is capable of self-propulsion if the rocket motor is ignited. The M55s are stored in igloos with many other rockets, almost 4,000 in each igloo at Blue Grass Army Depot, Kentucky, for example. Each rocket has about 10 pounds of agent. The propellant in the rocket motor is known to deteriorate in such a manner that under certain conditions it can autoignite. Indeed, the threat of autoignition of M55 rocket motors prompted the original U.S. Army Chemical Demilitarization Program, focused in the beginning entirely on that weapon.

The consequences of ignition of a single rocket within an igloo full of rockets would be severe, as confirmed by an Army test in which a small fire was started in such a storage site. The rockets contained agent simulant. After the fire had smoldered for some time, exploding rockets blew out the igloo's door. Some rockets were then propelled from the igloo while violent burning continued within, accompanied by periodic explosions. Clearly, the autoignition of an M55 rocket in a storage igloo would be a disaster of the first order; such an event is totally unacceptable. Double base propellants, the type used in the M55, contain nitrocellulose and nitroglycerin. Nitrocellulose is unstable, decaying in a process that is exothermic, accelerated by increasing temperature, and autocatalyzed by its own acidic nitrate products. Decay self-accelerates, due to both the rising temperature and the accumulating acidic nitrate catalysts. If unchecked, propellant temperature will continue to rise until violent combustion is initiated, particularly in thick propellant sections that cannot effectively dissipate heat.

The minimum propellant grain diameter for autoignition of similar double base unstabilized propellants has been estimated to be 3 inches (SAIC, 1985). The diameter of the M55 grain is 4.5 inches. Thus it presents the potential for autoignition, although the actual critical condition is a function of grain geometry as well as diameter.

A history of double base propellant autoignition has been corrected by the addition of a suitable stabilizer: "Early double base propellant formulations exhibited a tendency to undergo spontaneous combustion with unfortunate regularity; modern formulations, including the M28 propellant [used in the M55], incorporate a stabilizer to delay spontaneous combustion" (SAIC, 1985).

Decay of nitrocellulose cannot be inhibited, but a stabilizer, 2-nitrodiphenylamine (2-NDPA), is added to react with the acidic nitrate decay products before they can act as catalysts for further decay. In the process, 2-NDPA is consumed, thus eventually depleting the stabilizer concentration to a dangerous level.

There are differing models for the stabilizer depletion steps. One report (SAIC, 1985) indicates that three "daughter" compounds are formed as acidic nitrates are captured, having strengths of 0.75, 0.50, and 0.25 times that of the parent before becoming totally ineffective. Recent briefings to the committee have described depletion as a two-step process through daughters of 0.50 and 0.25 times the parent strength.

Stabilizer depletion rates are very slow—a small fraction of I percent per year—and essentially constant until levels are low enough to permit increasing autocatalysis, whereupon the propellant degradation and stabilizer depletion rates increase exponentially (SAIC, 1985; U.S. Army, 1993a). While there is agreement about this general model of depletion, substantial disagreements exist on the quantitative aspects of the kinetics of the deterioration process. This is discussed more fully below.

A maximum of about 2 percent 2-NDPA can be added to the propellant without degrading its ballistic properties (U.S. Army, 1993a). Army regulations call for increased surveillance of munitions when the stabilizer concentration diminishes to 0.50 percent and immediate disposal when it reaches 0.20 percent. Samples of propellant that have autoignited have had stabilizer concentration at or less than 0.20 percent (U.S. Army, 1993a).

The M55s were manufactured from 1959 to 1965, with stabilizer levels of about 1.8 percent. Insufficient time has passed for the stabilizer to be depleted, and no instances of M55 autoignition have occurred.

Since the effect of a stabilizer is to delay rather than eliminate autoignition, and in view of the serious consequences that would follow an M55 autoignition, several attempts have been made to estimate the safe storage life of these munitions. The Stockpile Committee has examined reports that address propellant stability (SAIC, 1985; OTA, 1992; MITRE, 1993d; U.S. Army, 1993a), though it has not directly examined original data and analyses.

Table 2-5 summarizes the estimates of safe storage life reported in the above sources. These sources contain significantly differing estimates of the remaining safe storage life. Although the committee is unable to resolve the differences, it can point out that there is considerable uncertainty in all of the results. Because that uncertainty raises the possibility that autoignition might occur prior to completion of the scheduled disposal programs, and because that schedule is in itself uncertain, this subject deserves greater attention.

The cited analyses are all based upon quite limited data and upon differing assumptions of stabilizer behavior. Field samples of M55 rocket propellant were collected in 1980, 1985, and 1989. Samples collected in 1980 were analyzed, but labeling errors prevented correlation with the collection site. Consequently, only analyses based upon the 1985 and 1989 samples have been used in stockpile assessment studies (Baronian, 1994).

TABLE 2-5 Estimated Date at Which 0.5 Percent Stabilizer Levels Would Be Reached in Most Rapidly Deteriorating M55 Lots

Source of Estimate	Year At Which 0.5 % Level Would be Reached
Original estimate of time from date of manufacture	1986-1992 ± 2[a]
MITRE, 1993 (based on 1985 samples)	2008
MITRE, 1993 (based on accelerated aging data)	2007
OTA	2010
U.S. Army, 1993[a]	1997[b]

[a] Data obtained from Science Applications International Corporation (SAIC, 1985).

[b] Mason estimated 2002 as the date to reach 0.2% stabilizer levels; 1997 has been inferred from his paper and analytic method.

- *1985 Science Applications International Corporation (SAIC) Report*. The SAIC report provides much of the background on stabilizer behavior and points out that additional testing, using field samples, must be done to refine the estimates of safe storage life. It cites tests performed at the time of manufacture (1959-1965) that projected safe storage life to be, conservatively, 27 years. At the time the SAIC report was prepared, the M55 stockpile was being subjected to a Special Assessment Program (a program of surveillance with a defined level of intensity). In this program, rockets were selected randomly from six locations: Umatilla, Tooele, Blue Grass, Anniston, Pine Bluff, and Johnston Island. The rockets, including their motors, were disassembled. Samples in 3-inch sections were taken from the front, middle, and rear of each propellant grain. A total of 1,302 samples were collected from two motors from each combination of storage site and propellant lot. At the time the SAIC report was prepared, testing on these samples was not complete, but enough data had been collected to show that the overall mean stabilizer content was 1.73 percent and the lowest lot mean was 1.31 percent. The average depletion of 2-NDPA, the virgin stabilizer material included in the propellant, was about 0.2 percent (of the original 1.96 percent). SAIC went on to say that depletion rates would have to be ten times greater than this for the rockets to present a hazard within the next ten years; comparison of the oldest lots of propellant with the newest showed no evidence of such acceleration.

The SAIC report notes that of the propellant lot samples showing the lowest concentration (less than 1.5 percent), one was from Johnston Island, while the others were from "small early lots which were manufactured to a lower stabilizer specification." The M55 rockets on Johnston Island have all since been destroyed during Operational Verification Testing (OVT) operations there. The report does not indicate what has happened to the few hundred rockets remaining from these small lots. Obviously, if they remain in the stockpile they justify intensive surveillance and perhaps early destruction.

Finally, the SAIC report presents an analysis of the chemical kinetics of the propellant deterioration process. This analysis shows that three daughter products, themselves stabilizers, are produced by the reaction of 2-NDPA and nitrocellulose. The 2-NDPA diminishes along a declining exponential curve. When the effects of the daughter products are added in, the total "stabilizer capacity," consisting of that of the virgin stabilizer and the daughters combined, declines along a straight line. These observations are important to later aspects of this discussion.

- *1992 Office of Technology Assessment (OTA) Report*. The OTA report summarizes a study carried out by the U.S. Army Material Systems Analysis Activity. In this study, conducted in 1985, 393 M55 rockets were randomly selected from the stockpile of 478,000. (Presumably these were the same rockets reported on by SAIC in 1985.) The rockets in the sample were disassembled, and individual components were inspected. Stabilizer levels were reported to be between 1.6 and 2.2 percent. However, because this 1985 assessment was the first since production, it was impossible to quantify stabilizer degradation over time. A worst-case estimate of remaining storage life was made by projecting stabilizer loss for the rocket lot showing greatest loss since manufacture. The conclusion was that the "increased surveillance" stabilizer level (0.50 percent) would be reached in 2010.
- *1993 MITRE Report.* The MITRE report contains two estimates. One stems from the same data reported by SAIC (and presumably OTA) and summarized above. After citing numerous uncertainties and error sources, MITRE said, "Given the underlying error problems and the non-comparability of data from before and after 1985, it is difficult to confidently predict remaining safe storage life." MITRE went on, however, to develop a worst case analysis based on the minimum lot mean stabilizer levels noted above. The resulting estimate for the date when stabilizer levels would reach 0.5 percent came out to be 2008.

  MITRE also made another bounding prediction based on accelerated aging tests that have been assumed to understate the time to stabilizer depletion. Based on this analysis, MITRE estimated the date at which 0.5 percent 2-NDPA, the virgin stabilizer, would be reached as 2007 at Tooele, the site with the earliest such date, while the 0.2 percent level would be reached in 2019. This projection assumed a decreasing rate of depletion of the stabilizer capacity.

The MITRE report emphasizes an important point not touched on by either SAIC or OTA. MITRE pointed out that "only one rocket needs to ignite or detonate to cause a serious accident. The reliance on lot segment sampling to monitor stockpile safety is based on an assumption of intra-lot homogeneity." MITRE underlined the fact that data show differences as high as 0.4 percent stabilizer content within the same lot segments. Moreover, the example of the low-stabilizer sample in the 1985 assessment showed nearly a 0.3 percent variation between sections of one grain.

- *1993 Mason Report*. Mason's analysis (U.S. Army, 1993a) begins with the same 1.31 percent lot mean concentration noted above. From that, he subtracts a 0.14 percent "measured deviation" to arrive at an initial (1985) concentration of 1.17 percent.[5] Citing a field-measured depletion rate of 0.00014976 percent per day, and assuming linear depletion of the 2-NDPA at this rate, Mason calculates that the critical 0.20 percent concentration would be reached in 17.7 years. He then concludes, "It is theoretically possible for a single rocket motor to autoignite by the year 2002."

Although Mason did not calculate the date at which 0.5 percent 2-NDPA would be reached, with his stated linear depletion rate this would be 5.5 years before 2002, or about 1996-1997. This makes it evident that Mason's analysis, if accurate, is cause for much greater concern than the others reported above. The difference stems in part from the assumption of linear diminution of stabilizer capacity and in part from the allowance for "measured deviation."

Mason raises another point that remains unresolved. He argues that 2-NDPA may not be as effective as assumed in the analysis cited by OTA and that it might have as little as one-fifth the capacity assumed to absorb oxides of nitrogen, the products of deterioration of the nitrocellulose and themselves catalysts for further deterioration.

Finally, Mason also compared measured concentrations of 2-NDPA with the as-loaded records, finding that some of the measured concentrations were higher than as-loaded values. Several explanations are suggested, but the discrepancy cannot be resolved with certainty. There is also some confusion as to whether measurements indicated 2-NDPA concentration or the combined concentration of 2-NDPA and its daughters.

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[5] Data cited by MITRE included 0.4 percent or ± 0.2 percent variation within a lot and a further variation of 0.3 percent or ± 0.15 percent between points within a single grain.

In summary, deterioration of the rocket propellant in the M55s is potentially a serious hazard to continued safe storage of the chemical agent and munitions stockpile. Most extant estimates of the dates when this danger might arise are at or beyond the end points of the current schedule for destruction of the stockpile. However, at least one analyst puts the date of potential danger much earlier. All of these estimates are very uncertain, based as they are on old and sparse data. Controversy is evident about the reaction kinetics and the effectiveness of the 2-NDPA stabilizer. Moreover, the schedule for the disposal program is also uncertain and it could easily slip into or beyond the dates at which significant depletion of stabilizer is now predicted.

It is the committee's conclusion that the consequences of an M55 autoignition are too great for this level of uncertainty to be tolerated. Thus, the committee recommends that the Army undertake a new and definitive study of M55 rocket propellant, including new sampling if that is appropriate, to develop more reliable assessment of these propellants. This study should address all the issues raised by the studies summarized above and by this discussion, including intralot and intragrain variations; degradation kinetics; the effectiveness of both 2-NDPA and its daughter products as stabilizers; the fate of the few hundred rockets manufactured with low stabilizer levels; and the autoignition characteristics of the M55 grain, given its actual configuration.

3

Fundamentals of Disposal

INTERMEDIATES AND END PRODUCTS OF AGENT DESTRUCTION

The U.S. chemical agent and munitions stockpile consists of a diverse collection of toxic agents and associated munitions, which present a complex disposal task regardless of the technology used. For disposal of the stockpile, waste products must be released from Army control. They must therefore be detoxified to a degree suitable for such release. There are several possibilities for the release of residual products, depending upon the state of the processed material: direct, on-site environmental discharge; final destruction at off-site hazardous waste facilities; long-term storage such as off-site landfill; or release to the general public for material reuse. There are three conditions that must be satisfied for the discharge of these materials: (1) Chemical Weapons Convention of 1993 specifications; (2) the applicable state and federal environmental regulations for hazardous waste materials; and (3) public acceptance of destruction and disposal technologies. Disposal of these processed materials will likely be complicated by special requirements or concerns related to their agent-based origin.

The selection of appropriate destruction technologies is bounded by the definition of acceptable end products from the processing of the chemical stockpile materials, including chemical agents and munition components. Determining whether a candidate process will yield acceptable end products requires a clear description of its residuals, including the physical and chemical states of the materials as well as their toxicity. Residual materials must lack toxicity for disposal according to national hazardous waste disposal standards. In order to comply with the Chemical Weapons Convention, the agents may have to be "irreversibly" altered so that remanufacture of agent is difficult.

Waste streams from all destruction technologies will include gases that can be vented to the atmosphere (or, in some cases, chemically converted to salts in a chemical scrubbing unit); water, which can be released to the atmosphere as a vapor with other gases or as a liquid; and various solids. Each of these waste streams must meet all applicable standards for any trace contaminants released. The solid waste materials may be inherently dry (such as metals) or in solution or slurry forms (such as salts). There may be varying quantities of organic materials present, ranging from simple agent chemical decomposition products to sewage-treatment-like sludges generated by biological processes. As a practical matter, solutions or slurries must be dried to reduce their volume for landfill disposal, with the extracted water discharged as a vapor or liquid stream.

The U.S. Army has conducted extensive health and safety tests and has established technical specifications on the maximum allowable concentrations of residual agent in various processed material streams, dependent upon the type of agent, the type of processing stream, and their subsequent disposition. The maximum allowable air concentrations have been defined and are relatively easily monitored in essentially homogeneous gaseous streams. Relevant air emission and exposure standards (the latter set by the Surgeon General' s Office) for agent are shown in Table 3-1, along with corresponding lethal doses. The standards have not been set for aqueous streams discharged from agent disposal operations. Drinking water standards might suffice, but it is possible that much higher standards will be established.

The monitoring of solids or mixtures of solids and liquids is much more difficult since they are not homogeneous and may involve agent-solid material interactions that hide the agent until subsequent activities result in its release. Thus, two additional decontamination parameters, 3X and 5X, have been developed.

A waste is deemed to be 3X material if an air sample taken over contained material at room temperature is below Army agent standards, when the most sensitive, currently available monitoring equipment is used. This level has been determined to be safe for unprotected handling by plant personnel, and 3X material can be shipped under Army control. However, since agent could still reside in the cracks and interstices of the solids or even in unopened areas (such as underneath a bolt), these materials cannot be released off-site unless sent to a controlled facility such as another Army chemical agent destruction facility or a licensed hazardous waste landfill. In order to be unconditionally released, or delisted, the solid must be submitted to a high-temperature treatment of 1000º F or greater for at least 15 minutes (5X material), which provides the needed assurance that residual agent will be destroyed.

No single, established technology is capable by itself of producing waste materials that meet both treaty and hazardous waste disposal criteria. For example, incineration requires a downstream pollution abatement system such as scrubbers to capture the acid gases and to dry the products for discharge as salts. Neutralization could require subsequent treatment for conversion of detoxification products to products that meet treaty irreversibility criteria.

TABLE 3-1 Air and Exposure Standards

	Permissible Hazard Levels in Air (mg/m^3)			Lethal Human Doses		
Agent	Workers[a]	Stack Emissions[b]	General Population[c]	Skin, LD_{50} (mg/kg)	Intravenous, LD_{50} (mg/kg)	Inhalation, LCt_{50} (mg-min/m^3)
GA	0.0001	0.0003	0.000003	14-21	0.014	135-400
GB	0.0001	0.0003	0.000003	24	0.014	70-100
VX	0.00001	0.0003	0.000003	0.04	0.008	20-50
H/HD/HT	0.003	0.03	0.0001	100		10,000

NOTE: The Army standards shown in the first three columns set the minimum level of performance required for gas release by any alternative process and are applicable to all four process streams. LCt_{50} and LD_{50} represent dosage and dose, respectively, that result in 50 percent lethality. LCt^{50} represents a concentration (mg/m^3) times the exposure time (min).

[a] For 8-hour exposure.

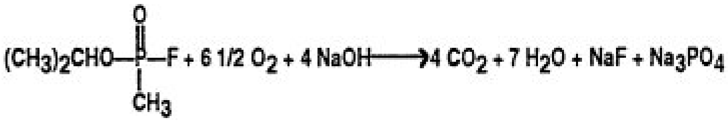
[b] Maximum concentration in exhaust stack.

[c] For 72-hour exposure.

SOURCE: U.S. Army 1974, 1975, 1988; NRC, 1993a.

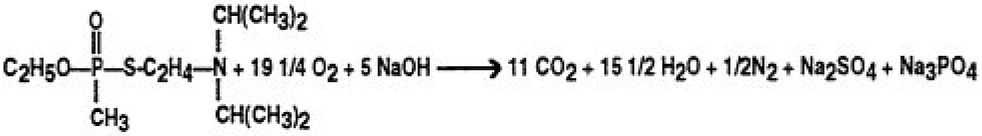
The conversion of chemical agents and munitions to the most stable final products would result in the production of completely decontaminated metal parts (5x) and the most basic chemical products (gases: carbon dioxide, water, and nitrogen, as well as various salts [calcium, sodium, or potassium salts of phosphate, chloride, sulfate, carbonate, and fluoride], depending on the process and the particular agent). This complete destruction process is referred to as "mineralization" because no complex organic molecules remain in the processed residue. By a number of different processes, mineralization involves the following chemical transformations and mass balance characteristics:

From Gel (Satin)



$$(\mathrm{CH_3})_2\mathrm{CHO}-\underset{\mathrm{CH_3}}{\overset{\mathrm{O}}{\mathrm{P}}}-\mathrm{F} + 6\,1/2\,\mathrm{O_2} + 4\,\mathrm{NaOH} \longrightarrow 4\,\mathrm{CO_2} + 7\,\mathrm{H_2O} + \mathrm{NaF} + \mathrm{Na_3PO_4}$$

From Vx



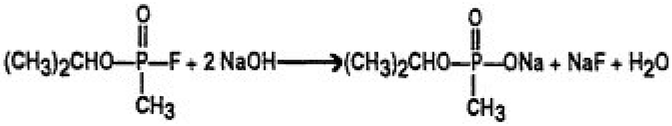
$$\mathrm{C_2H_5O}-\underset{\mathrm{CH_3}}{\overset{\mathrm{O}}{\mathrm{P}}}-\mathrm{S}\text{-}\mathrm{C_2H_4}-\underset{\mathrm{CH(CH_3)_2}}{\overset{\mathrm{CH(CH_3)_2}}{\mathrm{N}}} + 19\,1/4\,\mathrm{O_2} + 5\,\mathrm{NaOH} \longrightarrow 11\,\mathrm{CO_2} + 15\,1/2\,\mathrm{H_2O} + 1/2\mathrm{N_2} + \mathrm{Na_2SO_4} + \mathrm{Na_3PO_4}$$

From Hd (Mustard)

$$(\mathrm{ClCH_2CH_2})_2\mathrm{S} + 7\,\mathrm{O_2} + 4\,\mathrm{NaOH} \longrightarrow 4\,\mathrm{CO_2} + 6\,\mathrm{H_2O} + 2\,\mathrm{NaCl} + \mathrm{Na_2SO_4}$$

The baseline system accomplishes this mineralization in a series of steps: primary burner, secondary burner, gas scrubbing, and salt recovery. Any new technology will be expected to do the same or nearly the same. Suggestions have been made for recovery of useful chemical materials from agent processing; the committee considers this impractical and not economically advantageous. Intermediate products will have to be followed by further oxidation to yield a mineralized product.

In the mid-1970s, the U.S. Army disposed of more than 4,000 tons of GB by neutralization with caustic (NaOH) solution in water by the following reaction:



$$(CH_3)_2CHO{-}\underset{\displaystyle CH_3}{\overset{\displaystyle O}{\overset{\|}{\underset{|}{P}}}}{-}F + 2\,NaOH \longrightarrow (CH_3)_2CHO{-}\underset{\displaystyle CH_3}{\overset{\displaystyle O}{\overset{\|}{\underset{|}{P}}}}{-}ONa + NaF + H_2O$$

The residue was dried (8 pounds of water extracted per pound of agent treated), and the salt was placed in a landfill. Complete neutralization does meet the 3X condition. However, this reaction may not satisfy the current Chemical Weapons Convention requirements for an irreversible reaction because the fluorine removed could be reattached by a subsequent chemical reaction.

Chemical mineralization is not the only acceptable end point under the treaty. Biological processing of the products from a chemical neutralization of HD, for example, might produce acceptable residual products requiting no further treatment other than drying prior to hazardous waste landfill disposal. All technologies must convert the agents to products (generally mineralized) that can be disposed of safely. The mineralized products tend to be similar, but the distribution of products is different.

It is not essential that all steps to agent destruction occur at one site if an intermediate form is suitable for safe transportation to another site for final destruction or disposition, and if such transport is publicly acceptable. As noted, the 3X condition has been accepted for shipment under Army control. It remains to be seen whether sites can be found that are willing and able to receive such materials, and whether acceptable transport routes can be found. The governor of Utah, for instance, is already on record opposing the shipment of neutralized material to Utah for final processing (Michael O. Leavitt, to the Board on Army Science and Technology, August 1993). Public concerns will have to be carefully addressed if this option is to be exercised.

MATERIAL FEED AND PROCESSING STREAMS

The baseline system divides the agents and munitions into four material feed streams: agent, energetics (explosives and propellants), metal parts, and dunnage (packing materials and other miscellaneous waste). All of these streams may be contaminated by chemical agent. Although this division is not a true "fundamental of disposal," it provides an important perspective on destruction complexities. The four types of materials in these streams have widely differing physical properties that influence handling: the extremely toxic liquids may be pumped and stored with relative ease; energetic solids encased in thin metal containers burn vigorously if sufficiently exposed, and require careful treatment to avoid detonation; inert, heavy-walled metal vessels contain residual agent; and miscellaneous dunnage materials have various physical characteristics and chemical makeup. Separation of these materials into controlled processing streams allows optimal design of separate disposal processes for each, while simplifying the control and thereby maximizing the safety of operations. The benefits of separation apply equally to all disposal technologies, and no individual disposal technology is particularly well suited to processing mixed streams. The four main material feed streams are composed of the following materials:

1. *Agent*: There are three different agent types—GB, VX, and mustard—in varying degrees of purity and quantity, depending upon site inventory. Liquid agent is drained from bulk containers and munitions.
2. *Energetics* (explosives and propellants): M55 rockets, land mines, and some artillery projectiles contain energetic materials, including fuses, boosters, bursters, and solid rocket propellants. These energetics and associated small metal parts are often contaminated with agent.
3. *Metal parts*: Large metal parts include drained containers without energetic materials (ton containers, bombs, spray tanks, and artillery projectile bodies). All of these materials will be contaminated with agent. Some may contain significant amounts of gelled agent that does not drain readily (particularly mustard).
4. *Dunnage*: Miscellaneous wastes, which can be contaminated, include storage and handling pallets and packing materials, rags, protective clothing, and activated carbon from the ventilation air cleanup system.

Two auxiliary processing streams also result from all destruction technologies:

1. *Decontamination fluids*: Fluid materials, such as sodium hydroxide in water, are used throughout the facility, for example, to enable safe access to areas and equipment for maintenance. These fluids may contain minor residual agent contamination and dust or other particulate materials.
2. *Ventilation air*: Air from the process buildings and laboratories contains agent vapors.

PROCESSING OF NON-AGENT MATERIALS

Most alternative technology attention has been centered on agent destruction. However, the disposal program must provide for the destruction or decontamination of all stockpile materials. Metal parts are relatively easy to treat thermally to a 5X condition that is suitable for general release. Ton containers and projectiles in this condition may be sold for scrap. Small metal components associated with energetics, M55 aluminum rocket bodies, and fiberglass launch tubes are similarly treated, but the resulting mixed material has no scrap value.

Energetic materials cannot be disposed of safely in their existing state. They must be "deactivated," as are explosives from ordinary, nonchemical munitions. Of course, rocket propellants and explosives burn readily, but care must be taken to ensure that they burn rather than detonate. Complete destruction of these materials requires additional oxygen (typically from air) because the materials contain insufficient oxidant as formulated. Explosive elements from projectiles might be contaminated with agent; explosive and propellant elements from rockets are wetted by agent as now processed. Thus, any energetics disposal process must handle some agent as well as energetic materials. Other oxidation processes, such as supercritical water oxidation, are chemically applicable to energetic materials, but the physical extraction of cast-in-place bursters and propellants from their housings, and conversion to slurries that may be fed to these processes, would be difficult and perhaps hazardous. Reducing energetic materials to slurry form is a considerable complication over the relatively simple slicing or punching of housings as practiced in the baseline system.

Dunnage includes wood, paper, and other ordinary industrial waste materials. Most dunnage is not contaminated with agent, but some is. Disposal of this mixed waste must therefore safely process some agent as well as a mixture of typical industrial materials. Alternatives to proper combustion or landfill are not evident. Some of the waste streams from specific munitions may contain heavy metals (e.g., lead, chromium, and cadmium) as well as other materials of concern that must be handled according to current state and federal regulations.

WASTE STREAM REGULATIONS

Federal and state environmental laws and regulations govern continental U.S. site operations; these include Environmental Protection Agency regulations, Department of Defense and Army standards, Department of

Transportation regulations, and any local facility standing operating procedures. The regulatory provisions of the following federal statutes are applicable to the operation of all continental U.S. Facilities:

- Resource Conservation and Recovery Act;
- Toxic Substances Control Act (TSCA);
- Clean Air Act;
- Clean Water Act; and
- Hazardous Materials Transportation Act.

In addition, releases of certain process or waste streams that are not in accordance with design for continental U.S. facilities may result in reporting obligations under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

Through the RCRA permit, the U.S. Environmental Protection Agency establishes limits on the quantities of agent that may be emitted; however, some state regulations are more stringent than the federal standards. These restrictions are supplemented by Army policy and regulations. In addition, the RCRA permit regulates the more typical products of combustion that can be monitored on a more or less continuous basis (e.g., carbon monoxide that either may contribute to general pollution or may be indicative of incomplete combustion). It also sets detailed limits on operating conditions (e.g., temperature, residence time, oxygen levels) and metal emissions; establishes controls on the handling, storage, and disposal of hazardous materials; requires very detailed data collection, retention, and reporting; and requires a program to reduce the volume or quantity and toxicity of the hazardous waste generated and shipped off-site. TSCA regulates the incineration of PCBs (polychlorinated biphenyls).

U.S. plants will need permits for regulated air emissions in accordance with the Clean Air Act. The potential high levels of NO_x generated when destroying VX may require treatment prior to discharge-in nonattainment areas. As a result of the Programmatic Environmental Impact Statement, and pursuant to the Clean Water Act, National Pollutant Discharge Elimination System (NPDES) limits will be placed on the flow and discharge temperature of water discharged from the plant. In addition, recently promulgated regulations under the Clean Water Act will require monitoring and reporting of storm water discharges.

The Stockpile Committee is issuing two reports in early 1994, one that deals extensively with the effectiveness of operations of the Johnston Atoll Chemical Agent Disposal System, *Evaluation of the Johnston Atoll Chemical Agent Disposal System Operational Verification Testing: Part II* (NRC, 1994b), and one that examines the monitoring activities of the stockpile disposal program, *Review of Monitoring Activities Within the Army Chemical Stockpile Disposal Program* (NRC, 1994a). These reports provide a relatively up-to-date assessment and analysis of what waste streams are resulting from the disposal process and how the Army is dealing with them.

4

Selection Criteria

The health and safety of the public and the protection of the environment were clearly factors in the citizen concerns expressed at the public forum, discussed in Chapter 1, in other citizen communications, and in numerous publications. These concerns, as well as the committee's review of the accident and routine operation health risks of stockpile storage, handling, and disposal, guided the conduct of this study.

In view of the overriding public and committee concern for health and safety, the committee selected as its primary criterion, in formulating its recommendations, the minimization of the cumulative adverse consequences from all relevant risks over the full duration of the disposal program . Consequences of concern extend to effects on the environment, as well as on the health and safety of workers and citizens, resulting from the release of agents and other pollutants during accidents or in routine operation. They include both immediate and delayed effects. For brevity in the following sections, and with recognition that the consequences of sustained risk accumulate in time, this is referred to as the "cumulative total risk minimization criterion."

RISK

Risk can be defined as the expected value of a consequence. For accidents and normal operations, it is quantified by such measures as fatalities per year or latent cancer fatalities per year. As time increases, the cumulative effect of a continuing risk is an increase in the potential consequences. For example, if the risk from driving is one fatality per year for every 10,000 drivers, and that risk remains constant, then the expected consequences would be two fatalities after two years, ten after ten years, and so on. The expected consequences will continue to rise as long as the risk persists.

For the stockpile disposal program, risks will persist and consequences will accumulate until the entire stockpile is destroyed and all of the facilities are decommissioned. Because chemical agent and munitions inventory, storage conditions, and surrounding population and community conditions vary considerably among the sites, the cumulative total risk minimization strategy should ultimately be determined on a site-specific basis.

In keeping with an overall risk minimization criterion, and with the recognition that any selected technology must satisfy technical disposal requirements, the following criteria were used to choose among potential alternatives to the baseline system:

- Can the technology contribute to a program of disposal and associated storage that is safer than that of the baseline program?
- Can the technology treat agent, energetics, metal parts, and dunnage?
- Can the technology destroy all agents?
- Do waste products meet environmental disposal requirements?
- Can the technology achieve treaty requirements for irreversible agent destruction?

The primary criterion—safety—involves a number of issues, including the basic chemistry of the agents, operating temperature and pressure, the composition and quantity of waste streams, the disposal system complexity, and timely implementation. These issues are considered in the evaluation of potential alternative technologies in Chapter 6. Combinations of technologies may be necessary to satisfy some criteria. No technology can single-handedly satisfy both treaty and hazardous waste disposal requirements. For example, incineration must be followed by an effective pollution abatement system.

While it is the purpose of this report to recommend technologies on the basis of these criteria, technology decisions may ultimately be dictated by other than technical criteria. If, for example, those who oppose incineration demand use of an alternative technology, timely exploration and development of potential alternatives will be necessary even though "substantially safer" options may not be available.

RISK AS A MEASURE OF HEALTH AND SAFETY (WORKERS, THE PUBLIC, THE ENVIRONMENT)

With cumulative total risk minimization as the overriding criterion for the consideration of stockpile disposal technologies, it is important to clearly define what is meant by risk, particularly health risk. The U.S. chemical stockpile presents two distinctly different and important types of health risk to workers at the sites, persons living near the sites, or plant and animal life in the regions surrounding the sites:

1. the acute and latent health and environmental effects of direct exposure to agent and disposal products associated with accidents and incidents during the storage, handling, and processing of chemical munitions; and
2. the health and environmental effects of long-term or chronic exposure to agent and disposal products during and after routine operations of storage, handling, and chemical agent and munitions processing facilities.

These two types of risk are referred to as the *risks from accidents* and the *risks from normal operations, as* illustrated in Figure 4-1. To date, the development of risk assessments for the Chemical Stockpile Disposal Program has been motivated largely by consideration of the risks from accidents.

With respect to the risk from accidents, considerable progress has been made in recent years in designing safety into engineered facilities (e.g., nuclear power plants). This progress is a direct result of considering safety as a fundamental performance indicator similar to throughput rates, process efficiency, product quality, and cost. In this case there is a need to measure safety in some quantitative form and to integrate the results into the basic design and performance assessment process, and then into process safety management. One means of measuring safety is through a risk assessment that calculates the frequency of events, or series of events, leading to consequences of different levels of severity. In particular, this type of risk assessment answers three basic questions (Kaplan and Garrick, 1981):

1. What can go wrong?
2. How likely is it?
3. What are the consequences?

The first question is answered by structuring various scenarios (sequences of events) of the different ways that the facility can get into trouble. This step requires a clear understanding of how the facility operates and its sources of risk in order to identify those events that can initiate an accident scenario. The key to developing a complete set of initiating events is to recognize that the various contributors to risk can be many, including equipment failures, external phenomena (earthquakes, severe storms, lightning strikes, aircraft impact, terrorist attacks, etc.), human errors, and institutional failures (Figure 4-2). The likelihood of such rare events is difficult to estimate accurately. The degree of uncertainty in the estimate needs to be considered when risk decisions are made.

The question of likelihood and magnitude of an incident often requires a detailed analysis since, in many instances, there are too few data to assign statistically based frequencies. There are almost always gaps in quantitative data as well. Expert opinion must in some cases be substituted for the missing data, thereby adding one more source of uncertainty to the analysis. The most common approach is to develop frequencies and probabilities based on all available evidence; to integrate them into detailed logic models that decompose the system into components for which there are data and increased knowledge; and to do so in such a way as to recognize the uncertainties involved.

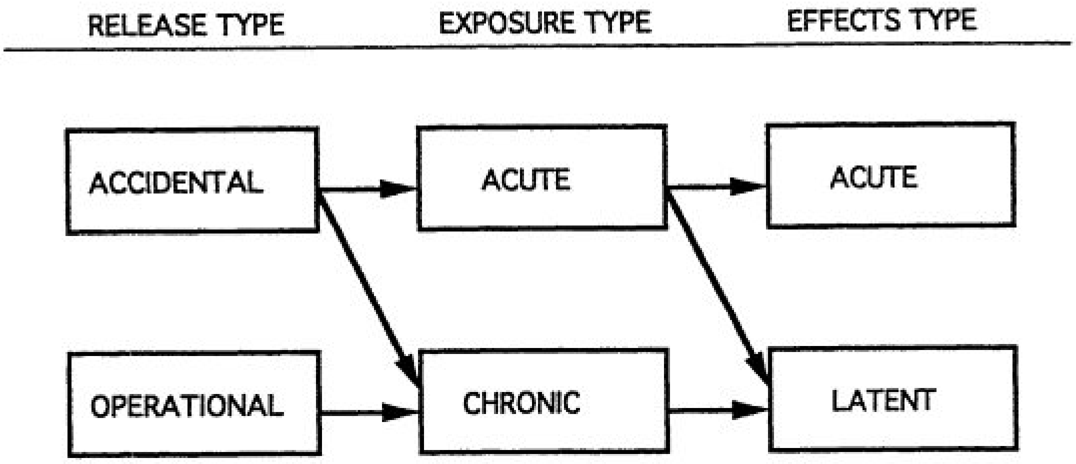


Figure 4-1 Types of Risk.

The Army's 1988 programmatic risk assessment of the Chemical Stockpile Disposal Program (discussed later in this chapter under risk assessment activities) notes that uncertainty in risk assessment arises from many causes, including the inadequacy of data, inaccuracies of modeling, and the incomplete identification and understanding of accident phenomena. Error factors used to characterize the uncertainty inherent in each accident probability "point estimate" were obtained from detailed analyses of accident scenarios (U.S. Army, 1988). The Programmatic Environmental Impact Statement (PEIS) took into account a number of uncertainties and assessed the variabilities of the estimated means used to present the results of the risk analysis.

Finally, the consequences axe defined in terms of injuries, fatalities, facility damage, environmental damage, etc., or combinations thereof in accordance with the purpose of the assessment. Thus, a risk assessment may be viewed as a structured set of scenarios, and their likelihoods and consequences. The results not only provide the likelihood of different levels of severity but also convey the analysts' confidence or uncertainty in the results. Equally important, the risk assessment for a specific facility (i.e., a site-specific risk assessment) exposes and ranks the importance of each contributor to risk. The results provide the ability to manage the risk at the most basic and effective level

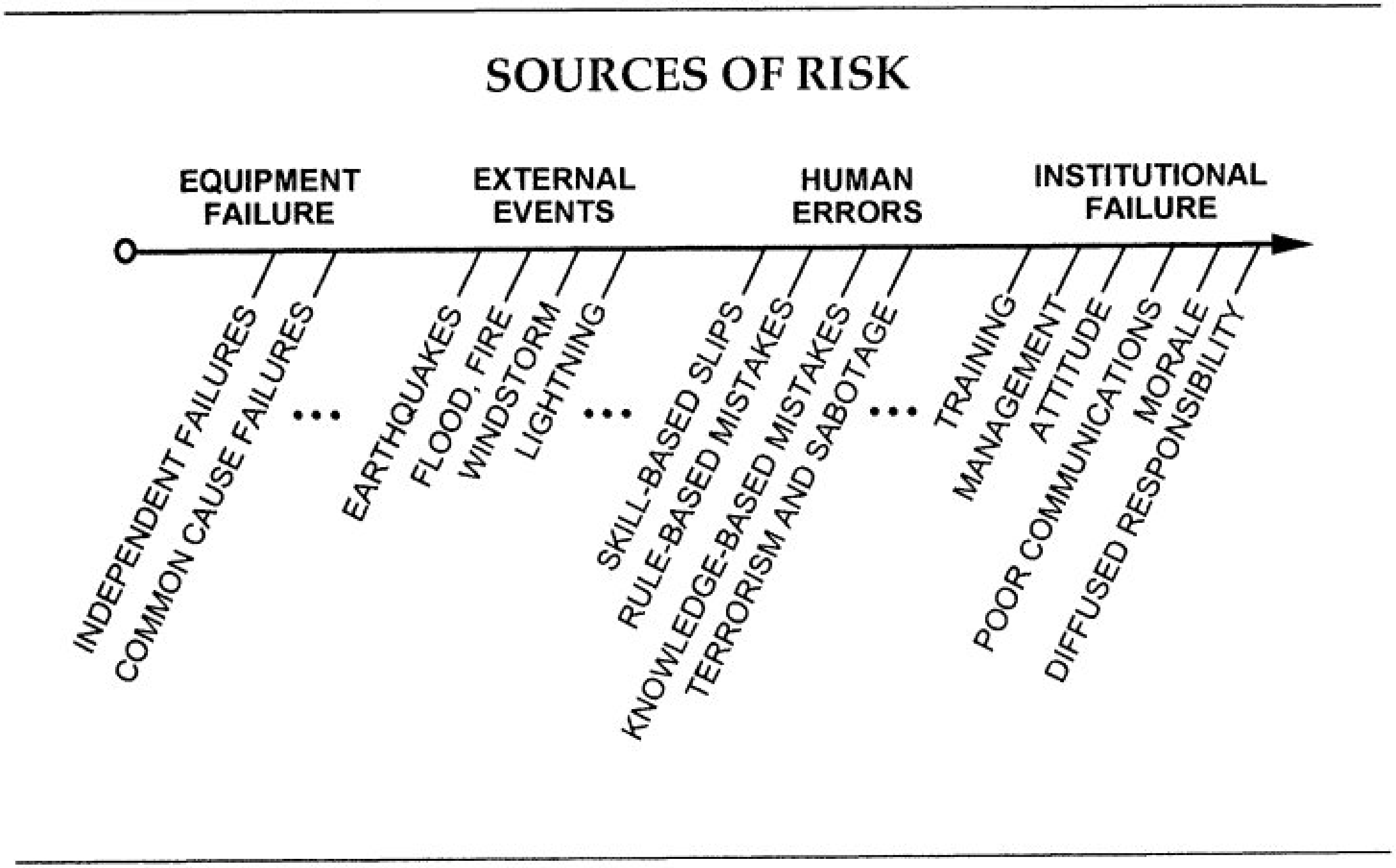


Figure 4-2 Sources of risk.
Source: PLG, Inc.

Risk assessment for releases of agent and pollutants that occur during normal operations and during transients or upsets must also be evaluated. In contrast to the risk assessment of accidents, these risk assessments address two basic questions:

1. What is the magnitude of the release?
2. What are the consequences?

An operational release is the release of a small concentration of agent below the limits of detection technology. It also refers to agent destruction by-products (i.e., stack emissions or other process discharges). It does not imply that agent or emissions are actually released in a deliberate sense. For example, Table 2-4 indicates that some releases of agent from storage do occur on a continuing basis. Most are detected during routine inspections inside igloos, and few if any are detectable at the boundaries of the storage area.

The magnitude of exposure is defined by an assessment that involves source definition (magnitude and chemical composition); environmental transport and transformation; and human, animal, and plant uptake. The consequences of this exposure, as in the case of accidents, are defined in terms of health effects, environmental damage, etc.

Generally, for operational releases, the health risk of major concern is the incremental cancer risk to the workers and surrounding population as a result of releases of agent and other pollutants. The standards for such releases are established by the U.S. Environmental Protection Agency (EPA), the U.S. Army, and regional agencies. Compliance with these standards requires specific actions such as monitored trial burns prior to operation and continuous monitoring during full-scale operations.

Risk assessments of accidents, transients or upsets, and normal operations can be developed at different levels of detail depending on the available knowledge and the intended uses of the results. Screening risk assessments can be used to identify major safety, health, and environmental concerns, even in the absence of detailed technical specifications. In addition, detailed, site-specific risk assessments can be used to evaluate and manage the risks associated with either accidents or normal operations.

Choice of the cumulative total risk minimization as the basis for technology selection has far-reaching effects on both the characteristics of acceptable technology and the timing of the disposal program. This influence on schedule is independent of treaty obligations or political agenda, which the committee considers of lesser importance. Rather, the significance of timing with regard to cumulative total risk arises from evidence that acute risk is dominated by risks from storage rather than from disposal operations. It suggests that prompt disposal will minimize total risk, as discussed in detail later under risk assessment activities. In fact, even if the storage risk is not currently large compared to the disposal risk, the cumulative consequence of storage risk will eventually outweigh that of any disposal operation.

THE RISK OF CHEMICAL STOCKPILE STORAGE

Communities near continental U.S. sites are already exposed to the risks associated with the storage of the unitary chemical agent and munitions stockpile as discussed in Chapter 2. Although these risks currently appear to be low and the condition of the aging stockpile is monitored continually, the agents and munitions will be a source of concern until they are destroyed. Of particular concern are the M55 rockets with propellant stabilizers that are deteriorating. Also, some aging mustard agent is deteriorating, producing a gel. In some cases, it produces a gas that increases pressure inside the storage containers and munitions. GB has also been found to produce a gel. Corrosion is another concern that both degrades the condition of the munitions in storage and increases the difficulty and associated risk of their ultimate disposal. Finally, there are accident risks that are still present due to external factors such as earthquakes, lightning strikes, and aircraft crashes (MITRE, 1993d; U.S. Army, 1988). As discussed in Chapter 2, the Stockpile Committee is not as confident as MITRE of the stockpile's stability over realistic estimates of the duration of the disposal program. In fact, the committee is concerned that continuing deterioration will increase the risks of disposal operations.

THE RISK OF CHEMICAL STOCKPILE DISPOSAL OPERATIONS

Planned or contemplated disposal operations pose their own independent risk. For the baseline system, there is evidence that the main source of risk to the public from accidental agent release is posed during transport of munitions and containers from the storage area to the disposal facility. This transport risk would be present for any other disposal technology. Once inside the disposal building, the risk of agent release to the environment is greatly reduced because of extensive physical containment safeguards inside the disposal facility.

In addition to the risks of accidental agent release during storage and handling, there is the risk from releases during normal disposal operations. All candidate disposal options must ultimately eliminate the same stockpile materials, and in the long term, all will eventually be released to the environment, though the exact form, timing, and location of the discharge may vary with the selection of agent disposal technology. Both the risk of storage and the risks of disposal operations are discussed later in terms of their relative contributions.

HEALTH EFFECTS

The Health Effects Of Accidental Releases

Significant exposure to GB or VX results in neurotoxic response, and exposure to H (mustard) causes epidermal blistering. It is possible that short-term exposure to high levels of mustard agent may result in cancer induction (discussed later). Since there have been no significant agent releases during operations of the Johnston Atoll Chemical Agent Disposal System (JACADS), Rocky Mountain Arsenal, or the Chemical Agent Munitions Disposal System (CAMDS) at Tooele Army Depot over the past 30 years, it has not been possible to conduct traditional dose-response exposure studies on individuals in or around the destruction facilities. In order to obtain reliable estimates of health effects from any specific event, it is first necessary to demonstrate actual physical release to the environment and to detect agent or destruction products in or on biological species. The Army has established sensitive no-observed-effect-level (NOEL) values for each of the chemical agents. There are extensive air monitoring programs at Tooele and JACADS, as there were at Rocky Mountain Arsenal. However, there are currently no dose-response monitoring programs at JACADS or Tooele, since accurate health effects studies cannot be performed unless it is possible to measure exposure dose.

The Army performs routine occupational health monitoring, including general health assays at all chemical agent and munitions storage sites. It also assays the neurotoxic-specific AChE (acetylcholinesterase) inhibition at facilities where nerve agent exposure might occur. In addition to this current monitoring, it may be possible to monitor other parameters, such as any decrease in maximal dilation of the pupils of the eyes or any changes in electroencephalograph (EEG) patterns. However, these are not being performed currently at any of the sites. Studies at the Rocky Mountain Arsenal in the 1970s demonstrated identifiable changes in EEG patterns after symptomatic minor worker exposures to GB, but the effects were very slight and required computer evaluation to be reproducibly identified (S. Leffingwell, personal communication, 1993). No long-term effects of any of these acute, symptomatic exposures have been documented. Similar EEG recordings were made of workers at Newport in the late 1970s; however, those tests were part of a medical monitoring program, not a research effort, and no analysis was undertaken (S. Leffingwell, personal communication, 1993).

There is little information about the neurotoxic effects, due to the rare instances of GB and VX exposure during production, storage, or warfare usage.

It has been possible to chronicle the effects of mustard agents from historical exposures. The United States and England have "mustard pensioners" who were exposed to HD during World War I, and who subsequently suffered from chronic bronchitis and increased rates of cancer when compared to World War I amputee casualties not exposed to the agent. During World War II, the Japanese had a chemically contaminated facility on Okuna-Jima Island where workers experienced severe blistering exposure, primarily to H mustard, but the badly contaminated sites also contained phosgene and Lewisite. Apparently, increased cancer rates have been documented from exposure during work-related activities at mustard production facilities. In addition to numerous reports on cancer incidence in the Okuna-Jima cohort, there have also been reports of increased cancer incidence among British workers from a World War II-era plant that manufactured mustard (S. Leffingwell, personal communication, 1993).

It has been difficult to provide a quantitative evaluation of the carcinogenicity of mustards since the mutagenicity is relatively low and the animal studies were limited; however, an Oak Ridge Study in 1980 suggested that H was three times as carcinogenic as benzo[a]pyrene. In 1993, the Institute of Medicine published a report, *Veterans at Risk: The Health Effects of Mustard Gas and Lewisite*, that considerably expands the list of health consequences of mustard (IOM, 1993). The Army currently enforces stringent, short-term, total concentration limits for working-level exposure and long-term general population limits that are far more protective in terms of public safety than are standards for other hazardous chemicals. This provides a comfortable safety margin to normal occupational exposure under current standards.

The Health Effects From Normal Operations

Most of the risk assessments that have been performed relative to chemical stockpile disposal have dealt with the accidental release of agent. However, there is increasing public concern over potential long-term, chronic health effects due to cumulative, low-level exposure to either agent or other pollutants (e.g., NO_x and dioxin) from the normal operations of chemical storage or disposal facilities. These long-term public health effects are much more difficult to evaluate than the effects of accidental releases, and they suffer from incomplete, variably interpretable data for effects that may have a latency of 20 to 30 years. Such studies usually lack pre-exposure controls and rely on nonrandomly collected data such as self-reported effects. In addition, site-similar epidemiology at chemical agent and munitions disposal sites or related hazardous waste disposal sites is currently quite limited in the scientific literature. These issues cannot be thoroughly addressed in this report; however, a separate National Research Council committee will address the nature and probability of health effects associated with incineration. This proposed evaluation has been titled "Health Effects of Waste Incineration" and will examine the potential health effects from incinerators in general (rather than from incinerators that handle specific substances such as the agents in the chemical stockpile), under both steady and upset operating conditions. It will be sponsored by the Agency for Toxic Substances and Disease Registry (ATSDR), the U.S. Environmental Protection Agency, and the U.S. Department of Energy.

In the limited studies that have evaluated the chemical nature of stack emissions, it has been observed that the levels of destruction and the nature of organic compound emissions vary significantly, depending on the parent compound. Thus, the principal organic hazardous constituents (POHCs) and the products of incomplete combustion (PICs) can be quite complex. For example, the combustion of natural gas may include more than 100 elementary chemical reactions, which may result in over 100 different products of incomplete combustion. Although it is possible to determine whether any individual product is released at significant toxicity levels, the overall biological effects of the mixtures are unknown. Only a few incinerator emission studies have been performed in detail, primarily because of the complexity of the chemical analysis and the lack of correlation of presumed effects with dosage. In such studies, it is critical to be able to separate presumed insult (neuropathy, allergy, cancer induction, etc.) from coincidental circumstances. These studies have generally concluded that the normal "nonupset" operation of incinerators results in stack emissions that are equivalent to those from comparable combustion systems such as fossil fuel power plants. Off-normal operation is not monitored by the EPA, but disposal facility permits will require cessation of agent feed if furnace conditions are outside normal operating limits. All such facilities must satisfy EPA emission standards. As a point of reference, the EPA Health Effects Research Laboratory in North Carolina, and others, have provided data on the mutagenicity of stack emissions suggesting that incineration facilities, if operating properly, produce no more toxic pollutants than many residential furnaces, cars, and wood stoves (Watts et al., 1989; 1992; Driver et al., 1990). Recent studies of industrial incinerators have provided some evidence of the low risk of proper routine operation (Dempsey and Oppelt, 1993).

An incinerator siting study oriented toward evaluating long-term, low-level toxicity effects is currently under way in North Carolina (ATSDR Division of Health Sciences). This study relies on self-reported symptoms from complex exposures that included direct worker exposure and fugitive emissions, not just stack emissions (S. Leffingwell, personal communication, 1993). Another community health evaluation has been performed with the Vertac Incinerator in Jacksonville, Arkansas, in which the result of dioxin contamination was examined before and after remediation. Only immediate acute effects were detected, and those were correlated with immediate symptomatic exposure. The study suffers from a lack of precontamination or fugitive exposure information. Overall, it is difficult to extract consistent conclusions from the generic occupational studies that have been performed over the past several years.

The difficulty involved in performing an epidemiological study before and after agent destruction could be very great. Such a study would be extremely difficult, if not impossible, because no correlation with dosage could be determined—since no measurable agent release would be expected and by-product releases could be very small. In addition, the maximal level of effect from chronic low-level exposures would be expected to be less than 5 percent differences, based on the correlations for AChE changes determined following symptomatic exposures described previously. Thus, the studies would be expected to produce data at the margin of detection accuracy, and any observed results might be strictly coincidental. Should a sublethal release occur, it would be possible to mark and develop a prospective cohort study.

It might be possible to evaluate the impact of incineration technologies at various hazardous waste sites around the world in a comprehensive health effects study, such as the National Research Council evaluation previously discussed. Such a study is beyond the intent of the stockpile disposal program. Such general population evaluations might be reinforced by insights gained from laboratory animal studies; however, these require extrapolation from short-term, high-dose treatments to long-term, low-dose exposures more likely to be encountered in the environment. In addition, the laboratory animal response must then be converted to potential human responses in which the target organs might have differing sensitivities or vary significantly for particularly sensitive subgroups. Such extrapolations have been shown to be extremely difficult to make and to be inconsistent in results.

It is not possible to assess the long-term impact of alternative technologies at this time because their engineering development is preliminary, and the extent of exposure to chemical agents or other destruction pollutants during processing is largely unknown.

Resolution of the issues of the long-term public health and environmental effects of normal, low-level exposure to either agent or other processing pollutants is beyond the scope of this report. For the purposes of this report, the number of useful studies is quite limited and the data base is incomplete. There is certainly no clear indication of increased incidence of cancer, neurological disruptions, or other negative health effects that can be associated with low-level, nonsymptomatic exposure or long-term proximity to hazardous waste incinerators. Likewise, there is no unequivocal evidence that the risk can be ignored.

RISK ASSESSMENT ACTIVITIES

Programmatic Risk Assessment

A programmatic quantitative risk assessment accomplished in the late 1980s (U.S. Army, 1988) was performed to evaluate the risk of agent exposure from accidents while using the baseline system for the Chemical Stockpile Disposal Program (CSDP). This report, prepared by an Army contractor more than five years ago, was undertaken to compare broad stockpile disposal alternatives (discussed below). The Stockpile Committee, while not endorsing the report, has accepted it as the principal extant, substantial, and comprehensive risk assessment on the CSDP. The assessment provides extensive data and information that the committee relied upon in its analysis.

The risk from agent or other potentially harmful emissions as a result of normal operations was not assessed because of the greater concern at the time with major accidents. In particular, quantitative risk assessment methods were used to assess the probabilities of fatalities from acute agent exposure outside the military base.

The following risk and reliability studies were performed relative to disposal by the baseline system:

- risk trade-off between storage and disposal of the stockpile;
- risk trade-offs between on-site or regional disposal plants and a national disposal facility; and
- reliability of unit operations.

Several alternatives for the application of the baseline system considered in the final environmental impact statement for the CSDP included

- continued storage (the "no-action" alternative);
- on-site disposal;
- regional disposal centers (involving rail shipments);
- national disposal center (involving rail shipments); and
- partial relocation (involving shipment of two stockpiles by air).

The risk assessment considered factors unique to each alternative application of the baseline system. For example, continued storage would involve maintenance activities; on-site disposal would involve handling, on-site transport, and plant operations; and national or regional disposal would involve handling, on-site transport, short-term storage, off-site transport (rail, air, or water), and plant operations, etc.

The risk parameters computed for each of the above alternatives included (1) human health risks, quantified as the probability of one or more fatalities, maximum fatalities, expected fatalities, and person-years at risk; and (2) relative ecological and socioeconomic impacts quantified by the expected gaseous discharge plume area as a surrogate measure of risk.

For each continental U.S. site, these assessments considered the risk (in terms of the likelihood of having an accident causing one or more fatalities in one year) to the surrounding population from agent releases due to continued storage and to operation of a baseline system disposal facility. Figure 4-3 was prepared by the Program Manager for Chemical Demilitarization. It summarizes the composite result of the programmatic risk assessment in terms of accident risk, expressed as expected annual off-site fatalities from agent exposure, for storage and disposal operations. In this analysis, annual storage risk was assumed to remain constant in time (at 0.18 estimated fatality per year) until disposal operations begin. It then declines steadily to zero as the stockpile is consumed. The striking feature of this result is that in terms of the total program, the risk from storage and attendant agent release, although still a low risk in absolute terms, is calculated to be far higher than that from disposal with the baseline system (estimated at 0.012 fatality per year at the peak of the disposal effort, by which time the disposal risk will be at 0.0004). Both storage and disposal risks are very low, that is, less than four orders of magnitude lower than those associated with everyday activities such as driving. Further, it stands to reason that disposal risks will be lower than storage risks because, in addition to the containment provided by the disposal facility, only small amounts of agent can be involved. In contrast, the "source term" for a major storage accident can be an entire igloo of munitions—perhaps as many as several thousand M55 rockets. Finally, Figure 4-3 does not show the uncertainty bounds associated with the individual analyses that make up this composite. Though those uncertainties were large, they effect storage and disposal analyses similarly. Thus they do not alter the conclusion that storage risks are relatively much larger than disposal risks.

Since the storage risk will continue with time, the total time at risk and its cumulative effect, represented by the area under the risk curve, will increase if the disposal program is delayed. This is true even if one does not consider the gradual increase of both storage and disposal risks as a result of

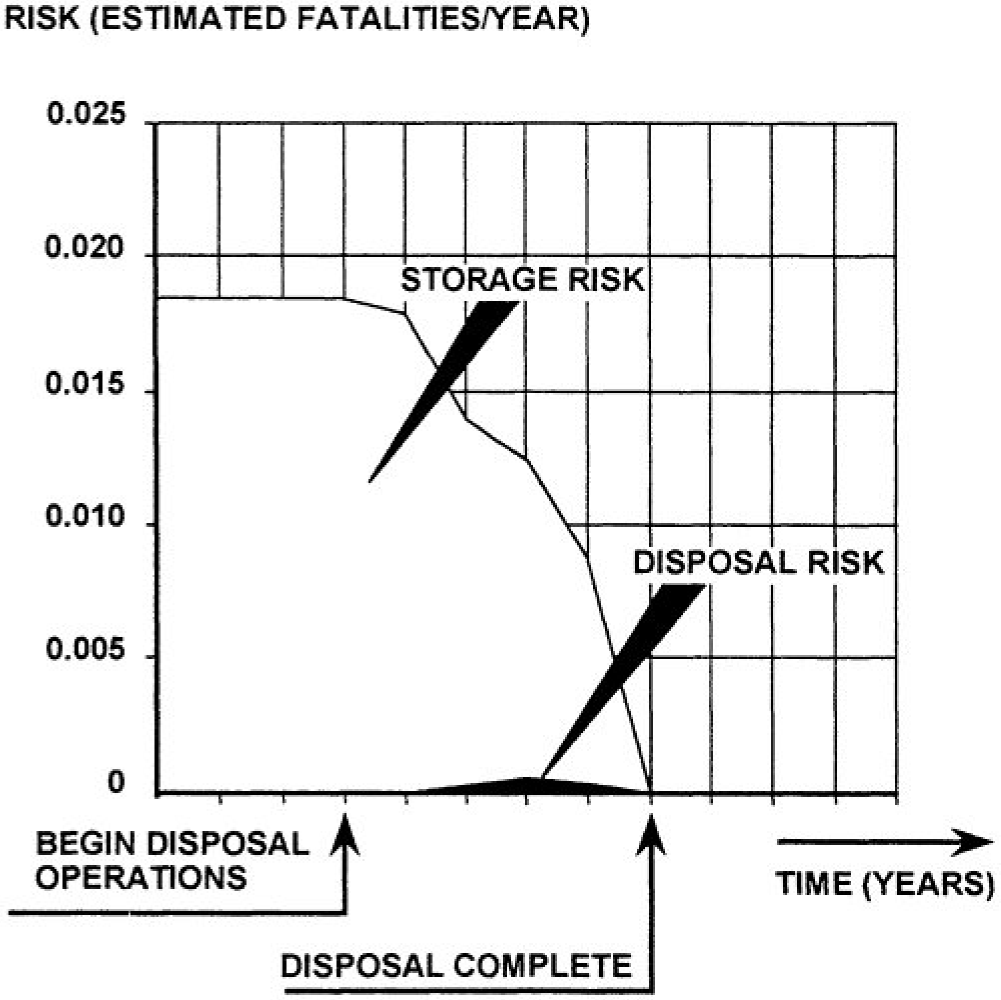


Figure 4-3 Risk of stockpile storage and disposal.
Source: U.S. Army, Office of the Program Manager for Chemical Demilitarization.

stockpile deterioration, as shown in Figure 4-4. In this case, the added cumulative risk is the rectangular shaded area under the risk curve between "Begin 1" and "Begin 2." As can be seen, this added area is much larger than any possible reduction of area under the disposal curve. Neglecting the adverse effects of deterioration is reasonable in the near term, but given the uncertainties in stockpile deterioration, this assumption would not be acceptable for extended program delays. In any case, at least for relative storage and disposal risks as indicated here, any decrease in disposal risk afforded by a new technology (lower disposal risk curve) would be quickly offset if a delay in starting date permits greater accumulation of storage consequences.

This programmatic risk assessment forced consideration of the risk of accidents for specific activities and operations in the context of the overall disposal program. Thus, insights were developed on the relative risks of such activities as storage, handling operations, transportation, munitions disassembly, agent destruction, pollution abatement, and final waste disposal.

Figure 4-3 brings into sharp focus the importance of considering both storage and disposal risks in minimizing cumulative total risk. If storage risks are dominant, then prompt disposal is the remedy. If processing risks are dominant, improved alternative disposal technologies are called for. It is important to note that Figure 4-3 conveys only the acute risks of storage and disposal operations. It does not consider latent health and environmental effects from both accidental and low-level releases of agent or other pollutants from either storage or disposal operations. Latent and acute risks are separate issues that are not easily compared.

Low-level releases from storage and transport operations external to the disposal facility are the same, regardless of the selected disposal technology, except that the total number of low-level releases from storage will of course increase if disposal is delayed. Low-level releases from the disposal operation itself may vary with the technology selected. As discussed in previous sections, this latter risk is not well documented for any alternative technology, but it is believed to be very low. Furthermore, only a fraction of the low-level release from disposal operations will be influenced by the choice of an alternative technology. Fortunately, separate and nonconflicting remedies can be recommended to reduce both acute and chronic exposure risks should either prove unacceptable (Chapter 7).

The Stockpile Committee is concerned about risk and is aware that it is a significant public concern as well. The conduct of the programmatic risk assessment was a necessary component in the construction of existing facilities. In light of experience with the baseline system since that assessment,

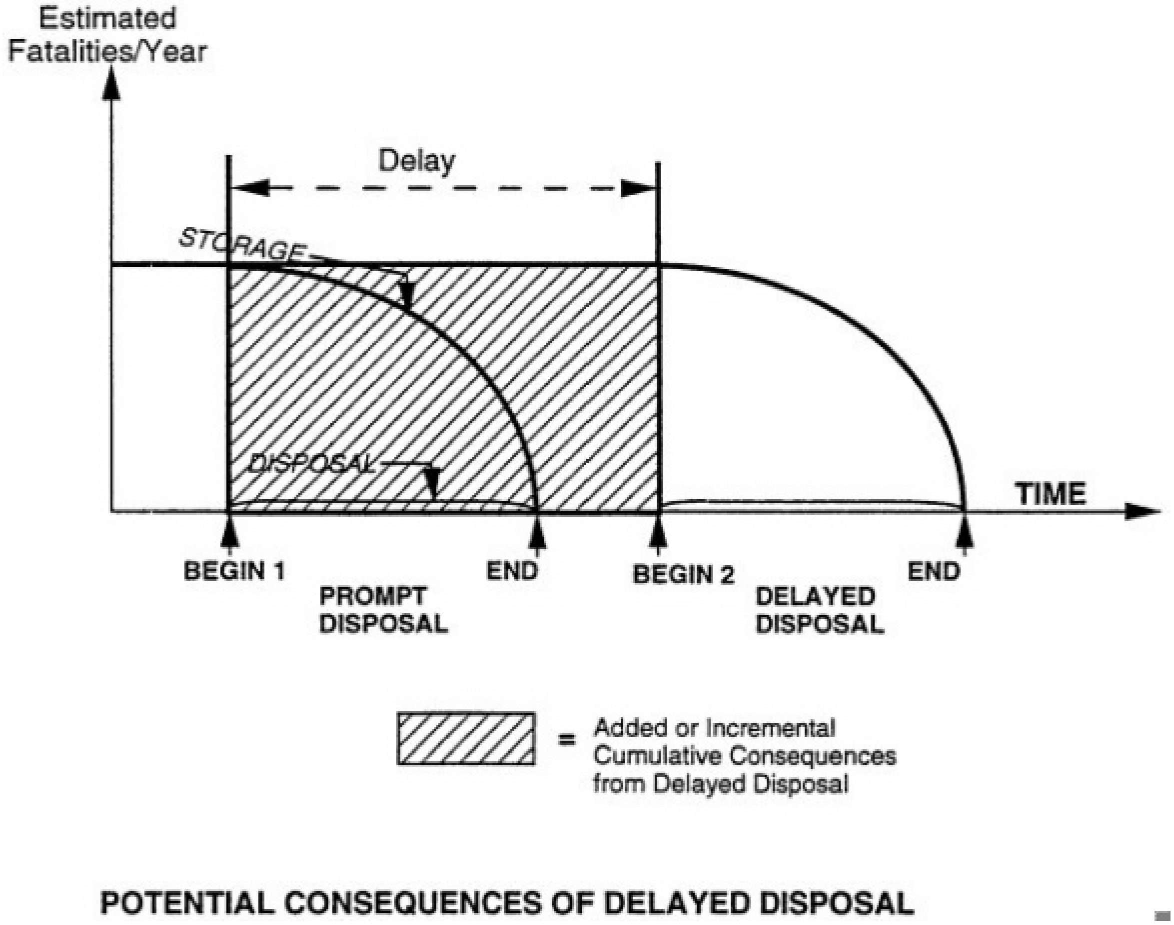


Figure 4-4 Potential cumulative consequences of delayed disposal, for constant storage and disposal risk.

and taking advanced assessment methods into consideration, the committee recommended an update of this assessment in the form of individual, site-specific risk assessments for each storage site (NRC, 1993c). The committee believes that sufficient investigations were performed in the cited PEIS, including site-specific variations, to reach the conclusion that, with the possible exception of the Blue Grass site where estimated storage and disposal risks were about equal, storage risks exceed risks from disposal operations at all sites. In some cases, the storage risk was calculated to be more than 100 times greater than that for disposal with existing disposal technology. These analyses showed that the highest storage risk was at the Aberdeen site due to the presence of ton mustard containers stored outdoors in an area close to airport operations. The committee believes that the new site-specific risk analyses, for which time has been incorporated in the Army's most recent construction schedule (Table 1-3), will confirm the relative risk estimates of the previous assessment.

Site-Specific Risk Assessment

The Army has committed to performing site- and facility-specific risk assessments for all of the U.S. disposal sites.[1] This action follows the recommendation of the Stockpile Committee, discussed above (NRC, 1993c). The Army also performed a preliminary and limited-scope site-specific risk assessment for the Johnston Atoll Chemical Agent Disposal System (GA Technologies, 1987).

Site-specific risk assessments using quantitative risk assessment techniques provide a way of assessing the safety performance of the chemical agent and munitions disposal and storage alternatives. Such analyses have been used successfully in other industries as the basis for managing risk, and these have given assurance regarding the safety of the facilities and the handling and processing of hazardous materials. Site-specific risk assessments identify the intersystem and intrasystem dependencies and the human roles in controlling the risks. They provide a quantification of risk from all reasonable causes, including both internal events (plant and plant-people failures) and external events.

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[1] A site-specific risk assessment accounts for unique features related to the distribution of population (and its transportation patterns) around the site, nearby topography, and land uses (e.g., truck farming versus grazing versus residential). A facility-specific risk assessment accounts for differences in the design of facility components (e.g., the site-specific layout of components; the particular mix and quantities of the on-site stockpile).

Each analysis evaluates site-specific hardware, software, procedures, training programs, maintenance practices, and operator response (including site-specific storage facilities and munitions handling activities). The contributions to risk in terms of random failures, common cause failures, multiple failures, and human errors are assessed. The total scope of a site-specific accident risk assessment includes a number of factors. A list of these factors ranging from human reliability and pollution abatement systems to final plant decommissioning is given in Table 4-1.

RELATIVE RISKS ASSOCIATED WITH INDIVIDUAL STEPS OF DISPOSAL OPERATIONS

The risk analysis (U.S. Army, 1987) supporting the PEIS considered the risks of accidents for individual operations in the baseline system as applied at JACADS. Individual operations involve such activities as punch-and-drain, disassembly (including the operation of rocket shearing machines), in-process agent storage, and furnace/incinerator performance.

The results are characterized only in terms of accidental agent release, as opposed to other process pollutants, and whether the release conditions are initiated by internal or external events. The only consequence considered was acute effects from accidental releases. Among the important general results are the following highlights:

Overall

- Accidents resulting from disposal operations have not been calculated to be major contributors to the risk from the overall Chemical Stockpile Disposal Program.
- The accident risk is estimated to be greater for those activities of the program having to do with storage, transportation, and munitions handling. The risk from disposal operations is less.
- The accident risk from storage and transport to the disposal facility, although much higher than for disposal operations, is still very much lower than the routine risk to the public of accidental death from such non-stockpile-related causes as automobile accidents, falls, drownings, or industrial accidents. These latter risks, for each individual, are in the range of a 10^{-4} to 10^{-5} chance of fatality per year. The storage risk shown in Figure 4-3, about 1.8×10^{-2} expected fatalities per year for a total at-risk population of 4 million, works out to an individual risk of 0.45×10^{-8} fatalities per year.

TABLE 4-1 Scope of Risk Assessment

Assessment Factors
• Human Reliability
• Equipment Performance
• Integrated Process
• Mitigation Systems
• Pollution Abatement Systems
• Waste Handling
• Munition Handling Operations
• Release Condition
• Atmospheric Dispersion
• Health Effects Evaluation
• Operating, Maintenance and Management Procedures
• Emergency Response
• Decommissioning

SOURCE: PLG, Inc.

Internal Events

- The historic frequency of releases associated with accidents initiated by equipment failure and human error has been low, so as to make its contribution to risk insignificant. In terms of magnitude, the largest amount of agent vapor release would occur for a metal parts furnace explosion simultaneously with ventilation failure.
- A similar event in terms of frequency and consequence involves a munition detonation in the explosive containment room vestibule with subsequent fire spreading to unpacked munitions outside the vestibule in the unpack area.
- The highest-frequency event calculated covering disposal operations would be initiated by an inadvertent feed of an unpunched munition containing a burster to the dunnage incinerator (10^{-2} per year for mines; $\sim 10^{-3}$ per year for other munitions). The feature of this event that keeps it from

being an important contributor to risk is the small amount of agent that might be involved, perhaps up to 15 pounds. Thus, the consequences were estimated to be small.

External Events

- Aircraft crashes dominate the external event risk among all the risks that were considered. Fire and lightning are real but unevaluated risks. These apply to both storage and disposal operations. For example, the frequency of accident scenarios induced by the crash of a large aircraft is estimated to be higher at the Anniston Army Depot than it is for the Tooele Army Depot.
- The frequencies of earthquake-induced accident scenarios also vary (e.g., they are generally higher for Tooele than for Anniston). The earthquake scenario having the highest relative frequency involves a munition fall and subsequent fire, leading to the detonation of munitions in the unpack area. The low frequency, of the order of 10^{-6} per year, keeps this scenario from being a major contributor to risk.
- Other external events such as tornadoes and meteorites did not initiate accidents of sufficient frequency to be a significant contributor to risk.

RELATIVE RISKS OF ALTERNATIVE DISPOSAL TECHNOLOGIES

The risks of accidents associated with agent and munitions disposal using the baseline system are now reasonably well identified. Detailed site-specific quantitative risk assessments are possible for both accidents and normal operations. In contrast, for many of the potential alternative technologies, full systems have not been designed, risks are not fully identified, and indeed, technical feasibility is yet to be proven. Obviously, comparable quantitative risk assessments cannot be completed at this time. It is the opinion of the Stockpile Committee, based upon its members' cumulative scientific, industrial, and programmatic experiences in similar technologies (see Appendix G) that, given sufficient time and funding, all technically feasible disposal technologies could be engineered to roughly the same level of safety. The immediate consequence of this opinion is that no potential alternative technology has been eliminated because it was believed to be inherently unsafe. However, if "sufficient time and funding" turns out to involve long delays and substantial increases in cost, engineering judgments can help identify alternatives that should be dropped from further consideration. At the same time, as more is learned of the alternatives and as new site-specific risk analyses become available, the potential for any increased safety when using alternative technologies should be reexamined.

The risks considered in this program are indeed low in comparison to other more familiar risks. However, they are important to program planning and management in at least three ways:

- Risk *is* the major source of public concern. Although there are widely varying opinions on the significance of the different sources of risk, risk is virtually the only common ground for communication among interested parties.
- Anxiety and uncertainty tend to be the response to low-probability, high-consequence, involuntary risk.
- The risk of stockpile storage, while not high, is nevertheless gradually increasing due to such phenomena as destabilizing propellants and deteriorating containment. Uncertainties in both the stockpile condition and the disposal schedule leave open the possibility of a significantly increased hazard if disposal is sufficiently delayed.

The result is the need for a better understanding of not only the levels of risk involved but also the contributing factors to that risk. Experience has indicated that improved understanding best comes from a systematic and deliberate analysis of the risks and their sources.

ISSUES OTHER THAN RISK

In addition to the principal criterion of risk minimization, a number of other factors are of concern to the communities and to the committee.

Socioeconomic Impacts

The construction, use, and decommissioning of the disposal facilities will cause community impacts related to jobs, transportation, and property values. As noted, there are serious concerns about the safety and environmental performance of the operations that need to be addressed. One concern involves a general distrust of incineration and fears about proper operation of such facilities. Use of an alternative technology to allay fears is a possibility, but the actual trade-offs between an alternative technology and any component of the baseline system needs to be considered explicitly in any decision about which technology to use.

Another of the concerns is that the facility might continue to be used for hazardous waste disposal after all agents and munitions have been disposed.

The facility would then become a continuing hazard in itself, even after the intended elimination of the stockpile hazard. The committee has considered this concern explicitly in its recommendations and agrees that continued use for nonstockpile destruction purposes imposes additional, but unquantifiable, risk.

Open Decision-Making Process

A formal and well-publicized process for public communication, as well as for receiving and considering public inputs to decisions on technology choices and monitoring operations, needs to be established on a continuing basis. Successful public participation processes for some hazardous waste facilities have included features such as having members of the board of directors nominated by the community, having funds to support expenses incurred by community members of a plant co-management committee, requiting the support of local government for any expansion of treatment capacity or change in technology, and guaranteeing nearby property values and crop prices (Castle, 1993; OFFE, 1993). A growing literature summarizes case studies and approaches that have been used to ensure public safety and to enhance the public's confidence in the safe operation of potentially risky hazardous materials facilities (Hance et al., 1988).

Schedule

Congress has set a date for completion of demilitarization by the end of 2004. Independent of that, schedule affects total risk since delays prolong exposure to cumulative storage risk. Although the committee is committed to expeditious disposal, it believes that schedule is secondary, per se, to overall safety. It is operating on the assumption that this date might well be extended if a valid reason for doing so exists.

Cost

Although cost is not a consideration in the committee's criterion regarding the reduction of overall risk, it is nevertheless a consideration after some adequate level of safety is reached. Storage costs, total capital investment, operating costs, costs of disposal of residual solid materials, etc., are all included in the costs of the disposal program. The committee could not develop accurate costs for as yet undeveloped alternatives. However, because the incremental costs for the process equipment in the baseline system are low compared with the total costs of the facilities and the overall program, cost has not been considered an important selection criterion in judging any technology. Nevertheless, cost is a factor that will ultimately be considered by Congress in committing federal revenues to the Army Chemical Stockpile Disposal Program.

The disposal program also presents the unusual possibility that maximum safety may correspond to minimum cost. This follows from the foregoing indications that risk may be dominated by storage rather than disposal operations. Investment in the research for and development of improved disposal technology could then be accompanied by delays that increase the total cumulative risk regardless of the characteristics of the new technology.

Citizen Involvement

In setting one primary criterion, cumulative total risk minimization, the committee recognizes that, while acting in what it believes to be the best interests of the public and of the environment, its views and recommendations cannot possibly satisfy all involved participants. The final selection of a technology or process should be made by considering the recommendations of the local citizenry as well as those of this committee. Effective mechanisms must be established to develop and communicate citizens' concerns throughout the selection process, and thereafter in the operation of the facilities. This must be accomplished in a manner that ensures safe and effective operation and monitoring of the disposal facility.

SUMMARY

Based on previous analyses, the risk from accidents associated with continued storage of chemical agents and munitions, with one possible exception (where the risks may be equal), exceeds the risk of disposal operations using the baseline system. Until disposal is completed, the risk of releases from storage will persist, and if the storage period is extended sufficiently, that risk will increase significantly as the munitions and agent deteriorate.

The Army's programmatic risk assessment was an adequate initial evaluation of the overall acute risks associated with storage and disposal using the baseline system. Both acute and chronic risks associated with storage operations and transport external to the disposal facility will be unaffected by the selection of disposal technology. Chronic risks from disposal operations are not well documented for any technology, but are believed to be very low for the baseline system and recommended alternatives.

In the absence of schedule and cost constraints, a number of agent disposal technologies can be engineered to satisfactory levels of safety, with regard to both acute and chronic health and environmental effects. To varying degrees, however, alternative technologies will incur both cost and delays (which add cumulative storage risk penalties) to complete necessary research and development work, and to demonstrate adequate performance.

Finally, the committee is keenly aware of citizen concerns *other* than risk associated with the Chemical Stockpile Disposal Program. These concerns include socioeconomic impacts, public participation in the decision-making process, program schedules, and program costs. It is important that all be considered in the program to eliminate the stockpile. The committee's emphasis on cumulative total risk minimization is an attempt to be sensitive to the overriding concerns of the public and of the committee itself.

5

The Present Baseline System

BASELINE SYSTEM IMPLEMENTATION

In this section, the baseline system as it is implemented in a second generation form at Tooele Army Depot is briefly described. The first generation, the Johnston Atoll Chemical Agent Disposal System (JACADS), is now operating on Johnston Island, having successfully completed Operational Verification Testing (OVT) in March 1993. This chapter is intended not only to describe the present system, but also to provide a base to which the technologies in the next chapter can be compared. It also serves to indicate that disposal of chemical agents and munitions requires an extensive and rather complex *system* . The concerns that have motivated a search for alternative technologies appear to address only a portion of that system. Figure 5-1 shows the major system components of the baseline system.

Storage, Transportation, And Unloading Of Munitions And Containers

Munitions are stored in vented igloos. The igloo area is monitored for agent. Most bulk containers are stored in the open or in monitored warehouses. Prior to transport of munitions and containers, the area is checked for any signs of leakage. If agent contamination is found, special procedures are followed to contain leaking munitions and to decontaminate the area. The munitions or ton containers are then loaded into a robust, vapor-tight, transport container that is designed to withstand impacts and fire exposures. (A transport container for spray tanks is yet to be designed.) The transport container is moved from the storage area to the unpacking area within the disposal building. Munitions and agent containers are unpacked manually. Packing materials (dunnage) are transported to the dunnage furnace.

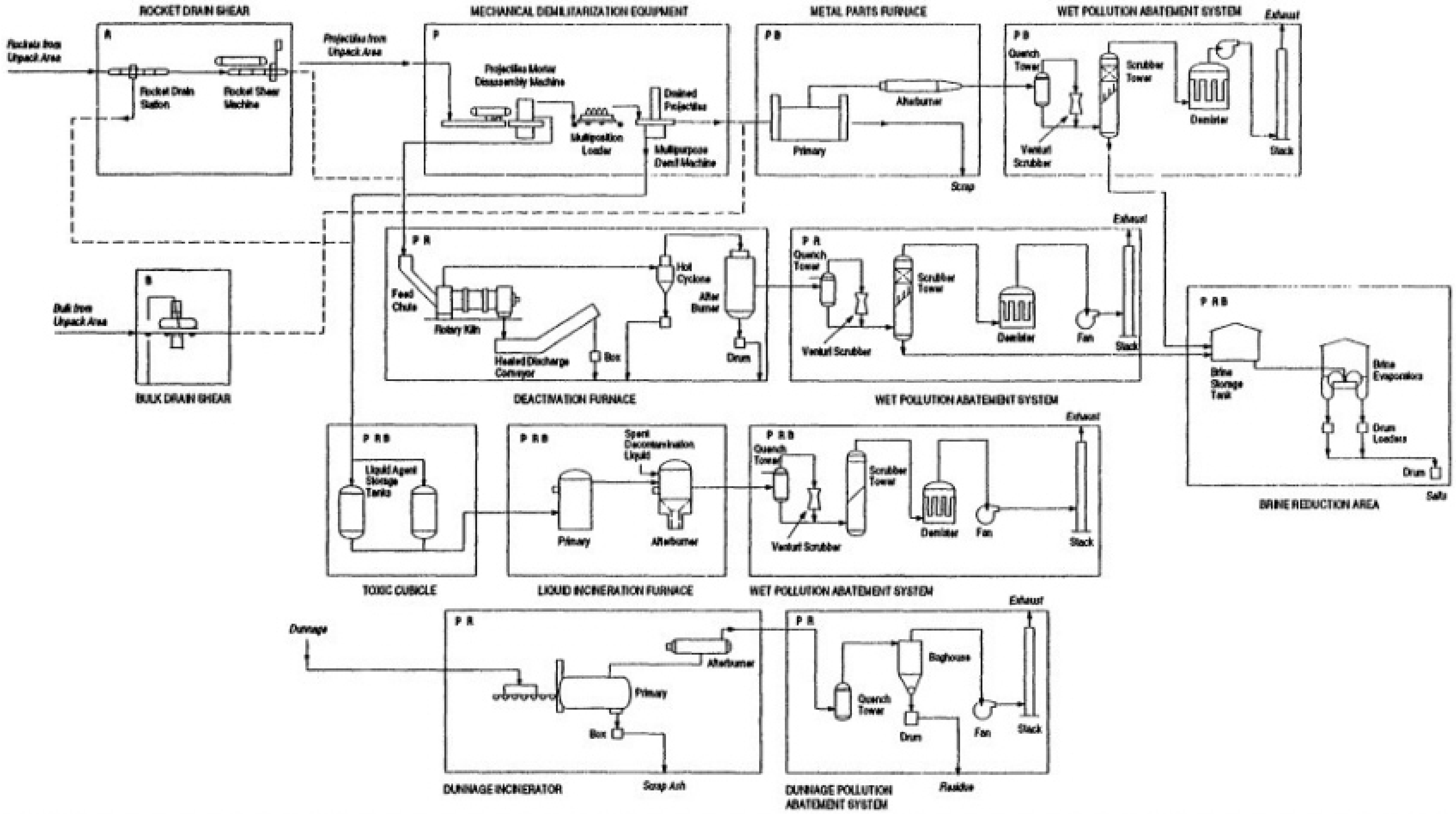

Figure 5-1 Schematic of the baseline technology.
Source: PEIS, 1988.

Disassembly and Draining

Munitions are moved into an explosive containment room that is maintained below atmospheric pressure (to prevent any leakage of agent) and is designed to withstand overpressures that might result from the explosion of munitions during processing. Ventilation air from this room is passed sequentially through six charcoal filter beds, with agent monitors after the first, second, and fourth beds. Agent traces were rarely found after the first bed and were never detected beyond the second bed throughout the OVT at JACADS.

Bulk storage containers are taken to a bulk drain station where they are punched and drained within a ventilated enclosure that also feeds to the charcoal bed filter banks.

Agent is removed from munitions and containers by automated machinery using one of two processes. Where possible, containers (M55 rockets, land mines, bombs, spray tanks, and ton containers) are simply punched and drained of agent. Heavy-walled steel artillery projectiles are disassembled to be drained of agent. Disassembly begins with removal of explosive elements in the case of armed projectiles. In all cases, mechanical extraction of a press-fit burster tube is the means to gain access to the agent. Agent drainage (and subsequent destruction) can be complicated by gelling or solidification of the material, particularly in the case of mustard, some of which then does not drain from the munition or ton container.

These operations result in three separate streams of material that are fed to specially designed destruction systems: an agent stream that is stored in a feed tank prior to injection into the liquid incinerator; a mixed stream of energetics, small metal components, and residual agent to be fed to the rotary kiln deactivation furnace system; and large metal parts (e.g., ton containers, spray tanks, artillery projectiles) with residual agent but no energetics, to be fed to the metal parts furnace. The separation of these three streams is an important safety feature of the baseline system. This provides the designer the freedom to tailor the design of each disposal system to the properties of the separate (and quite different) materials to ensure safe, controllable operations. As a result, most agent is treated in liquid form, separate from the energetics and metal parts. The energetics and metal parts, with only residual agent present, are then treated separately.

The only alternative to these baseline operations that has been considered extensively is the cryofracture process, in which assembled munitions are crushed after being cryogenically cooled in a liquid nitrogen bath. The resultant mixture of agents, energetics, and metal fragments is then fed, without separation, into a single rotary kiln, similar to but larger than the baseline deactivation furnace system. The Stockpile Committee has not recommended this process (NRC, 1989b, 1991a-c).

Agent Destruction

The drained agent at Tooele will be stored in a 500-gallon tank inside a room designed to contain toxic substances. The volume of agent storage has been greatly reduced at Tooele (by about a factor of 5 less than at JACADS) because of higher earthquake risks there. This tank represents the largest single volume of agent on-site. A larger emergency dump tank is also provided at Tooele but is not intended to be used for normal operations.

The liquid incinerator consists of two sequential combustion chambers and a pollution abatement system (discussed below). The first or "primary" combustion chamber is preheated to an operating temperature of 2700ºF with fuel before agent is injected. As agent flow increases, the fuel flow is decreased to maintain the desired temperature for effective agent destruction. Agent flow to the burner is stopped if this temperature drops below 2550ºF. Gases from the first chamber are sent to a secondary chamber, also preheated with fuel, for a final burn stage at 2200ºF. Some slag produced during nerve agent destruction was deposited on the lower-temperature walls of the secondary chamber. Spent decontamination fluid is also injected into the secondary chamber for destruction of any residual agent in the solution as well as for evaporation and discharge of the water. This fluid also contains salts that deposit in the bottom of the secondary chamber. The liquid incinerator had to be shut down periodically for manual removal of glasslike solidified salts. A better slag removal system is being developed to discharge molten salts during operation. Its effectiveness needs to be demonstrated during pre-agent testing at Tooele.

Energetics Destruction

Energetic materials (fuses, boosters, bursters, and solid rocket propellant) are burned in a counterflow rotary kiln (deactivation furnace system). Energetic materials are all contained in thin-walled metallic housings that must be punched or cut into pieces prior to burning, since confined energetics would detonate rather than burn in the kiln. M55 rockets, after being drained of agent, are sliced into seven pieces to expose enough energetic material surface area to allow burning without detonating. Draining and slicing both occur while the rocket is in its fiberglass launch tube. Bursters from artillery projectiles are similarly sliced after removal from the projectile. Explosive elements in land mines are punched in place to expose the explosive and are not removed from the munition. Properly exposed energetic elements, typically wetted with agent, are fed into the downstream end of the kiln (downstream in the sense of gas flow) in a controlled sequence to avoid excessive explosive concentrations within the kiln. Solid elements move upstream (against the gas flow) as the energetic materials burn and then exit onto an electrically heated discharge conveyor where their temperature is maintained at 1000ºF for 15 minutes. This results in a 5X decontaminated material that is suitable for release to the general public, although the mixture of light steel components, melted aluminum, and glass fibers is of no commercial value. Gases discharged from the rotary kiln pass through an afterburner where they are subjected to a temperature of 2200ºF for 2 seconds. These conditions are more stringent than those at JACADS (2000ºF for 1 second) and should allow the furnace to fully comply with removal efficiency requirements for destruction of polychlorinated biphenyls (PCBs). (Some fiberglass launch tubes contain small quantities of PCB.) The gases then are treated in the pollution abatement system described below.

Metal Parts Decontamination

Metal parts, drained of agent (ton containers, bombs, spray tanks, artillery projectiles and their burster wells, which were pulled to release the agent) are heated to 1000ºF and maintained at that temperature for 15 minutes in a fuel-fired metal parts furnace, producing 5X metal suitable for release as scrap. Residual or undrained (including gelled) agent that was not removed from these elements is vaporized and burned within the furnace. This process takes additional time and can limit the system's throughput. At JACADS, special procedures were implemented to allow increased quantities (over the design limit of 5 percent residual per projectile) of agent processing in the metal parts furnace. This procedure ensured compliance with the overall feed restriction contained in the Resource Conservation and Recovery Act permit. After successful testing and with proper monitoring and control, this is an acceptable practice, but the regulatory treatment of these conditions should be clarified so that waivers will not be required for operation.

Gases discharged from the metal parts furnace are passed through an afterburner, maintained at of 2200ºF, before being treated in the pollution abatement system described below.

Pollution Abatement Systems

The liquid incinerator, deactivation furnace system, and metal parts furnace employ identical and dedicated pollution abatement systems. Gases leaving the secondary chamber of the liquid incinerator or the metal parts furnace afterburner flow to separate dedicated pollution abatement systems for removal of gaseous pollutants and particles to meet emission standards. Hot gases leaving the deactivation furnace system kiln flow to a refractory lined cyclone that removes large particles (rocket launch tube glass fibers), enter the afterburner, and then flow to a similar pollution abatement system.

Each pollution abatement system consists of a quench tower, a venturi scrubber, a packed bed scrubber, a candle mist-eliminator vessel, brine or quench recycle pumps, and an induced draft (ID) blower. Figure 5-2 shows a schematic of a pollution abatement system.

The exhaust gas stream enters the quench tower near the bottom, where it is cooled by contact with a countercurrent spray of brine pumped from the packed bed scrubber sump. Acidic gases (e.g., hydrogen chloride, hydrogen fluoride, nitrogen oxides, carbon dioxide, and sulfur dioxide, depending on the chemical agent incinerated) in the exhaust gas react with caustic brine to form salts, which remain in solution in the brine. The cooled gas stream exits from the top of the quench tower and enters a variable throat venturi where it is scrubbed to remove particulates. The venturi uses a variable throat to maintain a constant pressure drop independent of the flow of exhaust gases. The brine streams from the quench and venturi scrubber are returned to the scrubber tower sump. Process water is added to the packed bed scrubber sump to make up for water evaporated in the quench tower. An 18 percent caustic (sodium hydroxide) solution is added as necessary to the sump to maintain the brine pH above 7.0.

The exhaust gas stream from the venturi scrubber enters the scrubber tower below the clear liquor reservoir tray, moves upward through the packed bed section, and exits at the top of the tower after passing through a mist eliminator pad. In the packed bed section, the gas stream contacts a brine solution flowing countercurrently through the bed. Acidic gases that remain in the exhaust gas stream are further scrubbed with caustic brine. The brine solution from the packed bed falls back to the reservoir tray and is recycled back to the top of the packed bed section. Excess brine overflows into the tower sump. Brine density is controlled by pumping a brine stream into the brine reduction area (BRA) storage tanks and replacing it with processing water.

The scrubbed gases enter a candle mist-eliminator vessel. Mist-eliminator candles (i.e., candle-shaped fabric filters) remove very fine mist and submicron particulate matter not removed in the venturi scrubber. The cooled and cleaned exhaust gases are pulled through an induced draft blower located downstream of the stack shared by the three furnace systems' pollution abatement systems.

Particulate emissions from the liquid incinerator, deactivation furnace system, and metal parts furnace were consistently low in tests at JACADS (the dunnage furnace was not tested). The mean for all trial burns for each incinerator was less than 5mg/m^3 at 7 percent dioxygen, with a maximum measured value of 10.9 mg/m^3. Permit requirement is less than 180 mg/m^3.

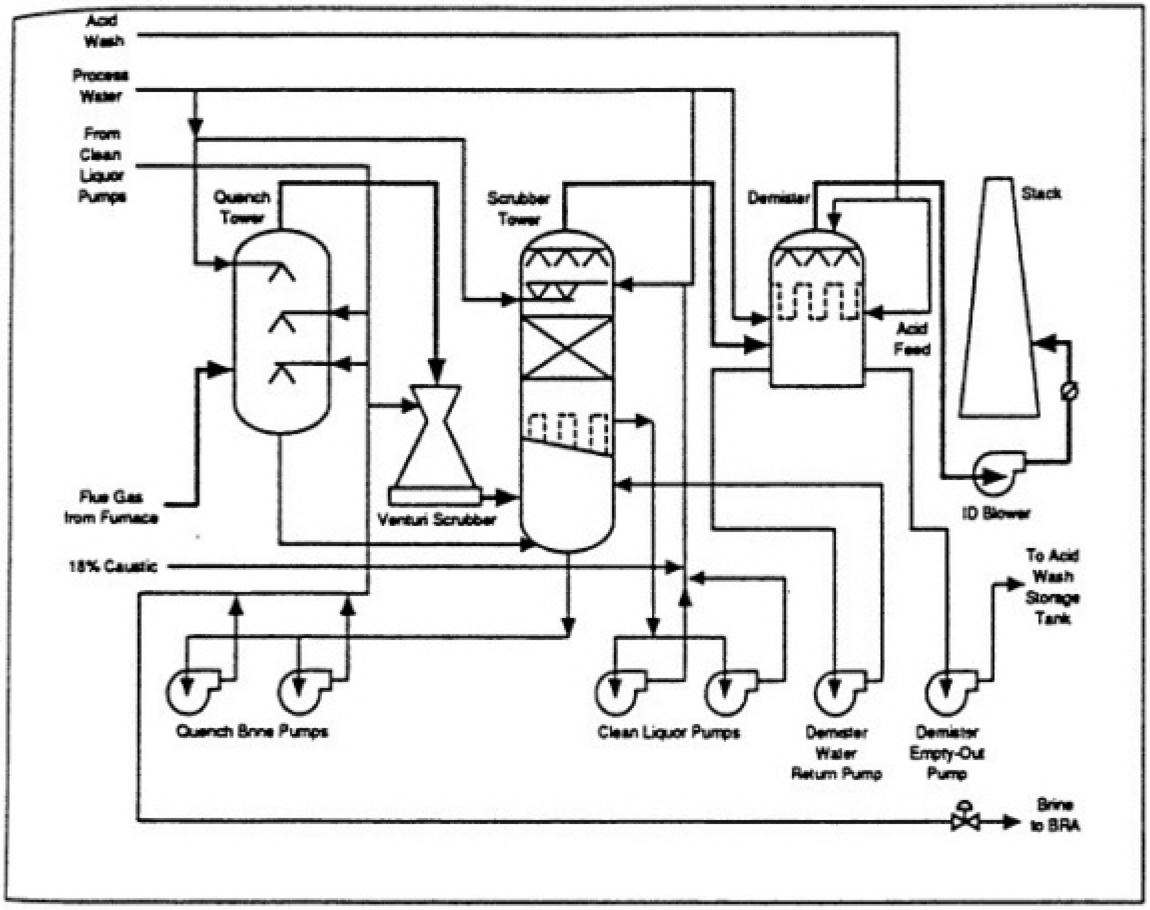

Figure 5-2 Schematic diagram of the pollution abatement systems.
Source: MITRE, 1993a.

Consequently, metal emissions (covered in Appendix VII of Environmental Protection Agency regulations) are extremely low, frequently below detectable limits.

Auxiliary Systems

The dunnage furnace and its pollution abatement system consist of a feed handling system, a primary chamber, an afterburner, a quench tower, a baghouse separator, an induced draft blower, and a separate exhaust stack. It is designed to burn noncontaminated and contaminated dunnage from the munitions processing operations, as well as charcoal and HEPA (high-efficiency particulate air) filter media from the air filters. Exhaust gases from the afterburner flow into the dunnage pollution abatement system quench tower. A water quench is used for cooling the exhaust gases, and a baghouse is used to remove particles. This pollution abatement system does not include acid gas scrubbing. The exhaust gases are maintained above the saturation temperature to prevent moisture condensation in downstream equipment. Gases exhaust to the atmosphere through a separate stack via the dunnage furnace induced draft blower.

To date, problems in demonstrating performance of this unit at JACADS have prevented incineration of most of the dunnage generated there. The alternative for JACADS has been disposal of decontaminated materials as hazardous waste. A dunnage incinerator is provided at Tooele and must be proven satisfactory, or else an alternative dunnage waste disposal strategy must be developed and proven prior to agent operations there. The Army has decided not to bum demilitarization protective ensemble suits (containing polyvinyl chloride) from Tooele operations in the dunnage furnace to avoid concerns about dioxins and furans.

The brine reduction area collects, stores, and evaporates discarded process brines and dries the salts produced by the three furnace pollution abatement systems. Operation of the brine reduction area produces salt that contains 10 percent or less water by weight. The brine reduction area consists of four subsystems: (1) steam generation (boilers) (2) brine evaporation (3) brine drying and, (4) pollution abatement. Entrained particles from the brines are collected in a baghouse before the exhaust is discharged to the atmosphere. The brine reduction area pollution abatement system consists of a heated, dual-module baghouse dust collection system. A fan pulls the exhaust gas through the baghouse modules prior to discharge to the atmosphere through a stack. A fuel-fired superheater heats the brine reduction area exhaust so that it remains above the dew point as it passes through the filters in the baghouse modules. The baghouse modules are equipped with a pulse air jet system to provide continuous cleaning of the bags. Solids accumulate in drums under the baghouse for packaging and storage prior to shipping for land disposal as hazardous waste.

The satisfactory operation of the brine reduction area was not demonstrated during the OVT. This must be done prior to agent operations at Tooele, or some alternative brine handling system must be developed and proven.

Agent Monitoring Systems

The agent monitoring systems to be installed at Tooele are the same as those in use at JACADS. There are two types of analyzers: (1) the ACAMS (Automated Continuous Agent Monitoring System), which is capable of detecting agent at concentrations well below those that present an immediate threat to plant personnel or the surrounding population, with 3-to-8 minute response time; and (2) the DAAMS (Depot Area Air Monitoring System) for collection of longer, time-averaged samples for more selective subsequent analysis in the laboratory. The ACAMS monitors in personnel areas and in the stack are set to give a warning alarm at 20 percent of permissible agent levels (Table 3-1). Plant operations are shut down upon an alarm at the 20 percent level. The DAAMS samples are analyzed for the much lower permissible general population levels (Table 3-1). Many ACAMS and DAAMS monitoring points are distributed throughout the facility at appropriate locations.

In the event of agent release, the ACAMS monitors provide alarms and automatic corrective actions such as stopping the processing of agent until the nature of the problem is determined. The DAAMS system serves the dual purpose of providing samples that are used to confirm or refute indications of the presence of agent from the ACAMS and of documenting any concentrations of agent at much lower levels of detection sensitivity. Both systems use the principle of drawing gas through a gas chromatograph equipped with a flame photometric detector. The detection of any agent present is interpreted by computer analysis.

These systems must be readjusted for each agent type. The ACAMS generates frequent false alarms because it cannot adequately differentiate agent from other commonly encountered organic contaminants (e.g., fuel contaminants, diesel exhaust, antifreeze). For example, during OVT4, there were 55 alarms suggesting that allowable stack concentrations had been exceeded during 151 days of testing. All were determined to be false positive alarms. Further, when an alarm sounds, the retrieval and laboratory analysis of the DAAMS collection tubes to verify conditions typically require half an hour or more. Frequent false alarms can make operators complacent and reluctant to stop operations, particularly when faced with production goals. At continental U.S. sites, such false alarms would erode public confidence in system safety.

The Stockpile Committee has prepared a special report on monitoring systems (NRC, 1994a), which recommends improvements to the Tooele system to allow more timely and agent-specific identification in the event of agent releases. The Army has begun development and testing of improved instrumentation.

BASELINE PERFORMANCE AT JACADS DURING OVT

To gain operational experience with the baseline system, and to confirm its ability to safely dispose of chemical agents and munitions, the JACADS facility was subjected to Operational Verification Testing, conducted in four campaigns (phases), from July 16, 1990, through March 6, 1993. The testing included a representative variety of munitions and containers and all three principal agents. The testing phases included

- OVT1—M55 rockets containing agent GB (7,490 destroyed over a seven month period);
- OVT2—M55 rockets containing agent VX (13,889 destroyed over a 19-week period);
- OVT3—Ton (bulk) containers of blister agent HD (67 destroyed over a 4-week period); and
- OVT4—105 mm M60 projectiles containing blister agent HD (18,949 destroyed over a 22-week period).

From the beginning of OVT, the MITRE Corporation, a not-for-profit corporation, was under contract to the Army to evaluate and report on each of the four campaigns (MITRE, 1991, 1992, 1993a, b) and to produce an overall OVT summary evaluation report (MITRE, 1993c). Based on these reports, its multiple visits to JACADS and other disposal sites, and its long-term study and examination of the baseline system, the Stockpile Committee evaluated OVT in two reports.

In July 1993, the Stockpile Committee issued a preliminary report: *Evaluation of the Johnston Atoll Chemical Agent Disposal System Operational Verification Testing: Part I* (NRC, 1993b). This report found that OVT "has provided additional assurance that the baseline system is capable of the safe disposal of the Army's chemical stockpile," and recommended that the Army initiate systemization of the almost completed Tooele Chemical Disposal Facility. Systemization will consist of a thorough testing of the plant using agent surrogates to ensure proper operation before beginning operations with agents. Additionally, the committee found that OVT identified some system deficiencies and indicated opportunities for improvements in operations and performance with regard to safety, environmental performance, and plant efficiency. The committee recommended that systemization at Tooele be used to implement these improvements prior to beginning the destruction of agent and munitions.

The Stockpile Committee has issued a more comprehensive follow-up report: *Evaluation of the Johnston Atoll Chemical Agent Disposal System Operational Verification Testing: Part II* (NRC, 1994b). This report details the committee's specific recommendations that should be implemented during the systemization at Tooele. For those recommendations requiring testing with agent (not possible yet at the Tooele facility), such as improved agent monitoring systems, testing can be conducted in parallel at JACADS or at the Chemical Agent Munitions Disposal System at Tooele.

The types of problems encountered during OVT show the importance of conducting full-scale demonstration tests on any complex prototype system to identify and correct any unanticipated weaknesses.

For example, during OVT, the lining of the liquid incinerator (LIC) deteriorated more rapidly than expected, requiring replacement with a more durable firebrick. Glassy slag accumulated in the secondary combustion chamber, and the system had to be shut down periodically for manual slag removal. A continuous system for molten slag removal has now been designed and will be tested during systemization at Tooele.

Other systems also encountered problems during OVT, requiring modifications to ensure safe operation. For example, several failures of munitions tracking systems allowed improperly processed munitions to be fed to furnaces. Also, unanticipated problems with gelled mustard required suited operators to perform tasks that were intended to be automated.

Some mishaps were indicative of deficiencies in training (e.g., operator errors, safety violations) or administrative procedures (e.g., poor recordkeeping, late incident reporting). These management issues are independent of the specific technology or system employed.

In the operation and maintenance of any complex system, safety is ultimately dependent upon effective management and trained operators. Public perception of the safety of a facility is heavily influenced by the performance and responsiveness of facility management. The OVT was important both because it revealed system and management weaknesses and because it demonstrated that management was generally able to respond to these incidents. Management's response has been a combination of equipment modifications, improved training for operators and maintenance personnel, and more realistic standard operating procedures.

In summary, though there were mishaps and mistakes during these startup tests, the multiple layers of safety designed into the facility avoided hazards to workers and to the surrounding community. There were no "showstopper" incidents during OVT. The Stockpile Committee, therefore, judged the baseline system capable of safe disposal of the chemical stockpile. As noted, the committee's second OVT report contains specific recommendations for improvements that can and should be made before destruction of agents begins at Tooele. These are discussed in the report by the Stockpile Committee, *Evaluation of the Johnston Atoll Chemical Agent Disposal System Operational Verification Testing: Part II* (NRC, 1994b).

The main recommendations from that report are as follows:

1. Give safety considerations priority over production goals.
2. Proceed with Tooele systemization, and during systemization, conduct needed testing and improvement activities, including the following:

- develop and demonstrate an improved agent monitoring and identification system;
- complete the brine reduction area and pollution abatement system performance tests, or develop a satisfactory brine disposal alternative;
- demonstrate the dunnage furnace performance with various levels of chlorinated waste; if needed, either modify the pollution abatement system design (e.g., add acid gas scrubbing) or limit feed materials to those that can be handled by the existing design (alternatively, satisfactory land disposal options must be' identified);
- review the probable levels of NO_x production from VX destruction and the allowable emission levels at the other continental U.S. sites requiring VX destruction; if appropriate, develop needed NO_x abatement systems;
- develop and demonstrate the proposed hot-slag removal system for the liquid incinerator system;
- eliminate furnace feed errors by improved monitoring and control of the deactivation furnace and metal parts furnace feed systems and by improved methods for tracking the various types of munitions; and
- address all problems associated with residual gelled mustard, in particular, the use of suited personnel to perform functions that were intended to be automated.

3. Establish and maintain close working relationships with permitting agencies, and support these efforts with careful analysis of operating parameters to ensure that permits provide for safe destruction of agent, adherence to regulatory requirements, and effective plant operations.
4. Establish programs, procedures, and management oversight to ensure continuing compliance with all environmental regulations.
5. Develop systems to improve overall management of safety.
6. Complete the risk assessment for the Tooele Chemical Disposal Facility during the systemization period.

Note that most of these recommendations are not specific to the agent destruction process.

The Stockpile Committee believes that the baseline system is fundamentally sound but that these improvements will provide worthwhile enhancement of the baseline system and will, if satisfactorily implemented, support safe and efficient operations at Tooele. This belief requires final confirmation after review of the results of the Tooele risk assessment.

As the first fully integrated baseline system, the JACADS facility was subject to startup problems, which would be the case for any complex system. As might be expected, these problems were often made more difficult by the remote location of the facility. Beyond these expected problems however, and as noted in its OVT reports, the Stockpile Committee believes that the Chemical Stockpile Disposal Program has been understaffed in view of the many major technical, regulatory, and public communications issues involved. This has led to administrative oversights and even to short-term technical modifications where longer-term solutions are necessary. If the program is now to include parallel efforts for alternative technologies, and if these alternatives are to be aggressively pursued, overall program staffing must be significantly increased.

6

Comparison of the Baseline System and Alternative Technologies

INTRODUCTION

This chapter compares candidate alternative technologies to the baseline for the purpose of identifying those that can reduce the total cumulative risk to the public and the environment from stockpile storage and disposal operations. As a basis for comparison, the screening and selection criteria mentioned in Chapter 4 are expanded in the next section.

A large number of potential alternatives were considered, which are presented later in the chapter, and have been taken directly from the report *Alternative Technologies for the Destruction of Chemical Agents and Munitions* (*Alternatives* report, NRC, 1993a). In that report and here, alternatives are conveniently grouped in six categories: low-temperature, low-pressure detoxification; low-temperature, low-pressure oxidation; moderate-temperature, high-pressure oxidation; high-temperature, low-pressure pyrolysis; high-temperature, low-pressure oxidation; and other technologies. Many of these technologies are, or can be, developed for safe disposal of a variety of hazardous materials in general. However, it was necessary for the committee to use engineering judgment in developing its recommendations for promising alternatives for the very special requirements of this disposal program. In addition to the necessary fundamental process capabilities, and in keeping with the committee's desire to minimize cumulative total risk, technology readiness becomes an important selection criterion. Promising technologies that require extensive research and development programs are unlikely to be of use to this program.

The section on agent destruction processes examines the candidate alternatives at two levels. A first screening is used to eliminate unattractive candidates, with brief comments in this report. For more detailed discussion of these technologies, the reader is directed to the *Alternatives* report. The second-level examination discusses in greater detail those alternatives that are considered attractive. Appendixes D, E, and F are provided for background on these technologies.

No single technology, including incineration, can meet all criteria with a single process. The committee recommends further study of four alternative technology combinations for agent destruction, all based upon neutralization of the agent as a first step. In addition, an "enhanced" baseline system is discussed. The issues involving handling of gelled agent as an impediment to all technologies that are designed to transfer or treat liquid materials are discussed after the alternative technologies have been presented.

The section on metals, energetics, and dunnage disposal describes why the committee could not identify feasible alternatives to baseline system for disposal of metal parts, energetics, or dunnage. Consequently, the remainder of the chapter focuses largely on alternative technologies for agent destruction, as have virtually all calls for alternative technologies. Successful alternatives will thus impact disposal operations only as replacement for the liquid incinerator.

All neutralization processes must be followed by secondary treatment to meet both environmental and treaty disposal requirements. This raises the option of transporting the relatively nontoxic neutralized material to another site for secondary treatment. This option may offer economic as well as safety advantages.

The chapter concludes with a section that estimates the time necessary to implement the recommended options.

BASES FOR SELECTING ALTERNATIVE TECHNOLOGIES

In Chapter 4, five criteria are listed as the bases for selecting disposal technologies. The first of these, safety, in the form of minimum cumulative total risk to workers, the public, and the environment is the principal criterion. The other four criteria all relate to the technical capabilities of the candidate technologies.

Safety

In the absence of detailed quantitative risk assessments of the alternative technologies it is necessary to consider the safety information that *is available* in some systematic and orderly form. In particular, the following safety factors were considered in reducing the number of potential technologies to those four on which specific findings and recommendations are made.

Inherent Safety Features

Obviously the objective in the design of any system is a facility that is inherently safe. Conditions that contribute to inherently safe systems are low temperature and pressure; simplicity in design; nontoxic effluents (gases, liquids, solids); and simple operations and maintenance.

Requirements for Engineered Safeguards

Facilities for processing and handling hazardous materials require engineered systems to ensure safety of operation. Such safeguards might be containment systems, effluent cleanup systems, fire suppression systems, emergency power sources, and specially designed systems for the control and mitigation of accidents.

Risk Potential

The two types of risk that were considered in the technology screening process included (1) the risk from accidents and operational upsets, and (2) the risk from normal facility operations in terms of the health and safety impact of waste streams.

Process Readiness

Process readiness involves time for process development, engineering and construction requirements, and startup and early operations. As discussed in Chapter 4, time is an important safety issue because disposal delays can adversely affect the cumulative total risk. Process readiness and time are also economic issues, in terms of research and development costs and extended storage costs, but these are of lesser concern than safety. Typical industrial development components are preliminary process design, bench scale testing, and pilot plant testing. The pilot plant phase can include design specifications, facility design modifications, procurement of equipment, and permits. The engineering and construction phase includes design specifications, final process design, and preliminary and final facility design, while obtaining permits and gaining public acceptance. Startup and operations include training; systems integration, testing, and checkout; and operational verification testing.

Technical Capabilities

Principal considerations in assessing a candidate technology's capabilities are the treatment of process materials, environmental impacts, and treaty compliance. Multiple materials must be processed, including agent (three types), energetics, metal parts, and dunnage. Successful technologies, or combinations of technologies, must produce environmentally acceptable waste products (gaseous, liquid, and solid) suitable for final disposal. Treaty compliance issues are the irreversibility of the agent destruction process and the schedule for completion of disposal operations.

LISTING OF ALTERNATIVES

The Committee on Alternative Chemical Demilitarization Technologies' *Alternatives* report presented a structured listing of potential alternative technologies and a detailed discussion of each. That listing (slightly amended by the Stockpile Committee) is repeated here as Table 6-1. Each of these technologies is then discussed briefly for preliminary selection, followed by a more detailed discussion of those technologies to be recommended for further development.

INITIAL SCREENING OF AGENT DESTRUCTION PROCESSES

Evaluations of Destruction Processes

All of the technologies of listed in Table 6-1 were evaluated, based on the preceding selection considerations. The evaluations are summarized below. Many of these technologies have been developed and will find application for ordinary industrial wastes. However, most were ruled out for the very special materials of interest here, (i.e., chemical agents or munitions). Only four are recommended for development.

Low-Temperature, Low-Pressure Detoxification

Several processes have been suggested for chemically altering the agents to render them nontoxic. The products in all cases would not be acceptable for immediate disposal, but would require further treatment. These processes therefore represent the first step of a multistep destruction system.

TABLE 6-1 Summary of Process Capabilities and Status

	Stream Treated							
	Agent			Metal and Energetics				
Process	Initial Agent Detoxification	Complete Organic Oxidization	Afterburner Needed	Energetics	Metal	Afterburner Needed	Next Step	Comments
Low-temperature, Low-pressure detoxification								
Base hydrolysis (NaOH)	GB, VX	No	?	No	No	N.A.	PP	Has been used in field; for HD, limited by contacting problems
NaOH + H_2O_2	VX	No	Yes	No	No	N.A.	Lab	New finding
$Ca(OH)_2$ (at 100°C)	HD	No	?	No	No	N.A.	Lab/PP	Limited use in England
KOH + ethanol	HD, GB, VX	No	?	No	No	N.A.	Lab	
Hypochlorite ion	HD	No	Yes	No	No	N.A.	Lab	Difficult contacting problem with HD
Organic base (ethanolamine)	GB, HD, possibly VX	No	?	No	No	N.A.	Lab/PP	Limited use in Russia; increase in organic waste
Acidic systems								
HCI hydrolysis	GB	No	?	No	No	N.A.	Lab/PP	
Peracid salts (Oxone, others)	VX, perhaps GB and HD	No	Yes	No	No	N.A.	Lab/PP	Increased waste
Chlorine	VX, perhaps GB and HD	No	Yes	No	No	N.A.	Lab/PP	Increased inorganic waste
Ionizing radiation	All	No	?	Yes?	Yes?	?	Lab	High conversion not yet established

	Stream Treated							
	Agent			Metal and Energetics				
Process	Initial Agent Detoxification	Complete Organic Oxidization	Afterburner Needed	Energetics	Metal	Afterburner Needed	Next Step	Comments
Low-temperature, low-pressure oxidation								
Peroxydisulfate, ClO_2, H_2O_2, O_3	All	Yes	Yes	No	No	N.A.	Lab	Catalysts generally needed for complete conversion; spent peroxydisulfate can he electrochemically regenerated
UV light with O_3 or H_2O_2	N.A.	Yes	Yes	No	No	N.A.	PP	Very large power requirement; applications have been for very dilute solutions
Electrochemical oxidation	All	Yes	Yes	No	No	N.A.	Lab	
Biological oxidation	N.A.	Yes	Yes	No	No	N.A.	Lab	
Enzyme-catalyzed hydrolysis[a]	GB Possibly VX; not mustard	No	Yes	No	No	N.A.	Lab	
Moderate-temperature, high-pressure oxidation								
Wet air and supercritical water oxidation (SCWO)	All	Partially	Yes	Yes?	No	Yes	PP	Residual organic components can be low for SCWO; residual materials are believed suitable for biodegradation

	Stream Treated							
	Agent			Metal and Energetics				
Process	Initial Agent Detoxification	Complete Organic Oxidization	Afterburner Needed	Energetics	Metal	Afterburner Needed	Next Step	Comments
High-temperature, low-pressure pyrolysis								
Kiln (external heat)	All	Partially	Yes	Yes	Yes	Yes	Demo	May need more than one trait to deal with all streams
Molten metal	All	No	Yes	Yes?	Yes	Yes	PP	
Plasma arc	All	No	Yes	Yes?	Yes	Yes	Lab/PP	
Steam reforming	All	Yes	Yes	No?	No	Yes	Lab/PP	
High-temperature, low-pressure oxidation								
Catalytic, fixed bed	N.A.	N.A.	N.A.	No	No	No	Lab/PP	Useful for afterburner
Catalytic, fluidized bed	All	Yes	Yes	Yes	No	Yes	PP	
Molten salt	All	Yes	Yes	Yes?	No	Yes	PP	Possible use for afterburner and acid gas removal
Combustion	All	Yes	Yes	Yes	Yes	Yes	—	Baseline technology
Other technologies								
Hydrogenation	All	No	Yes	No	No	No	Lab	
Reactions with sulfur	All	Yes	Yes	No	No	No	Lab	

NOTE: Question mark (?) indicates uncertainty about the noted application; N.A., not applicable; PP, pilot plant; demo, demonstration; lab, laboratory.
SOURCE: NRC, 1993a.

[a] The Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program added this information to the original Table, found in the 1993 report, *Alternative Technologies for the Destruction of Agents and Munitions*, NRC, 1993a.

The mild operating conditions—low temperature and pressure—are an attractive feature of these processes. There is little likelihood of large accidental release, and the formation of toxic gases is usually not a problem. The processes do generate a large volume of liquid solution, and in some cases this is a major handicap.

Chemical "neutralization" (or hydrolysis) is possible with any of several reagents. The most commonly used have been bases, such as sodium hydroxide, potassium hydroxide, calcium hydroxide, and ethanolamine (hydrolysis or solvolysis), and oxidizers such as sodium hypochlorite. See Appendix E for details. Neutralization of GB has been carried out on a large scale. Its application to VX and to HD has been held up by problems: both materials have limited water solubility; reaction rates have generally been slow; and some products of VX can themselves be highly toxic. However, a recent research program of very limited scope has already shown promising results for both VX and mustard, using hot (75-90º) alkaline hydrolysis. This work is described in detail in Appendix F. Much remains to be done to prove a full scale system capable of treating field-grade materials, including gelled mustard. Given proper support, this approach may well provide an effective alternative within a schedule compatible with minimum overall cumulative risk.

An advantage of neutralization with bases (exception—ethanolamine) is that no "additional" chemical material is added to the overall system; the bases are ultimately required to form salts with the acidic products of agent oxidation (i.e., NaCl, NaF, Na_3PO_4) that are acceptable for disposal.

Hydrolysis is also possible by use of acids, such as hydrogen chloride. The acidic solution has two disadvantages: (1) it is corrosive, and (2) the acid must ultimately be neutralized to form additional salts, which add to the solid waste from the process. Acidic hydrolysis appears unattractive compared with basic hydrolysis.

Low Temperature, Low Pressure Oxidation

Several reagents have been proposed for both hydrolysis and either partial or complete oxidation: hypochlorite, peracids such as oxone ($KHSO_5$), potassium persulfate ($K_2S_2O_8$), and other oxidizing agents such as hydrogen peroxide or chlorine oxide. Little experimental work with agents or surrogates has been done.

Potassium persulfate, a very strong oxidizing agent, is believed capable of completely mineralizing the agent. A very large amount is required however, leading to a large increase in the waste material to be handled—sulfuric acid or potassium sulfate solution diluted with the acidic products of the oxidation (HCl, H_3PO_4, etc.; see Appendix E). Recycle of the sulfuric acid is complicated by the presence of these other acidic materials. The persulfuric acid reagent is made electrolytically. The amount required would represent a large power consumption for the agent destruction (see discussion of electrochemical oxidation, below) The persulfate oxidation has been considered unattractive for this application.

The other oxidants are not strong enough to perform complete mineralization; a follow-on oxidation process would be required. At the same time, some of them complicate the process by adding to the final volume of solid waste. They are not considered sufficiently attractive to pursue. One oxidant, hydrogen peroxide, is under investigation as an aid to caustic neutralization (of VX).

Ultraviolet light with ozone or hydrogen peroxide and a catalyst (TiO_2) is another oxidizing system evaluated by the Alternatives Committee. However, it appears best suited for removal of trace quantities of contaminants. Bulk destruction on a large scale has not been attempted and appears to have severe limitations, including a large photon requirement and the low penetration of ultraviolet light into the reaction mixture.

Ionizing radiation has been suggested, but it is believed to be at an early research phase, with many problems anticipated.

Electrochemical oxidation has been proposed for many chemical reactions. Complete oxidation requires a very active catalyst; Ag(II) has been proposed. It also has a large power requirement—estimated at close to 1 megawatt for 24 hours, to mineralize 1 ton of GB. The process has serious disadvantages for agents because of their heteroatom content (Cl, F, P, and S), which greatly complicates recycle of the electrochemical agents (as in the sulfate/persulfate cycle). The committee believes that this process is not ready to handle agents; a substantial research and development effort would be required.

The committee considers biological oxidation to be an unlikely candidate for neat agents. No biological material has been found that is resistant to mustard, for example. A more likely application of biological oxidation is as a second step following initial detoxification of the agent. The committee has considered it for oxidation of the products of caustic neutralization or the products of wet air oxidation (see Appendix F for a more detailed discussion).

Finally, enzyme-catalyzed biological hydrolysis of nerve agents may be possible. Proof of concept has been demonstrated for GB on a laboratory scale. Hydrolysis of VX has been observed but currently at reaction rates too slow for practical application. The time required for development of enzymes with increased activity for VX is not predictable because of the nature of the basic research required. Similar enzyme-based processes for *both* GB and VX would have to be available for practical application to the stockpile configuration. Therefore, engineering development appears premature. Traditional biological oxidation processes (analogous to wastewater treatment processes) would not be appropriate for direct detoxification of GB or VX because of the extremely high destruction efficiencies required. No biological process has been found that is directly applicable to mustard. Discovery of such a process for mustard is extremely unlikely because of its general xenobiotic characteristics.

Moderate-Temperature, High-Pressure Oxidation

Two related processes are listed in Table 6-1: wet air oxidation and supercritical water oxidation.

Both processes are capable of destroying neat agent. They are both, however, high-pressure processes, operating at 2,000 to 4,000 psi (pounds per square inch). The committee questions the safety of handling toxic agent at this pressure.

Both processes are subject to severe corrosion problems because of the release of strong acids in the oxidation process, such as hydrogen fluoride (HF) and hydrogen chloride (HCl). Corrosion might be handled by very special materials of construction. Alternatively, it could be controlled by addition of caustic to neutralize the acids formed. If the latter approach is taken, the processes appear particularly suitable for cleanup of the products from caustic neutralization (discussed above). The neutralized material is in dilute aqueous solution and already contains excess caustic, conditions that would avoid the acids that cause corrosion. More detailed reviews of these two processes are provided in Appendix D.

High-Temperature, Low-Pressure Pyrolysis

Several pyrolysis processes developed for other applications have been suggested for chemical agents. All produce combustible gases at high temperature, which would then require the same kind of gas clean-up used in the baseline system. That is, they would be burned in an afterburner and then scrubbed of acidic material before release. These new processes would therefore replace only the first stage, the liquid agent incinerator, in the baseline system.

The molten metal furnace not only pyrolysis the agent but also should react some of the heteroatom materials in the metal or slag. There seems little question that the destruction process should be rapid and complete. However, it does not appear to offer a significant advantage over the current process, since a similar afterburner and gas scrubber will be required. As a consequence, the committee does not recommend a development program to demonstrate the process on agent.

The plasma arc furnace appears to be in the same category with molten metal. That is, it produces a combustible gas, which will then require the same follow-on equipment as the baseline system. As a result, it does not offer a significant advantage over the current incinerator design.

Several steam reforming gasification processes were reviewed: a synthetic process for waste destruction and several steam gasification processes for production of a synthesis gas. All can be expected to have trouble with the larger heteroatom content of the chemical agents. All will require follow-on steps resembling the baseline system (afterburner, gas scrubber). As a consequence, the committee judged them not to offer significant advantages over the baseline system.

High-Temperature, Low-Pressure Oxidation

The committee evaluated three alternative combustion processes.

Catalytic fixed-bed oxidation is applicable only to low concentrations of agent in air, well outside the normal flammable range, where a catalyst is needed. The process does not appear suitable as a result.

Fluidized-bed combustion, uncatalyzed or catalyzed to aid nitrogen oxides (NO_x) destruction, is a reasonably established process. As with other processes, it could replace the liquid incinerator but would require the rest of the baseline system. The committee judged it as not offering a significant advantage over the baseline.

Molten salt is a promising technology that can combine combustion with acid gas removal in one unit. Combustion reactions in molten salt have been demonstrated to produce high rates of conversion from feed material to oxidation products. However, the long-term mechanical operability of the process appears difficult: a considerable development effort would be required. In addition, the committee judged that to apply this technology to highly toxic materials, an afterburner and gas scrubber would still be required. It thus does not appear to offer sufficient advantage over the baseline incinerator to justify the development time required.

Ordinary high-temperature, low-pressure combustion, as in incineration, also fits in this category, but not as an "alternative" in the present sense. It is capable of mineralizing dunnage, agents, and energetics, but must be followed by an afterburner and proper pollution abatement systems to meet environmental requirements.

Other Technologies

The committee evaluated two technologies that did not fit the categories listed above.

Hydrogenation has been recommended by its proponents as a process for recovering useful chemicals, primarily fuels, from wastes. This process depends on suitable catalysts. Chemical agents, with their large content of heteroatoms would require a long-term development effort. As a consequence, the committee did not consider this alternative further.

An entirely different approach is the reaction of waste material with sulfur. The process has many interesting aspects. For instance, the major product is a hard, black solid, consisting primarily of carbon and sulfur, with uncertain composition. The process appears to be in an early research and development stage, with uncertain chemistry and possible mechanical problems, such as fine dust formation. The committee judged it not sufficiently mature to be recommended for agent destruction.

Alternative Processes Recommended for Further Research and Development

Although no single process, including incineration, can do the entire job of agent destruction and waste treatment, several combinations of processes deserve further study as alternatives to the liquid incinerator and follow-up components of the baseline system. The four most promising alternatives to destroy liquid agent are based on neutralization as an initial step.

Neutralization is an attractive approach because it operates at low temperature and atmospheric pressure in conventional chemical reactors (Appendix E). However, it is a limited technology that merely converts agents to less toxic products, rather than "mineralizing" them or destroying them as required by the 1993 Chemical Weapons Convention. To replace a liquid incinerator completely, it is necessary to follow neutralization with a process such as wet air, supercritical water, or biological oxidation that irreversibly destroys the products of neutralization. Although these combined processes offer no advantage in destroying energetics or in decontaminating agent-bearing metal parts, neutralization-based systems, with suitable posttreatment, can replace the liquid incinerator. They are, therefore, of particular interest where agent is stored only in bulk.

There are several neutralization-based combinations of processes that are potentially useful for destroying blister and nerve agents. The most promising integrated systems, in the committee's judgment, are described below.

- Neutralization can be followed by incineration of the hydrolysis products, either on site or after being transported to another site equipped with a liquid incinerator. If the neutralization products are to be transported to another site, a high hydrolysis efficiency will be required.
- Neutralization can be followed by wet air oxidation. This approach is attractive because wet air oxidation is a well-developed technology and can utilize a feed stream that is less completely hydrolyzed than would be needed for transportation. Because the wet air oxidation products would be water streams containing much organic matter (but little or no agent), a subsequent treatment for water-borne organics, such as conventional biological oxidation, would be required.
- Neutralization followed by supercritical water oxidation resembles the preceding option. However, as a consequence of the severe reaction conditions of supercritical water oxidation, it may yield a completely mineralized water stream without follow-up oxidation. In contrast to wet air oxidation, however, supercritical water oxidation is not a proven commercial technology. The utility of an agent destruction system based on supercritical water oxidation depends on successful outcomes of current research programs.
- Neutralization followed by biological treatment would operate under mild process conditions throughout the system and might yield products directly suitable for disposal. Development would require modified neutralization processes and identification of organisms or enzymes adapted to the hydrolysis reaction products from each type of neutralized chemical agent.

These integrated systems are discussed in more detail below. Although many other combinations of processes could yield useful integrated technologies, the four systems listed offer the greatest prospects for success. The Stockpile Committee urges aggressive research and development to evaluate the applicability of these integrated systems.

Neutralization—Incineration Systems

For the two arsenals that store only bulk agent, a system based on neutralization followed by incineration may be uniquely advantageous. In principle, the liquid agent (HD or VX) drained from ton containers can be detoxified by chemical hydrolysis. Treatment of mustard with aqueous sodium hydroxide at 90ºC produces a water solution of thiodiethanol, sodium chloride, and a mixture of thioethers. Early laboratory results indicate that treatment of VX with sodium hydroxide and hydrogen peroxide converts the agent to phosphonic and sulfuric acid derivatives of greatly reduced toxicity. Neither the HD nor the VX products, however, meet the irreversibility requirement of the Chemical Weapons Convention. This problem can be addressed by feeding the products to a liquid incinerator much as is done with decontamination fluids in the baseline system. Incineration achieves complete mineralization of the organic products.

A potentially attractive application of this approach might avoid incineration facilities at Aberdeen and Newport. To accomplish this goal, it will be necessary to

- achieve a high degree of hydrolytic destruction of agent in the neutralization step;
- obtain permission from other states to transport, store, and burn the neutralization products; and
- develop methods to decontaminate the drained ton containers to the extent that the metal can also be transported for thermal treatment at another site or deposited in a hazardous waste landfill.

If these requirements can be met, the neutralization-incineration system has the potential to be implemented rapidly at the two sites, probably with less capital investment than the baseline system would require. It will offer little advantage elsewhere except as a way to reduce the hazard of bulk agent storage prior to incineration.

On-Site Treatment of Products of Neutralization

As detailed previously, the "neutralization" process yields reasonably nontoxic products, which, however, are complex organic materials unsuitable for immediate disposal. Further oxidation is required, particularly for complete mineralization. Three processes have been recommended for further development:

1. wet air oxidation,
2. supercritical water oxidation, and
3. biological oxidation.

The operating characteristics, capabilities, and limitations of wet air oxidation and supercritical water oxidation are reviewed in Appendix D. Both are capable of oxidizing neat agent. Because both are high-pressure processes (1,000-2,000 psi for wet air oxidation; more than 3,200 psi for supercritical water oxidation), it is the committee's judgment that a neutralized-agent feed to either process is much preferred to the agents themselves as the process feed.

The combination of neutralization followed by one of these three alternatives is synergistic:

- The product from neutralization is a fairly dilute aqueous solution of organic material; it is the form required as feed to any of these processes.
- Corrosion is expected to be a problem with wet air oxidation and supercritical water oxidation (see Appendix D for details). This problem is minimized by the addition of caustics to neutralize the acids (HCl, HF, etc.) produced by oxidation. The excess caustic required for corrosion control can be added during neutralization to drive that process.
- Biological processing of neat agent may be impractical for nerve agents (GB, VX) and impossible for mustard agents (H, HD, HT). No process for mustard is known, but enzymatic hydrolysis has been demonstrated for the nerve agents (see Appendix F for details). Bioprocessing of the neutralized agents, however, appears more promising.

Research and development will be needed for each of these processes. Some important problems have been identified that require engineering solutions, for example:

- Materials of construction for wet air oxidation and supercritical water oxidation, capable of handling the corrosion problems, require further work (Appendix D).
- The salts formed by caustic addition are insoluble in the fluid phase in supercritical water oxidation: "plugging" problems caused by these salts have been a concern.
- Operating requirements will have to be determined to ensure that the products meet environmental standards.

Other problems will arise as the technologies—neutralization followed by an oxidation step—are integrated into an operating system.

Wet air oxidation is the most developed of the three oxidation processes. However, although it is capable of breaking down the chemical agents, it produces intermediate products that are refractory and persist in the product stream. The intermediates, partially oxygenated materials such as acetic acid or methylphosphonic acid, can represent 2040 percent of the carbon in the feed. As a consequence, the product solution from wet air oxidation will need further processing. This final treatment is usually done in commercial wet air oxidation processing by biodegradation. The agent destruction will then require a three-step process: neutralization, wet air oxidation, and bioprocessing.

The three oxidation processes offer other advantages in addition to their natural synergism with neutralization:

- They can all be operated with oxygen (or air highly enriched in oxygen) instead of air. They thus have the potential of being operated as "closed-cycle" systems. That is, the gaseous product can be reduced to a small enough volume that it can be conveniently stored for analysis before release to the atmosphere.
- The carbon dioxide normally produced can be largely collected as additional salt (sodium carbonate) by excess caustic. This has a further benefit for a closed-cycle system (as defined above), but results in a large solid waste stream.

Gelled Agent

Occurrence of gelled HD is common, as discussed in Chapter 3. Gelling has also been observed in GB. The gel and other solids do not drain completely. Containers with a major "heel" of undrained material will be very difficult, if not impossible, to decontaminate by nonthermal processes. A process for gel removal will be needed if metal parts, decontaminated to 3X, are to be shipped to another location. Some possibilities are

- chemical treatment to depolymerize the gel;
- use of high-pressure water jets to wash out gel; and
- moderate heating (˜300ºF) plus steam purging to distill agent, which can be recondensed in a closed system for routine processing with liquid agent.

METALS, ENERGETICS, AND DUNNAGE DISPOSAL

Energetics Treatment

Energetic materials cannot be safety disposed of in their existing state. They must be "deactivated" as are explosives and propellants from ordinary, nonchemical munitions. This has normally been done by burning the materials. Propellants and explosives are formulated to burn spontaneously, though not completely. They are fuelrich: additional oxidant (air) is needed to complete their combustion. Furthermore, care must be exercised to ensure that they burn rather than detonate, principally by avoiding confinement of the burning materials. The baseline components for disposing of these materials—slicing or punching containers to avoid confinement, and burning in a rotary kiln followed by an afterburner and gas scrubber—has been effective. Indeed, the baseline deactivation furnace system is a scaleup of the

Ammunition Peculiar Equipment (APE) rotary kiln in successful use for many years to dispose of conventional munitions.

Many of the technologies listed in Table 6-1 are capable, in terms of chemical reactions, of destroying (mineralizing) the energetics in the chemical stockpile. However, physical extraction of cast-in-place bursters and propellants from their metal housings and conversion to finely divided slurries that could be fed to these processes would be difficult and perhaps hazardous.

A Joint Services Large Rocket Motor Disposal Program has been undertaken to explore environmentally acceptable alternative means for large rocket motor demilitarization to replace open burning and detonation (DOD, 1993). The program includes two research goals: removal of the propellant from its containers, and disposal or reclamation of the propellant. Propellant removal options were mechanical excavation, and high-pressure liquid jet excavation using water or liquid nitrogen (the latter, in a conceptual stage, for subsequent reclamation of the propellant and to avoid a liquid waste stream). Although feasible for large containers, all options were judged by program researchers to be unlikely means to excavate explosives from a long, small-diameter cavity such as a burster tube.

Reclamation techniques are of no interest for propellants and explosives contaminated with agent. Disposal techniques ranged from conventional two-stage combustion followed by exhaust gas cleanup (including an enhanced version of the APE kiln) to biodegradation. The latter, having shown some experimental promise in treating highly diluted "pink water" propellant solutions, is in an early experimental stage and would require even further research to treat agent-contaminated solutions.

Wet air oxidation and supercritical water oxidation are under consideration in that program and could destroy the energetics effectively if the materials are properly prepared for a slurry feed (see Appendix D regarding limitations of these technologies). Development work would be needed to demonstrate extraction and preparation systems for chemical munitions, as well as the subsequent oxidation process. Because effluent treatment and waste products are similar to those for the baseline system, there would appear to be no safety advantage over baseline system (and possibly a disadvantage in view of the more complex preparation processes).

All of the high-temperature pyrolysis processes and most of the high-temperature oxidation processes are capable of destroying the energetics. None appears to offer any significant advantage over the baseline system, however. All would require an afterburner to complete oxidation, followed by a gas cleanup system. Waste production would be the same as baseline, with no apparent increase in safety.

Molten salt is claimed to perform a very complete oxidation so that secondary combustion is not needed. Although this may be generally true, the highly unsteady discharge from energetics reactions, coupled with significant agent contamination, dictates secondary combustion for safety in this case.

Other technologies such as hydrogenation of energetics and sulfur oxidation are judged to be at very early research and development stages and are not applicable to this program.

Metal Parts Decontamination

Virtually all metal parts will be contaminated with agents, and some may contain significant amounts of gelled agent. No alternative to high-temperature treatment (1000ºF for 15 minutes) has been proven to render metal parts safe for release to the public (the 5X condition). The baseline system uses a fuel-fired metal parts furnace to provide this treatment for large metal parts and an electrically heated discharge conveyor for treatment of solids emerging from the deactivation furnace system. Many of the oxidation and pyrolysis processes are capable of detoxifying metal parts to this condition, but they are not suited to metal parts feed, especially large metal parts such as ton containers. Low-pressure processes such as molten metal, plasma arc, and steam reforming could in principle handle intermittent feed, but they offer no improvement in safety or waste products over the baseline system.

The use of electrical power, rather than combustion of fuel, to provide heat in the first stage of the metal parts furnace would reduce the flue gas generated by this system. Gases discharged from this first stage would still require an afterburner and gas cleanup system, just as in the present baseline system.

Chemical decontamination of metal parts to the 3X level for transport to another facility or for disposal in a hazardous waste landfill remains an attractive alternative if the transport option is available and if gelled agent problems can be overcome.

Dunnage Disposal

Dunnage includes wood, paper, and other ordinary industrial waste materials. Most dunnage is not contaminated with agent, but some is, and all must be handled as if it is. Disposal of this waste must therefore safely process some agent as well as a mixture of typical industrial materials. Because the dunnage incinerator has not yet been proven at the Johnston Atoll Chemical Agent Disposal System (JACADS), dunnage from that operation has been packaged (after being decontaminated to 3X) for disposal at a hazardous waste landfill. Alternatives to acceptable incineration or landfill are not evident.

Landfill works, but it may not be a satisfactory solution for the disposal program as a whole. The volume to be processed over a period of years, as well as the mixed nature of this stream, makes a waste reduction process highly desirable. The most efficient of these is reduction by incineration.

ENHANCED BASELINE SYSTEM

Flue gas emissions from the incinerators of the baseline system are the source of greatest public concern from the deployment of this system. The operations at Johnston Atoll have more than satisfied all requirements for control of agent and toxics discharge concentrations, but accidents or upsets could, in principle, produce unacceptable performance until the problem is detected and corrected (or operations ceased). For agent emissions in the stack gases, the time delay for detection with today's monitoring systems is about 3 to 8 minutes, when detecting at 0.2 of the allowable stack concentration. Detection at this level triggers an automatic shutdown. Confirmation of agent release (versus interfering compounds) requires about 30 minutes. In addition, the public fears unknown emissions of products of incomplete combustion.

The following options are available to improve the management of flue gas emissions from the baseline system:

- capture and temporarily store the entire gas stream until chemical analyses confirm it is safe for release;
- drastically reduce the volume of waste gas by using electrical power for process heat, using pure oxygen rather than air, condensing all water vapor, and capturing carbon dioxide on lime to produce solid calcium carbonate; and
- use charcoal scrubbing, as with ventilation air, to remove virtually all residual agent as well as other toxics such as dioxins and other high molecular weight chlorinated compounds.

Of these options, which are discussed in more detail in the *Alternatives* report, only charcoal scrubbing is considered in detail here (and in Appendix C). The first two options are not considered as attractive as charcoal scrubbing due to the complexity and size of the systems required and the more extensive development and testing program that would be necessary for implementation.

For charcoal scrubbing, gas is typically passed through a stack of six 3-inch-deep beds of high-surface area, activated carbon. High molecular weight, moderately polar molecules, such as agent and dioxins, are adsorbed on the charcoal and drastically reduced in gas concentration. The ventilation air scrubbers at JACADS, for example, were designed to reduce agent concentration by a factor of 10,000 in each 3-inch bed and demonstrated a reduction of 400,000 with fresh beds during the Operational Verification Testing (OVT) VX rocket test.

The JACADS ventilation air charcoal beds are monitored after the first, second, and fourth 3-inch beds to detect breakthrough of agent as the first beds become saturated. These saturated beds are replaced when agent is detected beyond bed 2. The lifetime of the first bed was months, even though it was exposed to an appreciable agent content in the ventilation air, providing adequate time for analysis and shutdown before breakthrough in the stack of six beds. Subsequent beds thus remain "fresh" for months.

Lower molecular weight compounds are also removed by charcoal with an efficiency inversely related to gas temperature. Water vapor must be held to a level that avoids formation of liquid water within the beds.[1] The combination of these two factors requires cooling of flue gas upstream of the bed to condense water, followed by some reheat to eliminate further condensation in the charcoal. Drying the stack gases in this way would also avoid formation of a visible plume. By removing most organic compounds, charcoal scrubbing would greatly reduce the number of false alarms from stack gas monitors. The choice of operating temperature is an important compromise, since cooling is expensive, but removal of organic contaminants improves as temperature is reduced. For example, a desirable temperature might be about 100-150ºF, compared to the present stack temperature of approximately 230ºF at JACADS.

Advantages of the charcoal system are

- elimination of agent discharge from the stack, even during system upsets or accidents;
- long advance warning and simple monitoring for system maintenance;
- reduction of other industrial pollutant discharges; and
- elimination of visible stack plume.

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[1] Activated charcoal can be used to adsorb unwanted materials from gases or from water (as in gas masks or in common filters used in the home to improve drinking water). However, if the charcoal is wet, gaseous contact with the charcoal is blocked and gas cleanup is ineffective.

Disadvantages are

- increased requirement for disposal of spent charcoal; and
- the potential fire hazard presented by the charcoal bed.

There is already a requirement for disposal of charcoal from ventilation air scrubbers, so no new risk or technology is added. Adequate fire protection will be necessary. In any case, as with every proposed system change, the decision to install a charcoal scrubber system must be justified by a proper evaluation of advantages and disadvantages. Appendix C contains a more detailed discussion of charcoal bed technology.

Charcoal scrubbing is a proven technology for agents (gas masks and JACADS ventilation air experience). It is being increasingly used (in another form) for scrubbing waste gases from European incinerators, but it cannot yet be considered an industrially proven technology at the temperatures considered here. Some development work will be necessary for the proposed charcoal scrubber system and for the associated gas cooling and dewatering system, but the committee foresees no unusual problems.

DEVELOPMENT REQUIREMENTS FOR ALTERNATIVE TECHNOLOGIES

The potential alternative chemical agent destruction systems identified here have not yet undergone the range of scientific research and engineering development required to certify that they will indeed provide safe, effective, and efficient alternatives to incineration. Key component processes for each of these systems have not progressed past a scientific proof-of-principle stage for at least one, if not more, of the chemical agents to be destroyed. In many cases, even scientific proof of principle has not been demonstrated for individual component processes with agent or agent decomposition products.

In order to advance to the status of a viable alternative technology, each potential alternative technology must progress through three levels of research and development:

1. laboratory-scale scientific proof-of-principle demonstration for each system component over the full range of agent chemical and physical compositions and agent decomposition products expected under operational conditions;
2. component process integration into a bench-scale simulation of the alternative technology system and successful demonstration with a full range of agent compositions to provide basic data for further scaleup; and

3. engineering, construction, and successful test demonstration (OVT) of an essentially full-scale pilot plant.

The time and resources required to progress through each of these research and development levels increase substantially at each step. Time estimates for a slightly more complex alternative technology research, development, and demonstration program were developed in the *Alternatives* report. That report estimated that 9-to-12 years would be required to move from the laboratory to successful demonstration, if each research and development level is carried to completion before starting the next is started.

This time estimate can be reduced by carrying out work on various research and development levels simultaneously. For example, the full-scale demonstration plant could be designed and built while laboratory research and development and small pilot plant work were still under way (at some financial risk, of course).

This telescoping of research and development stages is practiced in the chemical industry and is becoming more common, because of the drive for cost reduction and a more competitive market position. A total time of 3-to-5 years after scientific proof of principle is not uncommon. The committee believes that a well-managed and well-funded program, with a strong staff, can develop and demonstrate the alternative(s) of interest in as little as five to seven years. However, this laboratory-through-demonstration schedule assumes that excessive permitting delays (greater than a two-year permitting cycle) for the demonstration and production plants are not encountered. It is significant that permitting for the JACADS and Tooele facilities has required three years each despite the Army's strong efforts to meet permitting requirements expeditiously.

Given the increased risk of accidental or chronic exposure from storage imposed by delaying the stockpile destruction, it is important that the most promising of the identified potential alternative technologies be advanced past scientific proof-of-principle as soon as possible. A second reason for moving forward promptly is the fact that the third level of research (pilot plant), described earlier, to be conducted at the Chemical Agent Munitions Disposal System (CAMDS), will require the use of a portion of the stockpile currently stored at Tooele. The Tooele baseline disposal system is scheduled to commence operation soon, and the committee does not recommend that complete destruction of the Tooele stockpile be artificially delayed just to preserve feedstock for an alternative technology demonstration plant at CAMDS.

7

Findings and Recommendations

OVERVIEW

The Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program has reviewed various alternative technologies for the disposal of the nation's stockpile of chemical agents and munitions. A number of specific recommendations are made in this chapter regarding the future conduct of the disposal program. Before the presentation of specific recommendations, however, it is important to present the committee's overall view of the program as background. Following the specific findings and recommendations, the chapter closes with a summary of the recommendations within the overall context of the program objectives.

Risk analyses of both storage and disposal operations have shown that cumulative total risk to the public and to the environment is dominated by storage rather than disposal operations, at least in terms of the risk of acute agent exposure. These risk analyses are being updated, but the evidence is strong that new studies will not significantly alter this distribution of risk. Furthermore, though there is no evidence of imminent disaster, storage and disposal risks must increase in time as the stockpile continues to deteriorate. The only way to avoid the continuing and growing risk from storage, of both acute agent exposure and long-term health risks, is to eliminate the hazardous materials.

The baseline system, which employs a number of preparation steps followed by incineration to destroy or decontaminate four distinctly different process streams, has been demonstrated as a safe and effective disposal process for the stockpile. However, the use of incineration for the disposal of hazardous materials has been generically challenged by some critics. The Stockpile Committee recognizes this objection and has made recommendations for alternative technologies that would replace the incinerator where the bulk of the agent is destroyed. The committee believes these technologies can be successfully developed with aggressive research and development programs. Furthermore, the committee believes that with sufficient effort, these technologies can be proven to afford essentially the same level of processing safety and effectiveness for disposal of agents as the baseline system. The current status of potential alternative technologies ranges from some that are in commercial use for other applications to those that are based only on preliminary laboratory research.

Given the availability of a proven disposal system, it is the committee's view that the total risk will be minimized if the baseline disposal program proceeds expeditiously at a pace in keeping with reasonable and safe facility construction and operating schedules. At the same time, promising alternative technologies for agent disposal have been identified. These should be developed at an accelerated pace in order that they might prove beneficial within that expeditious schedule. Given the persistent storage risk, the disposal schedule should not be deliberately delayed or interrupted in order to foster the application of emerging alternative agent disposal technologies, particularly since the committee does not believe that any alternative disposal technology will significantly reduce the total processing risk.

SPECIFIC FINDINGS AND RECOMMENDATIONS

The findings and recommendations are organized in seven categories: expeditious progress, risk analyses, public concerns, current systems, alternatives, stockpile safety, and staffing needs.

Expeditious Progress

Finding 1. The storage risk will persist until disposal of all stockpile materials is complete. Both storage risk and disposal risk will increase with time as the stockpile deteriorates further. Existing analyses indicate that the annual storage risk to the public at each site is the same as or greater than the annual risk due to disposal. Thus, total risk to the public will be reduced by prompt disposal of the stockpile.

> **Recommendation 1.** *The Chemical Stockpile Disposal Program should proceed expeditiously and with technology that will minimize total risk to the public at each site.*

Risk Analyses

Finding 2. Existing risk analyses did not evaluate the latent health hazards associated with storage, handling, and disposal activities. These latent risks represent one of the major concerns voiced by the public.

> **Recommendation 2.** *The committee expects the latent risks from storage, handling; and disposal activities to be low. However, new risk analyses should be conducted that explicitly account for latent health risks from storage, handling; and disposal.*

Finding 3. The finding that total risk will be reduced by prompt disposal, although apparently reasonable, is based upon earlier analyses that do not reflect current risk assessment methods and knowledge about the storage, handling, and disposal activities.

> **Recommendation 3.** *Updated analyses of the relative risk of storage, handling; and disposal activities should be completed as soon as possible.*

Finding 4. The Stockpile Committee is confident that site-specific risk analyses will confirm the wisdom of proceeding promptly. Further, the schedule of the disposal program should not be delayed pending completion of the updated analyses, because they can be conducted concurrently with other activities within the overall construction and operations schedule. Both storage risk and processing risk differ from site to site. Storage risks differ greatly depending on storage configuration, types and mix of munitions, and the potential for external events, as well as nearby community conditions.

> **Recommendation 4A.** *New risk analyses should be site specific, using the latest available information and methods of analysis. At this time, since there is insufficient knowledge of potential alternative technologies, a first-cut series of analyses should compare the relative risks of continued storage and disposal by the baseline system. Analyses should identify the major contributors to total risk including storage. The analyses will confirm or refute the present belief that maximum safety dictates prompt disposal*

> **Recommendation 4B.** *As new, site-specific risk analyses become available, the Army should reconsider the schedule of construction and operation of disposal facilities and, if indicated, reorder the remaining sequence so as to minimize any subsequent cumulative total risk: The Army should also consider reconfiguring each high-risk stockpile to a safer condition prior to disposal if this will significantly decrease cumulative total risk.*

Finding 5. The committee does not foresee that any alternative agent destruction technology will substantially reduce the total agent processing risk. Site-specific risk analyses will identify the potential to improve safety over the baseline system and thus serve as a check on this belief.

> **Recommendation 5.** *As research progresses on potential alternative technologies and as their potential for improved safety becomes apparent, site-specific risk analyses should be reexamined, with the potential alternative substituted in the baseline system, to estimate overall system performance. In view of the limited potential for overall safety improvement, however, the disposal program should not be delayed pending completion of such research.*

Public Concerns

Finding 6. The members of the public in communities near the chemical stockpile sites have voiced diverse views and opinions regarding the stockpile disposal program, and their desire to have greater access and input into decisions concerning that program. The committee's public forum, as well as correspondence and telephone calls to the committee, indicate that the Army is not as well informed of public sentiment as desirable. The public wants a larger role in the selection of disposal technology, the monitoring of operations that ensure its own safety, and determining the fate of the facility after completion of disposal efforts.

> **Recommendation 6.** *The Army should develop a program of increased scope aimed at improving communication with the public at the storage sites. In addition, the Army should proactively seek out greater community involvement in decisions regarding the technology selection process, oversight of operations, and plans for decommissioning facilities. Finally, the Army should work closely with*

the Chemical Demilitarization Advisory Citizen's Commissions, which have been (or will be) established in affected states. There must be a firmer and more visible commitment to engaging the public and addressing its concerns in the program.

Current System

Finding 7. Chemical agents and munitions materials have been successfully divided into four distinct process streams having widely differing properties. Separation of these materials for processing in distinct, well-engineered systems provides a safer and more reliable operation than would processing of a mixed stream in a single process.

Recommendation 7. *All disposal systems should be designed to separately process agent, energetics and associated small metal components, large metal parts, and dunnage streams.*

Finding 8. The committee found no acceptable alternative to mechanical methods to gain access to agent in munitions and to separate agent, energetics, and associated small metal components, and large metal parts.

Recommendation 8. *The Army should continue with mechanical methods to gain access to agent and to separate material streams. Alternative mechanical systems should be pursued if simpler, more durable concepts, which also permit separation of the streams, are discovered.*

Finding 9. Gelled agent, particularly mustard, is difficult to separate from its container and will hamper any agent destruction or neutralization process or any attempt to decontaminate containers.

Recommendation 9. *Research to develop means to extract, handle, and process gelled agents should be accelerated, to sustain the advantages of handling separate streams and to facilitate the use of alternative technologies.*

Finding 10. The committee found no readily applicable alternative to incineration of energetic components. Energetics are solid materials, cast in place in metal containers. In this form they are not compatible with alternative oxidation technologies that require liquid or finely divided feed materials. Extraction of energetics and reduction to suitable slurry form would be difficult and hazardous.

Recommendation 10. *Dispose of energetic materials by incineration.*

Finding 11. The committee found no alternative to high-temperature treatment for reliable decontamination of metal parts to a level suitable for release to the public.

Recommendation 11. *Use of the baseline metal parts furnace or other high-temperature treatment is recommended.*

Finding 12. The Johnston Atoll Chemical Agent Disposal System (JACADS) Operational Verification Testing (OVT) provided additional assurance that the baseline system is capable of the safe disposal of the Army's chemical stockpile. However, the committee found that OVT identified opportunities for improvements in operations, management practices, and training with regard to safety, environmental performance, and plant efficiency. The committee has recommended that systemization be used to implement these improvements prior to the initiation of the destruction of agent and munitions at Tooele.

Recommendation 12. *The Chemical Stockpile Disposal Program should continue on schedule with implementation of the baseline system, unless and until alternatives are developed and proven to offer safer, less costly, or more rapidly implementable technologies (without sacrifice in any of these areas). Baseline system improvements should be implemented as identified and successfully demonstrated.*

Finding 13. The Stockpile Committee finds the baseline system to be adequate for disposal of the stockpile. Addition of activated carbon filter beds to treat all exhaust gases would add further protection against agent and trace organic emissions, even in the unlikely event of a substantial system upset. If the beds are designed with sufficient capacity to adsorb the largest amount of agent that might be released during processing, addition of these beds could provide further protection against inadvertent release of agent.

> **Recommendation 13.** *The application of activated charcoal filter beds to the discharge from baseline system incinerators should be evaluated in detail, including estimations of the magnitude and consequences of upsets, and site-specific estimates of benefits and risks. If warranted, in terms of site-specific advantages, such equipment should be installed.*

Alternatives

Finding 14. After examination of all the technologies brought to the attention of the Stockpile Committee by the Alternatives Committee and others, the Stockpile Committee has determined that four neutralization-based systems offer the most promise for agent destruction. Neutralization has been demonstrated to be effective for GB but is not yet proven for mustard and VX. Utilizing lower temperatures and pressures and ordinary chemical processing equipment, neutralization is simpler than incineration, and it may be lower in cost for some sites. Recent laboratory studies have reported encouraging results for the neutralization of neat VX and mustard (see Appendix E), though questions remain for neutralizing impure and gelled materials. Reaction products from neutralization processes will require further treatment prior to disposal. Potentially applicable processes for further treatment of these reaction products are incineration, wet air oxidation, supercritical water oxidation, and biological treatment. All of these combinations will require further research and demonstration to ensure that the combination of these processes treats agent to levels consistent with treaty and environmental requirements.

In view of the increasing total risk associated with disposal program delays, and recognizing that public opposition might delay the program for a number of reasons, including opposition to incineration, it is imperative that alternative technologies be developed promptly.

> **Recommendation 14A.** *Neutralization research should be substantially accelerated and expanded to include field-grade and gelled material as appropriate and the neutralization of drained containers.*

> **Recommendation 14B.** *Neutralization research should be accompanied by preliminary analyses of integrated systems capable of reducing agents all the way to materials acceptable for transport or disposal*

> **Recommendation 14C.** *These analyses and research should be conducted in parallel to lead to the selection of a single system for further development*.

Finding 15. There has been continued development of various research programs involving potential alternatives since the National Research Council report *Alternative Technologies for the Destruction of Chemical Agents and Munitions* was issued.

> **Recommendation 15.** *The Army should continue to monitor research developments in pertinent areas.*

Finding 16. Neutralization of agent and decontamination of containers, followed by transport of both to another facility for final treatment, offer an attractive alternative to the baseline liquid incinerator, especially for sites with no stored energetics. Receiving sites might be another chemical agent disposal site or commercial hazardous waste incineration facilities (if possible). This option could be viable at Newport Army Ammunition Plant and at Aberdeen Proving Ground, provided complications with gelled mustards do not arise.

> **Recommendation 16.** *Neutralization followed by transport for final treatment should be examined as an alternative, at the Aberdeen and Newport sites. This examination should include location of acceptable receiver sites and transport routes, and a comparison of costs and schedules relative to on-site baseline treatment. If favorable results are indicated, the examination should be expanded as an option to eliminate the liquid incinerator at other sites. At those locations, on-site incineration of energetics and associated metal parts is still recommended.*

Finding 17. The current chemical stockpile disposal schedule may provide time for site-specific substitution or integration of proven alternative agent disposal processes at selected sites if research and development efforts are accelerated and results are favorable.

> **Recommendation 17.** *Proven alternative technologies, if available without increasing risk; should be considered for application on the basis of site-specific assessments.*

Finding 18. Future developments for the baseline system as well as for a number of alternative technologies will require a flexible, agent-qualified experimental facility.

> **Recommendation 18.** *The facility and staff at the Chemical Agent Munitions Disposal System (CAMDS) facility should be maintained at an effective operating level for the foreseeable future. However, agent stocks should not be deliberately retained at Tooele in order to feed an alternative technology demonstration.*

Finding 19. Application of all known alternative agent disposal systems will require research and development, and demonstrated safe operation (operational verification testing) with chemical agents.

> **Recommendation 19.** *Application of an alternative technology at any site should be preceded by demonstration of safe, pilot operation (operational verification testing) at the Chemical Agent Munitions Disposal System facility. These operations should not be carried out on a trial basis at storage sites.*

Stockpile Safety

Finding 20. A recent MITRE Corporation evaluation of stockpile condition with respect to propellant stabilization in M55 rockets suggests that the stockpile is safe until 2007 or later, whereas a similar Army report suggests 2002. The MITRE report notes that stockpile surveillance may be reduced in the belief that the stockpile will be disposed of by 2004. The committee is concerned that there is considerable uncertainty in all of the attempts to estimate safe storage life of the M55 rocket propellant. Degradation is not well understood. If surveillance is reduced, it would leave the stockpile subject to dangerous uncertainty. Further, other signs of degradation—gelled mustard, foaming mustard artillery shells, leaking and corroded ton containers—suggest that stockpile degradation can adversely affect disposal processes. Finally, realistic estimates of the duration of the disposal effort will extend well beyond 2004, particularly if alternative technologies are to be used.

Recommendation 20. *Further research into the nature and sequence of propellant stabilizer degradation should be undertaken promptly. The present condition of the stockpile should be evaluated with sufficient new field sampling of propellant grains, including grains from representative leakers that have been overpacked. Stockpile surveillance should be increased rather than decreased, particularly for M55 rockets.*

Staffing Needs

Finding 21. The Army faces significant challenges in executing the Chemical Stockpile Disposal Program. As more sites begin development, important engineering and technical issues will be faced. These will cover a large spectrum over the life of this program, and will include, for example, development and maturation of alternative technologies, as well as development of a method for extracting and disposing of gelled mustard. These challenges will create more demand for planning, management, and supervision than the office of the Program Manager for Chemical Demilitarization will be capable of providing without augmentation. A shortage of skilled staff could have safety implications for the program, as well as its more obvious implications for program slowdown with attendant increased risk.

Recommendation 21. *The Army should establish a program to incrementally hire (or assign military) personnel to ensure that staff growth is consistent with the workload and with technical and operational challenges. These additional personnel must be assigned and trained before the project office gets deeply involved in addressing each challenge.*

SUMMARY

Existing information indicates that the disposal risk at individual sites, using the baseline system, is generally less than the stockpile storage risk, often substantially less. Further, even if this were not true, the accumulating risk of continuing storage would offset any decrease in disposal risk afforded by an alternative technology, particularly since alternative technologies are not likely to significantly reduce the disposal risks. The existing evidence is therefore strong enough to suggest that the baseline program proceed in parallel with the analyses and without deliberate delay. It is also clear that the updating of risk analyses should be undertaken promptly to check this conclusion.

Emphasis on overall safety in the selection of technologies for the disposal of chemical agents and munitions leads to a program that also happens to have favorable cost and schedule consequences, which will be of interest to those who must make the final decision. This follows from the unusual circumstance that time and money spent in search of better technology are likely to result in delays that increase overall risk, whatever the characteristics of the new technology. It should be reemphasized that the Stockpile Committee recommends proceeding expeditiously entirely on the basis of minimizing total cumulative risk. The committee does not endorse programs that would increase risk. Others who may wish to delay the schedule in order to develop and prove alternative technologies, or to delay for any other reason, should proceed in the full knowledge that they do so at the expense of increased risk.

The baseline system has a demonstrated safety record, and means have been recommended to reinforce that safety. Of the alternatives, neutralization offers the greatest direct experience and, together with a process to dispose of neutralized products, the greatest potential for utilization without a needless delay and increase in overall risk.

Sticking with existing system, or with the most proven alternative, in the apparent interest of short-term savings in time and cost is a criticism often leveled at complacent U.S. industries in the face of progressive foreign competition, and rightly so. Failure to develop for the future can lead to failure of the industry. However, short-term savings in time and cost are not the issues that have driven the Stockpile Committee's recommendations. Furthermore, as this committee and previous National Research Council committees have repeatedly written, the disposal of chemical agents and munitions is an industry without a future. The task at hand is to dispose of the existing stockpile as safely as possible. It is not to build an industry for disposal of future materials or of foreign stockpiles. It is well beyond the scope of the Army Chemical Stockpile Disposal Program, and unfair to the affected communities, to use this program for the experimental development and pioneering demonstration of new waste disposal technologies that might be used in some future facility to dispose of materials far less hazardous than chemical warfare agents.

A

Public Law 102-484—Oct. 23, 1992 (Extract)

SUBTITLE G—CHEMICAL DEMILITARIZATION PROGRAM

SEC. 171 CHANGE IN CHEMICAL WEAPONS STOCKPILE ELIMINATION DEADLINE

Section 1412(b)(5) of the Department of Defense Authorization Act, 1986 (50 U.S.C. 1521 (b)(5), is amended by striking out "July 31, 1999" and inserting in lieu thereof "December 31, 2004".

SEC. 172 CHEMICAL DEMILITARIZATION CITIZENS ADVISORY COMMISSIONS

(a) ESTABLISHMENT.—(1) The Secretary of the Army shall establish a citizens' commission for each State in which there is a low-volume site (as defined in section 180). Each such commission shall be known as the "Chemical Demilitarization Citizens' Advisory Commission" for that State.

(2) The Secretary shall also establish a Chemical Demilitarization Citizens' Advisory Commission for any State in which there is located a chemical weapons storage site other than a low-volume site, if the establishment of such a commission for such State is requested by the Governor of that Sate.

(b) FUNCTIONS.—The Secretary of the Army shall provide for a representative from the Office of the Assistant Secretary of the Army (Installations, Logistics, and Environment) to meet with each commission under this section to receive citizen and State concerns regarding the ongoing program of the Army for the disposal of the lethal chemical agents and munitions in the stockpile referred to in section 1412(a)(1) of the Department of Defense Authorization Act, 1986 (50 U.S.C. 1521(a)(1)) at each of the sites with respect to which a commission is established pursuant to subsection (a).

(c) MEMBERSHIP.—(1) Each commission established for a State pursuant to subsection (a) shall be composed of nine members appointed by the Governor of the State. Seven of such members shall be citizens from the local affected areas in the State; the other two shall be representatives of State government who have direct responsibilities related to the chemical demilitarization program.

(2) For purposes of paragraph (1), affected areas are those areas located within a 50-mile radius of a chemical weapons storage site.

(d) CONFLICTS OF INTEREST.—For a period of five years after the termination of any commission, no corporation, partnership, or other organization in which a member of that commission, a spouse of a member of that commission, or a natural or adopted child of a member of that commission has an ownership interest may be awarded—

(l) a contract related to the disposal of lethal chemical agents or munitions in the stockpile referred to in section 1412(a)(1) of the Department of Defense Authorization Act, 1986 (50 U.S.C. 1521(a)(1)); or

(2) a subcontract under such a contract.

(e) CHAIRMAN.—The members of each commission shall designate the chairman of the commission from among the members of the commission.

(f) MEETINGS.—Each commission shall meet with a representative from the Office of the Assistant Secretary of the Army (Installations, Logistics, and Environment) upon joint agreement between the chairman of the commission and that representative. The two parties shall meet not less often than twice a year and may meet more often at their discretion.

(g) PAY AND EXPENSES.—Members of each commission shall receive no pay or compensation for their involvement in their activities of the commission.

(h) TERMINATION OF COMMISSIONS.—Each commission shall be terminated after the stockpile located in that commission's State has been destroyed.

SEC. 173 EVALUATION OF ALTERNATIVE TECHNOLOGIES

(a) REPORT.—Not later than December 31, 1993, the Secretary of the Army shall submit to Congress a report on the potential alternatives to the use of the Army's baseline disassembly and incineration process for the disposal of lethal chemical agents and munitions. The report shall include the following:

(1) An analysis of the report of the Committee on Alternative Chemical Demilitarization Technologies of the National Research Council of the National Academy of Sciences.

(2) Any recommendations that the National Academy of Sciences makes to the Army regarding the report of that committee, together with the Secretary's evaluation of those recommendations.

(3) A comparison of the baseline disassembly and incineration process with each alternative technology evaluated in the report of such committee that the National Academy of Sciences recommends for use in the Army Chemical Stockpile Disposal Program, taking into consideration each of the following factors:

(A) Safety.

(B) Environmental protection.

(C) Cost effectiveness.

(4) For each alternative technology recommended by the National Academy of Sciences, the date by which the Army could reasonably be expected to systematize, construct, and test the technology, obtain all necessary environmental and other permits necessary for using that technology for the disposal of lethal chemical agents and munitions, and have the technology available for full-scale chemical weapons destruction and demilitarization operations.

(5) A description of alternatives to incineration that are being developed by Russia for use in its chemical demilitarization program and an assessment of the extent to which such alternatives could be used to destroy lethal chemical weapons in the United States inventory of such weapons.

(6) Consideration of appropriate concerns arising from meetings of the Chemical Demilitarization Citizens' Advisory Commissions established pursuant to section 172.

(7) In any case in which the criteria specified in section 174 are met, notification that the Secretary intends to implement an alternative technology disposal process at a low-volume site.

(b) LIMITATION.—(1) Except as provided in paragraphs (2) and (3), the Secretary of the Army may not commence site preparation for, or construction of, a facility for disassembly and incineration of chemical agents until the report required under subsection (a) is submitted to Congress.

(2) The limitation in paragraph (1) does not apply to any facility for disassembly and incineration of chemical agents (of the eight such facilities identified in the Army Chemical Stockpile Disposal Program) at which site preparation or construction has commenced before the date of the enactment of this Act.

(3) Except as provided in section 175, the limitation in paragraph (1) does not apply to the following:

(A) Facility design activities.

(B) The obtaining of environmental permits.

(C) Project planning.

(D) Procurement of equipment for installation in a facility.

(E) Dual purpose depot support construction projects which are needed to ensure the continuing safe storage of chemical weapons stocks and their ultimate disposal regardless of the technology employed.

SEC. 174 ALTERNATIVE DISPOSAL PROCESS FOR LOW-VOLUME SITES

(a) REQUIREMENT FOR ALTERNATIVE PROCESS.—If the date by which chemical weapons destruction and demilitarization operations can be completed at a low-volume site using an alternative technology process evaluated by the Secretary of the Army falls within the deadline established by the amendment made by section 171 and the Secretary determines that the use of that alternative technology process for the destruction of chemical weapons at that site is significantly safer and equally or more cost-effective than the use of the baseline disassembly and incineration process, then the Secretary of the Army, as part of the requirement of section 1412 (a) of Public Law 99-145, shall carry out the disposal of chemical weapons at sites other than low-volume sites using an alternative technology process (rather than the baseline process) after notifying Congress of the Secretary's intent to do so.

(b) APPLICABILITY OF CERTAIN PROVISIONS OF SECTION 1412.—Subsections (c), (e), (f), and (g) of section 1412 of Public Law 99-145 (50 U.S.C. 1521) shall apply to this section and to activities under this section in the same manner as if this section were part of that section 1412.

SEC. 175 REVISED CHEMICAL WEAPONS DISPOSAL CONCEPT PLAN

(a) REVISED PLAN.—If, pursuant to section 174, the Secretary of the Army is required to implement an alternative technology process for destruction of chemical weapons at any low-volume site, the Secretary shall submit to Congress a revised chemical weapons disposal concept plan incorporating the alternative technology process and reflecting the revised stockpile disposal schedule developed under section 1412(b) of Public Law 99-145 (50 U.S.C. 1521(b)), as amended by section 171. In developing the revised concept plan, the Secretary should consider, to the maximum extent practicable, revisions to the program and program schedule that capitalize on the changes to the chemical demilitarization schedule resulting from the revised stockpile elimination deadline by reducing cost and decreasing program risk.

(b) MATTERS TO BE INCLUDED.—The revised concept plan should include—

(1) life-cycle cost estimates and schedules; and

(2) a description of the facilities and operating procedures to be employed using the alternative technology process.

(c) APPLICABILITY OF CERTAIN PROVISIONS OF SECTION 1412.—Subsection (c) of section 1412 of Public Law 99-145 (50 U.S.C. 1521) shall apply to the revised concept plan in the same manner as if this section were part of that section 1412.

(d) SUBMISSION OF REVISED PLAN.—If the Secretary is required to submit a revised concept plan under this section, the Secretary shall submit the revised concept plan not later than 180 days after the date on which the Secretary submits the report required under section 173.

(e) LIMITATION.—If the Secretary is required to submit a revised concept plan under this section, no funds may be obligated for procurement of equipment or for facilities planning and design activities (other than for those preliminary planning and design activities required to comply with Subsection(b)(2)) for a chemical weapons disposal facility at any low volume site at which the Secretary intends to implement an alternative technology process until the Secretary submits the revised concept plan.

B

Public Forum

PURPOSE

Media coverage, Army reporting on interactions with the public, and letters and calls to the Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program (Stockpile Committee) and Committee on Alternative Chemical Demilitarization Technologies (Alternatives Committee) have made it obvious that the public has many concerns about the chemical stockpile and plans for its disposal. As part of its deliberations, the Stockpile Committee wanted an opportunity to discuss those concerns directly with the interested parties. One step to enhance the committee's understanding was to hold a public forum.

On June 30, 1993, an Alternative Technologies Forum was held in the main building of the National Academy of Sciences in Washington, D.C. The forum represented a major undertaking by the Alternatives and Stockpile Committees to obtain public input and comment. The morning session summarized and received comment on the National Research Council report *Alternative Technologies for the Destruction of Chemical Agents and Munitions* (NRC, 1993a). The afternoon was devoted to explaining the Stockpile Committee's plans and processes for producing its final report for the Army. The public commented on and suggested revisions in some of the committee's plans, both at the forum and through written submissions.

AGENDA

Public Forum, June 30, 1993
Washington, D.C.

The following committee and U.S. Army presentations were made during the one-day forum:

Morning Session

(a) Briefing by Dr. John P. Longwell, Chairman, Committee on Alternative Chemical Demilitarization Technologies (Alternatives Committee), Review of committee's report *Alternative Technologies for the Destruction of Chemical Agents and Munitions.* This presentation was followed by a question and answer period.

Afternoon Session

(b) Briefing by Dr. Carl R. Peterson, Chairman, Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program (Stockpile Committee), including discussion on (1) introduction and background of the chemical disposal program and the Stockpile Committee's involvement in recommendations for alternative technologies; (2) description of the munitions; and (3) the technology evaluation considerations.

(c) Briefing by Mr. Charles Baronian, Program Manager and Technical Director for Chemical Demilitarization, on the Army's plans for its report to Congress and on the Army's mechanism and process for public participation.

(d) Briefing by Dr. B. John Garrick, Member, Stockpile Committee," Quantitative Risk Assessment."

A question and answer period followed the afternoon briefing session.

ATTENDEES

The forum was conducted by both the Alternatives and the Stockpile Committees. Attendees were as follows:

Committee on Alternative Chemical Demilitarization Technologies

Dr. John P. Longwell, *Chairman*	Massachusetts Institute of Technology
Dr. George Apostolakis	University of California, Los Angeles
Dr. Joseph F. Bunnett	University of California, Santa Cruz
Dr. Peter S. Daley	Waste Management International
Dr. Gene H. Dyer	Bechtel Corporation, *Retired*
Dr. David S. Kosson	Rutgers, The State University of New Jersey
Dr. Walter G. May	University of Illinois
Dr. Matthew Meselson	Harvard University
Dr. Henry Shaw	New Jersey Institute of Technology

Dr. Thomas O. Tiernan	Wright State University
Dr. Barry M. Trost[*]	Stanford University
Dr. James R. Wild	Texas A & M University

Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program

Dr. Carl R. Peterson, *Chairman*	Massachusetts Institute of Technology
Dr. Elisabeth M. Drake	Massachusetts Institute of Technology
Dr. Colin G. Drury	University of Buffalo
Mr. Gene H. Dyer	Bechtel Corporation, *Retired*
MG Vincent E. Falter	U.S. Army, *Retired*
Dr. Ann Fisher	The Pennsylvania State University
Dr. B. John Garrick	PLG, Inc.
Dr. John P. Longwell	Massachusetts Institute of Technology
Dr. Richard S. Magee	New Jersey Institute of Technology
Dr. Alvin Mushkatel	Arizona State University
Mr. Peter J. Niemiec	Greenberg, Glusker, Fields, Claman and Machtinger
Dr. George Parshall	E.I. du Pont de Nemours and Company, *Retired*
Dr. Gavriel Salvendy[*]	Purdue University

Committee Staff

Mr. Donald L. Siebenaler, Study Director
Dr. James J. Zucchetto, Co-Study Director, Alternatives Committee
Ms. Ann Covalt, Technical Writer/Editor
Ms. Margo Francesco, Senior Program Assistant

NRC's Commission on Engineering and Technical Systems

Mr. Archie L. Wood, Executive Director

NRC's Board on Army Science and Technology

Mr. Bruce Braun, Director
Mr. Tracy Wilson, Senior Program Officer

NRC's Office of News and Public Information

Mr. Lee Tune, Media Relations Associate

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[*] Unable to attend.

Invited Attendees

Department of the Army

Mr. Charles Baronian, Program Manager and Technical Director for Chemical Demilitarization

COL James Coverstone, Assistant Deputy for Chemical Demilitarization, Office of the Assistant Secretary of the Army (Installations, Logistics and Environment)

Mr. Mark Evans, Special Assistant to the Program Manager, Office of the Program Manager for Chemical Demilitarization

Mr. Wayne Jennings, Chief, Program Planning Division, for Non-Stockpile Chemical Material, U.S. Army Chemical Material Destruction Agency

Ms. Diane Kotras, Physical Scientist, Office of the Deputy Chief of Staff for Operations, The Pentagon

MAJ Jean-Luc Ontiveros, Acting Chief, Engineering and Technology Division, Office of the Program Manager for Chemical Demilitarization

Ms. Margo Robinson, Program Analyst, Office of the Assistant Secretary of the Army (Installations, Logistics and Environment)

Ms. Marilyn Tischbin, Chief, Public Affairs Office, Office of the Program Manager for Chemical Demilitarization

Congressional

Mr. Alan Dayton, on behalf of Senator Robert Bennett, State of Utah

Mr. Ken Lane, on behalf of Senator Benjamin Campbell, State of Colorado

Ms. Lasca Low, on behalf of Congressman John Myers, State of Indiana

Ms. Vickie Plunkett, on behalf of Congressman Glen Browder, State of Alabama

State of Alabama

Dr. Doris Gertler, Families Concerned About Nerve Gas Incineration, Anniston

Mr. William Gerald Hardy, Alabama Department of Environmental Management, Land Division, Montgomery

Mr. Jim Harmon, Families Concerned About Nerve Gas Incineration, Anniston

Mr. Nate Hartman, Alabama Department of Environmental Management, Air Division, Montgomery

Mr. Griffin "Buddy" Holcomb, Jr., Talladega County Emergency Management Agency, Talladega

Mr. Jerry D. Mullinix, Director of Chemical Demilitarization, U.S. Army Corps of Engineers, Huntsville Division, Huntsville

Mr. Rudy Noll, Citizens for SPRING, Anniston

COL Leo E. Norton, Deputy Commander, Chemical Demilitarization and Special Projects, U.S. Army Corps of Engineers, Huntsville

Mr. Boyce L. Ross, Chief, Design Management and Integration Division, U.S. Army Corps of Engineers, Huntsville

State of Arkansas

Ms. Kim Konecny, Assistant Environmental Liaison, The Office of Governor Jim Guy Tucker, Little Rock

State of Colorado

Ms. Jacqueline Beradini, Office of the Environment, Colorado Department of Health, Denver

Dr. Richard A. Martinez, Pueblo County Commission, and Chairperson, PDA Chemical Demilitarization Commission, Pueblo

Mr. Ross Vincent, Chair, Rocky Mountain Chapter, Sierra Club, Pueblo

State of Indiana

Mr. Jim Gross, Indiana Department of Environmental Management, Indianapolis

Dr. Gregory Steele, Indiana State Department of Health, Indianapolis

State of Kentucky

MG Robert L. DeZarn, Adjutant General of Kentucky and Head, Department of Military Affairs, Frankfort

Mr. Ken Hudson, Chemical Stockpile Emergency Preparedness Program (CSEPP) Branch Manager, Division of Disaster and Emergency Services, Department of Military Affairs, Frankfort

Ms. Valerie Hudson, Principal Assistant, Department for Environmental Protection, Natural Resources and Environmental Protection Cabinet, Frankfort

Mr. Thomas Pendleton, Jr., Kentucky Department of Military Affairs, Frankfort
Mr. Craig Williams, Kentucky Environmental Foundation, Berea

State of Maryland

Ms. Lisa Albin, on behalf of Mr. David McMillion, Maryland Emergency Management Agency, Pikesville
Mr. John Chalda, Maryland Department of Environment, Baltimore
Mr. Harold L. Dye, Jr., Maryland Department of Environment, Baltimore
Mr. Walter B. Harris, Chesapeake Bay Protection, Worton
Mr. Robert Hukill and Mrs. Jane Hukill, Coalition for Safe Disposal, Worton
Mr. Robert T. Jaske, P.E., Public Safety Consultant, Bethesda
Dr. Peter Montague, Environmental Research Foundation, Annapolis
Mr. John Nunn and Mrs. Nancy Nunn, Coalition for Safe Disposal, Worton
Mr. Jim Peavler, Chesapeake Development, Inc., Towson

State of Oregon

Lisa Brenner, Ph.D., on behalf of John Charles, Citizens for Quality Living, Sherwood
Mr. Brett McKnight, on behalf of Ms. Stephanie Hallock, Oregon Department of Environmental Quality, Portland
Dr. Thomas Stibolt, Kaiser Permanente, Kaiser Sunnyside Medical Center, Clackamos
Ms. Katherina Woodward, Portland

State of Utah

Mr. Myron W. Lee, Tooele County, Department of Emergency Management, Tooele
Ms. Connie Nakahara, representing Mr. Dennis Downs, Utah Department of Environmental Quality and State and Territorial Waste Management Official, Salt Lake City
Mr. Jim Wangsgard, representing Mr. Dennis Downs, Utah Department of Environmental Quality and State and Territorial Waste Management Official, Salt Lake City

Additional Interest Groups and Individuals

Ms. Elizabeth Bartlett, U.S. Environmental Protection Agency, Region 4, Atlanta, Georgia

Dr. Dupont Durst, U.S. Army Chemical Research, Development and Engineering Center, Aberdeen Proving Ground, Maryland

Mr. Alan Goldfarb, MITRE Corporation, McLean, Virginia

Mr. Matthew Hale, Office of Solid Waste, U.S. Environmental Protection Agency, Washington, D.C.

Dr. Paul Johnston, The Earth Resources Center, University of Exeter, United Kingdom

Mr. Gerwyn Jones, Madison, New Jersey

Mr. David Keefer, Evaluator, U.S. General Accounting Office, Washington, D.C.

Mr. David Koplow, Lawyers Alliance for World Security, Georgetown University Law Center, Washington, D.C.

Mr. Kier Lieber, Research Associate, The Henry L. Stimson Center, Washington, D.C.

Mr. Stephen A. McFadden, M.S., Independent Research Advocate, Pasco, Washington

Mr. Blaine McKusik, International Union of Pure and Applied Chemistry (IUPAC) Task Force, War Gas Disposal Committee, Wilmington, Delaware

Mr. Kyle Olson, Chemical and Biological Arms Control Institute, Alexandria, Virginia

Mrs. June Ottinger, Chemical Weapons Working Group, Anniston, Alabama

Mr. John Parachini, Executive Director, Lawyers Alliance for World Security, Washington, D.C.

Mr. Bob Pikul, MITRE Corporation, McLean, Virginia

Lawrence Plumlee, M.D., Washington Center for Environmental Health (former EPA Medical Science Advisor), Cabin John, Maryland

Mr. David Rowan, U.S. General Accounting Office, Washington, D.C.

Mr. Steven Setzer, Engineering News Record, McGraw-Hill, Atlanta, Georgia

Ms. Amy Smithson, The Henry L. Stimson Center, Washington, D.C.

Ms. Maria Vorel, Federal Emergency Management Agency, Congressional Relations, Washington, D.C.

Invitees Who Submitted Written Statements and Comments

The Honorable Jack Jones, County Judge; the Honorable Jerry Taylor, Mayor, Pine Bluff, Arkansas; and the Honorable Raymond Ross, Mayor, White Hall, Arkansas

Mr. Thomas L. Askcraft, Coordinator, Office of Emergency Services, Jefferson County, Pine Bluff, Arkansas

Mr. Brainard Bivens, Chemical Weapons Working Group Delegate, Pine Bluff, Arkansas

The Honorable Ben Nighthorse Campbell, Congressman, State of Colorado

Mr. Dennis R. Downs, Director, Utah Division of Solid and Hazardous Waste, Department of Environmental Quality, Salt Lake City, Utah

Ms. Donna M. Heivilin, Director, Defense Management and NASA Issues, National Security and International Affairs Division, U.S. General Accounting Office, Washington, D.C.

Mr. Douglas Hindman, Vice Chair, Kentucky Chemical Demilitarization Citizens' Advisory Commission, Richmond, Kentucky

Mr. Robert P. Hukill, Coalition for Safe Disposal, Worton, Maryland

Mr. Robert T. Jaske, P.E., Bethesda, Maryland

Ms. Karyn J. Jones, Citizens for Environmental Quality, Hermiston, Oregon

Ms. Susan Lee Jones, Citizens for Environmental Quality, Hermiston, Oregon

Ms. Toni Lampkin, Springfield, Oklahoma

Mr. Stephen A. McFadden, Independent Research Advocate, Pasco, Washington

Mr. John E. Nunn, III, Worton, Maryland (Letter—July 21, 1993 to the Stockpile Committee, copy of letter —July 30, 1993 to General Walter L. Busbee)

Mr. Wilbur Slockish, Jr., Rural Alliance for Military Accountability (RAMA), The Dalles, Oregon

Dr. John L. Spomer, Citizens for Environmental Quality, Hermiston, Oregon

Thomas B. Stibolt, MD, and Lis P. Brenner, Ph.D., Sherwood, Oregon

Stephen B. Thacker, M.D., M.Sc., Acting Director, National Center for Environmental Health, Centers for Disease Control, Atlanta, Georgia

Mr. Craig Williams, National Spokesperson, Chemical Weapons Working Group, Berea, Kentucky

June 10, 1993

Dear:

Our nation has a large stockpile of lethal unitary chemical agents and munitions. Congress has directed that the Department of Defense, which chose the Department of the Army as its principal agent, destroy this stockpile in a safe and effective manner. Though long embarked on a disposal program involving the incineration of all agent and munitions components, in October 1992 the Army was further directed to report to Congress by December 31, 1993, on potential alternatives to its baseline disassembly and incineration process. The Army report would include an evaluation of the report of the Committee on Alternative Chemical Demilitarization Technologies (Alternatives Committee) of the National Research Council (NRC) of the National Academy of Sciences (NAS). It would also include recommendations made by the NAS, or more specifically, the Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program (Stockpile Committee). On June 30, 1993, these Committees will sponsor a Forum on disposal technologies for lethal chemical agents and munitions.

Before giving details on the Forum, I would like to provide some background on the overall NRC effort with regard to the Army Chemical Stockpile Disposal Program. The Stockpile Committee suggested to the Army in March 1991 that an evaluation of alternative technologies be undertaken. In November 1991, the Office of the Assistant Secretary of the Army (Installations, Logistics and Environment) formally requested that the NRC undertake an independent study of alternative technologies. In early 1992, the NRC initiated a two-step effort.

First, the Alternatives Committee was established, with the task of preparing a broad review of potential alternative technologies. The Committee's report, *Alternative Technologies for the Destruction of Chemical Agents and Munitions, is* being released to the public today, June 10, 1993. A copy is enclosed for your perusal.

Second, based upon that report, and on the Stockpile Committee's knowledge of and considerable experience with disposal program requirements, it was asked to make recommendations to the Army on disposal processes that might be appropriate for systems capable of safe, economic, and timely disposal of lethal unitary chemical agents and munitions. This report is due from the Stockpile Committee in November 1993. As indicated above, information and recommendations from these reports would be included in the Army's December 1993 report to Congress.

FIGURE B-1 Letter of invitation to public forum.

As Chairman of the Stockpile Committee, I am writing to seek your participation in the June 30 Forum, which will be sponsored by both the Stockpile and the Alternatives Committees. The Forum will explore and discuss issues raised by the Alternatives Committee report, and is intended for those interested in agent and munitions elimination. A copy of the tentative agenda is enclosed. The Forum has four fundamental purposes:

- to briefly review the findings of the Alternatives Committee report;
- to review the technical issues being considered by the Stockpile Committee;
- to ensure that the Stockpile Committee is informed of citizens' concerns; and
- to review the evaluation methods and process that the Stockpile Committee will use to formulate its recommendations.

We hope to establish a sound, common language for discussing technical issues, for comparing alternatives, and for obtaining effective public comment on the planning of the disposal effort. Invitees to the Forum will include citizens and representatives from affected states (copy of Letter of Invitation to Governor enclosed), government agencies, environmental groups, and members from interested Congressional Staffs. An informal list of interested parties from your state is enclosed.

Your interest in these matters has come to our attention, which is why I am extending this invitation to you to attend the Forum. Should you be unable to do so, your written comments with regard to alternatives would be most welcome. Space at the Forum will be limited; therefore, please indicate your intentions to attend as soon as possible, but absolutely no later than June 24, 1993. Should you desire to submit written comments, please have them to us no later than June 25 in order that we may have them available at the Forum. A response form is attached for your convenience.

I apologize for this short notice. If you have any questions about the Forum, please feel free to contact Ms. Margo Francesco, National Research Council staff, by telephone at (202) 334-1902 or by facsimile at (202) 334-2620 for further details and information.

Sincerely yours,
Carl R. Peterson,
Chairman
Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program

C

Use of Activated Carbon Adsorption Systems for Exhaust Gas Cleaning

Incineration technologies produce large volumes of gaseous emissions containing trace amounts of impurities. In the case of the Chemical Stockpile Disposal Program, these impurities may consist of residual agent or non-agent materials. Both have the potential of causing chronic health effects. The amount of these impurities can be greatly reduced by passing all effluent gas through an activated carbon (charcoal) adsorption bed (the method used in gas masks) before discharging the gas.

TECHNICAL DESCRIPTION

Because of its high surface area, activated carbon has the ability to selectively adsorb and retain certain types of molecules on the internal surfaces of tiny pores and interstices of its granules. The selectivity and capacity for adsorption depend on the method of carbon production or activation, and can be very high for removal of agents and chlorinated hydrocarbons.

Activated carbons are typically manufactured by heating carbonaceous materials such as nut shells or coke to a high temperature in the presence of an oxidizing gas such as steam or dilute oxygen. They can have an extremely high surface area (500-1,200 square meters per gram) in the many small pores that are formed. These pores adsorb ambient molecules on their surface, **and** for the contaminants of interest, as much as 20-50 percent of the activated carbon weight can be adsorbed before saturation. However, for the very low concentrations expected with waste gas from stockpile disposal, the amount adsorbed is less and is proportional to the concentration of contaminant, which might be around 1 percent of the carbon weight.

Industrial gas filtration processes commonly employ several sequential vertical beds of charcoal, each several inches thick. They have gas velocities of 1 foot per second or less to ensure essentially complete removal (adsorption) of organic compounds from the waste stream. Metals leaving a system in the form of particulates are also removed by the charcoal. (The ventilation air filtration system at Tooele has six beds of charcoal.) The space in between beds allows for gas flow redistribution and gas sampling equipment, to permit analysis of the gas as it flows through the beds. (Gas analysis following the second, fourth, and final beds is typical.) Provisions to provide bed bypass or diversion of gas to alternate beds to allow bed replacement without overall system shutdown are typical in engineered systems.

The results of these design considerations are that a typical charcoal filter system for a chemical agent and munitions processing plant the size of Tooele might be 20 feet by 20 feet square (or equivalent in smaller units) by 50 feet long, containing on the order of 30 tons of charcoal.

Contaminants are quickly adsorbed in the upstream portion of the first bed, and work their way through it and subsequent beds as illustrated in Figure C-1.

Initially, the carbon becomes saturated in the upstream part of the first bed but it drops to an extremely low-level at further distances from the leading face, so that contaminants in the gas leaving the first bed are below the level of detection. At a later time, the drop-off occurs further along in subsequent beds. If the concentration was monitored downstream of the second bed, "breakthrough" of contaminant when detected there would indicate that it was time to replace or regenerate the carbon in the preceding beds.

The speed at which breakthrough travels through the bed increases as gas velocity and temperature are increased, and is faster for less strongly adsorbed contaminants.

The velocity of the breakthrough wave and the depth of the bed determine time to breakthrough. For low concentrations of high molecular weight contaminants, such as agents and dioxins, this time can be designed to be on the order of several months. This duration easily allows adequate time for chemical analyses between the beds to certify contaminant removal and to determine breakthrough upstream of the final bed with adequate time for bed replacement or other remedial action. The system therefore approaches the desirable features of "closed-loop" systems in that contaminants are stored on the charcoal until removed for regeneration or disposal. A charcoal bed followed by gas storage has also been suggested. The committee believes that the charcoal bed, storing the contaminants, eliminates the need for gas storage.

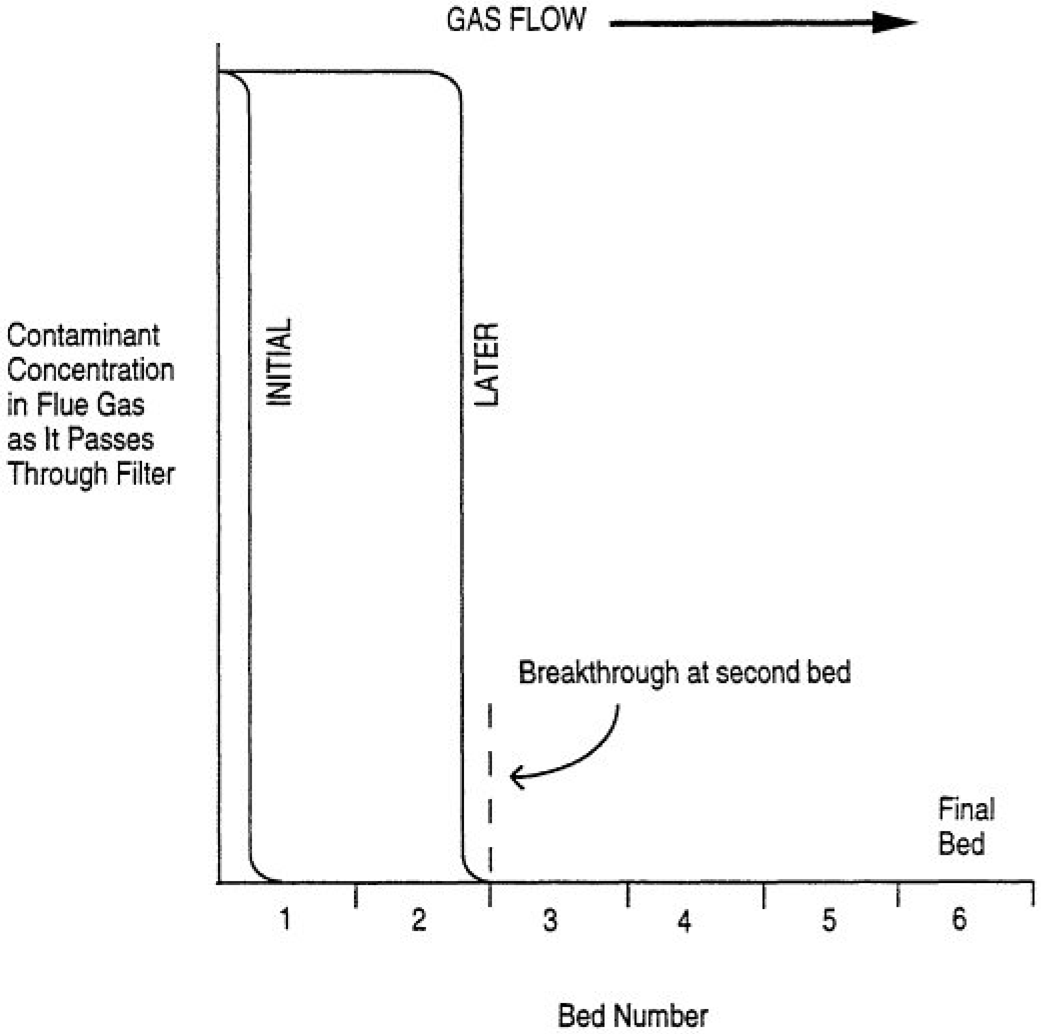


FIGURE C-1 Contaminant concentration profiles in a series of charcoal beds.

If a pulse of high agent concentration occurred, it would also be captured, and the leading edge of the pulse would then migrate through the bed at about the same speed as the wave from lower concentrations, as long as it did not exceed the storage capacity of the bed. If the bed could hold 10 percent of its weight of agent, for a high-concentration pulse, 10 pounds of agent (typical of the amount in a projectile) could be retained by 100 pounds of charcoal. The same amount of agent for a lower-concentration pulse would require more charcoal for storage since the storage capacity for low contaminant concentrations is proportional to the contaminant concentration.

The current agent monitoring system produces frequent false alarms (NRC, 1994a) due to non-agent molecules that are counted as agent. Use of charcoal adsorption will significantly reduce these compounds and should greatly reduce false alarms in the exhaust gases.

Liquid water, if present in the pores, can effectively eliminate the adsorption capacity of the filled pores. Gases are therefore adjusted to less than 50 percent relative humidity. This is accomplished by either heating the gases to reduce the relative humidity or cooling the gases to condense the water, followed by heating. Flue gases, which have been water quenched and scrubbed, contain large amounts of water (typically around 5 percent) and must be dried—generally by cooling—and then reheated. However, for ventilation air, simple heating will suffice. Since cooling and water condensation are expensive, it is desirable to minimize this activity. However, doing so leaves a higher exit gas dew point (the point at which water will condense) because of the higher water concentration and requires the gas to be reheated to a higher temperature to avoid condensation problems.

As the exit gas temperature is increased, the adsorptive capacity of the charcoal decreases, time to breakthrough decreases, and the probability of hot spots or fires is increased. The optimum temperature will then depend on the specific application. For example, the Hugo Peterson company in Germany (U.S. Army, 1993b) designs and manufactures activated charcoal filters for flue gas treatment. Typical operating temperatures are in the range of 120-130ºC (250-265ºF). Even at this relatively high temperature, the concentrations of dioxins and furans are reduced by a factor of 50 with the meter-thick Peterson filters.

Activated carbon has been used at Johnston Atoll Chemical Agent Disposal System (JACADS) to capture agent in plant ventilation air. Here, a stack of six 3-inch beds is used. Typical initial reductions of agent in the first bed have been on the order of 400,000 to 1, showing the pronounced effect of operating at near ambient air temperature (the agents are believed to be somewhat more difficult to remove than the higher molecular weight dioxins). An optimum operating temperature for agent destruction systems between these two extremes (Peterson filter operating temperatures and ambient air temperature) would probably provide the best balance between cost and the extent of contaminant removal.

The Hugo Peterson systems use a moving bed with continuous addition and removal of activated carbon. Because of their simplicity and proven high performance, fixed-bed systems such as those used at JACADS are expected to be a better choice for backing up the high-performance destruction systems planned for the stockpile destruction program.

Problems that might be encountered include

- poor removal efficiency due to leakage around or through the carbon beds;
- hot spots or fires; and
- loss of capacity from contact with water.

Leakage around or through the beds of charcoal was initially encountered in the development of the JACADS system. This problem can be detected by measuring contaminant removal efficiency and, once detected, is not difficult to correct.

Hot spots have been encountered in the Hugo Peterson and other high-temperature systems. If not controlled, these hot spots can develop into a fire. Development of hot spots can be monitored by continuous measurement of carbon monoxide concentration and can be controlled by increasing the flue gas velocity or switching to an inert gas or steam. To the committee's knowledge, hot spots are less of a problem at lower temperature and have not been encountered in the JACADS installation.

Fires can also be initiated rapidly if a major upstream process upset should occur, such as the failure of power to the quench, wet scrubbing, and/or cooling water supply pumps. Without corrective action, such a failure would rapidly inject into the carbon beds a high-temperature gas stream with sufficient residual oxygen to cause a fire. The results of such a fire might also involve the rapid release of previously stored contaminants, although some would obviously be destroyed in the fire. An obvious corrective action would be to divert the flue gas flow to a backup bed after cooling the gas with a backup system. Such solutions Will require care in both design and system operation.

Loss of capacity due to contact of the charcoal with water can be caused by several different system failures:

- Failure to maintain the gas temperature an adequate number of degrees above the dew point will allow condensation on the cooler walls of the duct work. Typical systems maintain an adequate thermal margin or provide for heating of the walls. Failure to do so may result in a continuous but slow addition of water, and in its contact with portions of the bed, producing lack of adsorption in such portions of the bed. Such failures are not likely to be catastrophic, but they will degrade bed performance.
- Sudden injections of water, such as might be caused by the failure of one or more components in the water removal process upstream of the charcoal filter units, would cause a massive failure in the ability of the charcoal to adsorb further gases. This would not likely result in any sudden release of previously adsorbed agent or toxics due to their greater adsorptivity

than water. The water would merely block the interstitial passages in the carbon granules, preventing further gas adsorption. It would not likely block the bulk gas flow through the much larger void spaces between the charcoal granules. Again, diverting the flow to a backup bed and water removal system would reduce this risk.

- Provisions would normally be made for easy removal and replacement of individual charcoal beds. Under normal industrial circumstances, these would likely be thermally regenerated. However, beds that have been potentially contaminated with agent would likely be destroyed by incineration or sent to a hazardous waste landfill.

Careful and frequent monitoring of bed performance is clearly needed. This may require special techniques, such as periodic injection of a tracer material chosen for this purpose.

Choice of a specific charcoal type, operating temperature, gas velocity, and monitoring technique will require some further study and testing. However, major problems are not anticipated.

A charcoal system is believed to be superior to the storage and release system described in the report *Alternative Technologies for the Destruction of Chemical Agents and Munitions* (NRC, 1993a), since the use of charcoal would reduce toxics to a level below that of the current baseline pollution abatement system.

D

Supercritical Water Oxidation and Wet Air Oxidation

Supercritical water oxidation and wet air oxidation—two moderate-temperature, high-pressure processes—have attracted interest because of some potential advantage over components of the baseline system:

- The processes lend themselves to the use of oxygen rather than air; the volume of off-gases can be reduced as a result.
- Some potential gas pollutants do not appear to be formed: particulates, NO_x, and dioxins, for example (Some nitrogen in feed materials has shown up as N_2O).
- The processes operate with low or moderate concentration of material in water, typically 1 to 10 weight percent; consequently, they are particularly useful when the feed material is already available in dilute form.
- The processes are like incineration in that they are broadly applicable to any oxidizable organic compound.

Typical operating conditions for these two processes are

1. for wet air oxidation,

- temperature 200-300ºC,
- pressure 600-2,000 pounds per square inch; and
- residence time in reactor, 1-2 hours; and

2. for supercritical water oxidation,

- temperature 450-600ºC,
- pressure 3,500+ pounds per square inch, and
- residence time in reactor, 10 seconds to 2 minutes.

Wet air oxidation has been in commercial use for more than 20 years. There are more than 200 plants in operation worldwide, working on a variety of feedstocks: spent caustics, sludge from municipal and industrial wastewater, pulp and paper waste, metallurgical processing waste streams, etc. Supercritical water oxidation is being actively studied by many research groups; commercial applications are believed to be imminent.

The higher temperature of Supercritical water oxidation (SCWO) compared with wet air oxidation (WAO) has a large effect on reaction rates, which shows up in the different reactor residence times. Additionally, the oxidation process in wet air oxidation is far from complete; 20 to 50 percent of the organic carbon will remain, though in altered form, as small organics such as acetic acid. In contrast, Supercritical water oxidation can oxidize organic material almost completely. The aqueous phase from wet air oxidation will require further treatment; it is usually fed to a biological treatment process. The aqueous phase from Supercritical water oxidation may not need this type of further treatment.

Reaction rates for chemical agents or surrogate compounds have not been measured directly. Test results on wet air oxidation for a large number of related materials have been reported (Copa and Lehmann, 1992). For example, various herbicides and pesticides—phosphorus compounds related to nerve agents—have been destroyed to high destruction removal efficiency (DRE) levels (99.99 percent):

- round-up—a phosphono compound (i.e., C—P bond);
- dursban—a thinophosphorus compound; and
- malathion—a dithiophosphorus compound.

The reaction rates for large molecules appear to be high. Some of the oxidation products, however (e.g., acetic acid), are much more refractory and persist in the wet air oxidation product. They require the higher temperature and pressure of supercritical water oxidation for their oxidation in reasonable time.

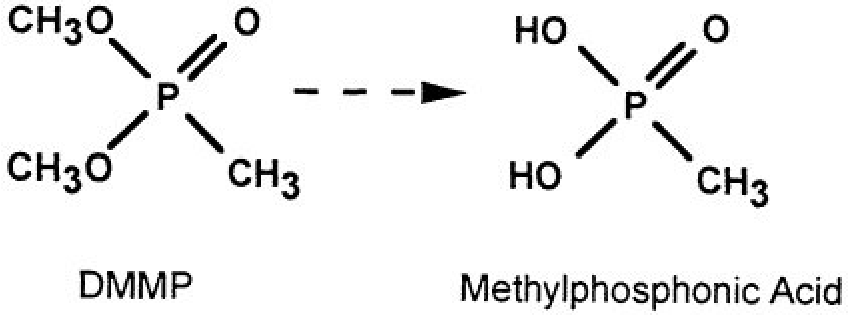
Reaction rate data for some small molecules have been reported in the form of first-order reaction rate constants (Testor et al., 1991). Some materials (e.g., methanol), which are intermediates in the oxidation of larger species, show large rate dependence on temperature. The data illustrate why wet air oxidation leaves a large fraction of the organic carbon remaining as small molecules such as methyl alcohol; the higher temperature of supercritical water oxidation ensures a much higher level of destruction.

For example

Half-Life of Methanol 3,500-psi Pressure

Temperature (ºC)	Half-Life (Seconds)
450	2,065
500	21
530	1.5

Data on surrogates of chemical agents have shown that the C—P bond (as in GB and VX) is the most resistant to cleavage under supercritical water oxidation conditions (E. Gloyna, personal communication with Dr. Walter May, 1993). For example, it was shown that DMMP (dimethoxy methylphosphonate) is hydrolyzed readily to the corresponding methylphosphonic acid.



The acid product however was more resistant to attack; 10 percent of theoretical oxygen demand remained in a test at 520ºC, 7 seconds residence time.

Small scale pilot plant tests have recently been carried out on GB and VX, under supercritical water oxidation conditions (ARPA, 1993). Conditions were 4,000 pounds per square inch, 450-525ºC, and residence times of 10 seconds or more. The agents were "completely" destroyed (DRE of more than six 9s). Traces of acetic acid and formic acid were reported in some runs. The data indicate that temperatures and residence times can be chosen to reduce the organic content of the water to negligible levels; no after-treatment for removal of organics should be needed.

No pilot plant tests on mustard have been attempted yet. The reactivity should exceed that of GB and VX, based on some surrogate compound work. (There is no C—P bond, the resistant bond in nerve agents.) Other problems are expected, however.

Corrosion has been a major problem with both supercritical water and wet air oxidation, particularly in the presence of the acidic reaction products that result from chemical agent oxidation. A lot of metals and a few refractories were tested for reactivity or solubility under acidic conditions expected for GB or VX oxidation, at 350 and 550ºC. Some of the results (Gloyna, personal communication with Dr. Walter May, 1993) follow:

Material	Loss rate (mils/year))
Pt, Pt-Ir, Pt-Rh	0.1-1
Ta, Nb	50-3,000
Ti	100
Ni alloys	100
ZrO_2	10-150
$A1_2 O_3$	100-800
SiC	1,000

Platinum or other noble metals stood up well, as shown. They do not stand up to chloride ion, or to chloride-nitrate, at low pH, however. The corrosion rate in HCl or in $HCl\text{-}HNO_3$ solutions was increased a thousandfold or more over other reagents such as HF. Other refractory metals (Ta, Nb, Hastelloy C) also dissolved excessively in acidic chloride solution.

A platinum liner was chosen for the pilot reactor used at the Illinois Institute of Technology Research Institute for the GB and VX tests (ARPA, 1993). Mustard however presents a problem because of its high chlorine content (44 weight percent).

Corrosion can be sharply reduced by caustic addition to increase the pH. This raises a serious problem with supercritical water oxidation, however: the salts formed are insoluble in the supercritical fluid under the "usual" supercritical water oxidation conditions. Insoluble salts have led to plugging problems in the reactor. Techniques for handling the problem, or getting around it, are under investigation. The problem will arise with mustard because of the need to control corrosion under supercritical water oxidation conditions. The "plugging" problem is not expected to arise with wet air oxidation; the alkali salts formed at high pH are soluble in the liquid water present.

The control of corrosion by increased pH has another possible disadvantage: the CO_2 from the reaction products can react with the excess caustic to form additional salt—sodium carbonate. The total solid product can be increased two- or threefold as a consequence, which is generally considered undesirable.

SUMMARY

The two processes are in different stages of development. Wet air oxidation has been in commercial use for many years. Supercritical water oxidation is under active research and development.

Both processes are generally applicable to organic materials. They have somewhat different advantages and disadvantages:

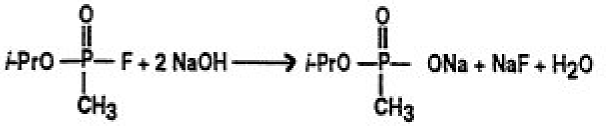
- Wet air oxidation does not perform a complete mineralization. The high organic content of the effluent water will require further processing (e.g., biological treatment).
- Corrosion is expected to be a severe problem with both technologies, requiring control by suitable choice of material and/or control of pH. Corrosion is a particular problem with supercritical water oxidation, where pH control has thus far led to plugging problems.

E

Neutralization (Chemical Hydrolysis)

GENERAL CHARACTERISTICS AND EXPERIENCE

One potentially attractive approach to the destruction of chemical agents is chemical hydrolysis (i.e., reaction with water to form products of reduced toxicity). Because some of the reaction products are acids, a base such as lime or sodium hydroxide is generally used to neutralize the acidic products, hence, the generic description of the process as neutralization. The base may also catalyze the hydrolysis to permit it to be carried out more rapidly and with more efficient use of process equipment. The hydrolysis of the nerve agent GB (sarin) has been studied extensively and is described by the reaction:

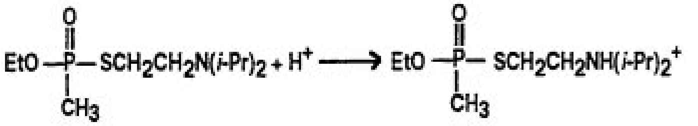


$$i\text{-PrO}-\underset{\underset{CH_3}{|}}{\overset{\overset{O}{\|}}{P}}-F + 2\,NaOH \longrightarrow i\text{-PrO}-\underset{\underset{CH_3}{|}}{\overset{\overset{O}{\|}}{P}}-ONa + NaF + H_2O \qquad (1)$$

Neutralization is potentially applicable to the whole family of phosphate-based nerve agents and to blister agents such as the sulfur "mustards" and arsenic-based Lewisite, although the processes for agents other than GB have had much less study. Despite several known problems in hydrolysis technology, neutralization has attractive features that commend it for study as an alternative to the liquid incinerator of the baseline system. Hydrolysis is usually carried out under mild conditions, generally atmospheric pressure and less than 100ºC, in fairly conventional chemical process equipment. After neutralization, the products are nearly neutral solutions containing inorganic salts and organic compounds of greatly reduced toxicity. The product solutions can be treated further by a variety of processes to produce "mineralized" products suitable for disposal like normal chemical wastes. Because process conditions are mild, the volatile components of the reaction mixtures should be contained easily.

The U.S. Army's experience with neutralization of the nerve agent GB has confirmed some of the potential virtues as well as the practical problems associated with this technology. In an extensive field program carried out at the Rocky Mountain Arsenal from 1973 to 1976, 4,188 tons of GB were hydrolyzed successfully (Flamm et al., 1987). The nerve agent was treated with a large excess of aqueous sodium hydroxide to produce a water solution of inorganic salts and organic compounds. The solutions were evaporated, and the solid residues were deposited in a hazardous waste landfill. With hindsight and better analytical capabilities, it appears that the amount of solid waste could have been substantially reduced by working with a much smaller ratio of alkali to GB. In addition to the U.S. Army experience with hydrolysis of GB, various neutralization processes have been used to destroy multi-ton quantifies of the agent in Great Britain, Canada, the Soviet Union, and most recently, Iraq. Overall chemical hydrolysis has much to recommend it for destruction of bulk quantities of agent GB.

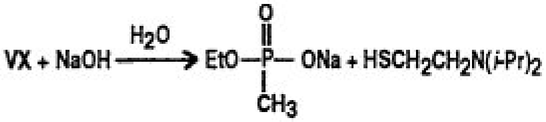
In contrast to the large-scale use of neutralization to destroy GB, the experience with hydrolysis of nerve agent VX and the various mustard agents is largely confined to laboratory- and pilot-scale studies. A major problem is that these agents, in contrast to GB, are much less soluble in water and react slowly under neutral or alkaline conditions. Several approaches to deal with this problem have been explored (Yang et al., 1992). For agent VX, aqueous solubility is greatly increased by working in acidic solution because the acid protonates the amine function of the agent to form a soluble salt:



$$\mathrm{EtO}-\underset{\mathrm{CH_3}}{\overset{\mathrm{O}}{\overset{\|}{\underset{|}{\mathrm{P}}}}}-\mathrm{SCH_2CH_2N}(i\text{-}\mathrm{Pr})_2 + \mathrm{H}^+ \longrightarrow \mathrm{EtO}-\underset{\mathrm{CH_3}}{\overset{\mathrm{O}}{\overset{\|}{\underset{|}{\mathrm{P}}}}}-\mathrm{SCH_2CH_2NH}(i\text{-}\mathrm{Pr})_2^+ \qquad (2)$$

VX

Although both acid and base catalyze the hydrolysis of the P—S and P—O bonds, these reactions are slow and incomplete at ambient temperature. At elevated temperature (75-90ºC), alkaline hydrolysis detoxifies VX in less than one hour (NRC, 1993a).



$$\mathrm{VX} + \mathrm{NaOH} \xrightarrow{\mathrm{H_2O}} \mathrm{EtO}-\underset{\mathrm{CH_3}}{\overset{\mathrm{O}}{\overset{\|}{\underset{|}{\mathrm{P}}}}}-\mathrm{ONa} + \mathrm{HSCH_2CH_2N}(i\text{-}\mathrm{Pr})_2 \qquad (3)$$

In a related process, Russian workers have utilized an acid-catalyzed *transesterification* of VX with ethylene glycol to give glycol esters of methylphosphonic acid that had low toxicity and could be burned safely.

The alkaline hydrolysis of VX can be accelerated by the addition of a stoichiometric quantity of hydrogen peroxide to the conventional sodium hydroxide solution (Yang et al., 1993). The peroxide has a twofold role in the process. With base, it generates a powerful nucleophile, the hydroperoxide anion, that catalyzes specific P—S bond cleavage to form products of lower toxicity than are formed by base alone. It also oxidizes the aminothiol hydrolysis product to a sulfonic acid of low toxicity, which is not readily converted back to VX. The peroxide-accelerated reaction appears promising as a means to detoxify VX. Use of hydrogen peroxide is convenient because the reagent is widely available commercially and because the only reagent-derived product is water.

A second approach to dealing with water-insoluble agents such as VX and mustard is to carry out the hydrolysis in a polar organic solvent or in a mixture of water and an organic solvent. With VX, the alkaline hydrolysis can be carried out in a polar solvent to give mixed hydrolysis products. The products retaining the P—S bond are toxic. With mustard agents, hydrolysis in the presence of an organic solvent should follow the simple equation:

$$\underset{\textbf{Mustard}}{S(CH_2CH_2Cl)_2 + 2\,NaOH} \rightleftharpoons \underset{\textbf{TDE}}{S(CH_2CH_2OH)_2} + 2\,NaCl \qquad (4)$$

If the reaction proceeded simply as written, it might be attractive to consider isolation of the thiodiethanol (TDE) product for sale through normal commercial channels. In practical terms, however, this strategy seems unlikely because (a) TDE is easily reconverted to mustard agent by treatment with concentrated hydrochloric (muriatic) acid and, hence, is regulated as a chemical agent precursor under the terms of the Chemical Weapons Convention; (b) it would be difficult and expensive to purify by-product TDE to the purity required for normal commercial uses such as textile finishes; and (c) the hydrolysis under mild conditions does not follow the simple equation shown above.

This last point (c) derives from the fact that military-grade mustard agents are not simple compounds, but complex mixtures of chemicals, many of which are polymeric. Apart from deliberate addition of polymeric gelling agents for military purposes, much of the mustard agent in the U.S. Army's stockpile is gelled through a normal autopolymerization reaction that occurs on prolonged storage. The initial step in the polymerization is ideally represented as

$$\text{2 Mustard} \longrightarrow ClCH_2CH_2SCH_2CH_2S^+(CH_2CH_2Cl)_2\,Cl^- \qquad (5)$$

In practice, the polymerization is much more complex and leads to gelatinous masses that are difficult to drain from munitions and storage containers. Hydrolysis of these complex species gives complex mixtures of products.

An important concern in the neutralization approach to the destruction of both nerve and blister agents is that the agent must be destroyed "irreversibly" to meet the requirements of the 1993 Chemical Weapons Convention. The document specifies destruction by "a process by which the chemicals are converted in an essentially irreversible way to a form unsuitable for the production of chemical weapons." This requirement is not always met by hydrolysis processes alone. As noted above, hydrolysis of mustard to TDE is not irreversible because treatment of the product with concentrated hydrochloric acid regenerates the mustard agent. Similarly, hydrolysis of phosphate-based nerve agents may give compounds that can be reconverted to the agents. Destruction of the C—P bond in the methylphosphonate agents GB and VX is needed to meet the requirement for irreversible destruction because methylphosphonic acid is a "scheduled" precursor.

The limitations on the effectiveness of hydrolysis in destroying nerve and mustard agents suggest that neutralization may not be an adequate destruction system in itself. It may, however, constitute part of an effective system when combined with other techniques such as chemical, biological, or supercritical water oxidation. Potentially useful systems are sketched below. These integrated systems must be compared with the baseline system to establish their effectiveness for application at various stockpile locations in the continental United States.

LIMITATIONS ON THE USE OF NEUTRALIZATION

Because neutralization may not do the whole task of munitions destruction, it may be used as part of an integrated system containing several discrete processes. The general system constraints have been discussed earlier. For chemical hydrolysis specifically, the constraints and requirements may be classified as either chemical or physical.

Chemical Concerns

Hydrolysis only reduces the toxicity of liquid streams containing chemical agents. Both to ensure worker safety and to meet the "irreversibility" treaty requirement, hydrolysis may have to be followed by some other process (generally oxidation) that totally destroys the toxic agent and yields products that cannot be reconverted to agent.

To meet U.S. environmental requirements, the products of agent destruction must generally be "mineralized" (i.e., converted to carbon dioxide, water, and inorganic salts, which may be stored safely in a landfill).

Three major waste streams must be dealt with effectively:

1. *Gases*: Although the gaseous waste streams from a hydrolysis process are likely to be small, they must be handled and treated like those arising from the baseline system. The treatment must ensure that there is no agent release and that there is no release of other volatile organic compounds that would impair air quality.
2. *Liquids*: Hydrolysis, whether carried out with aqueous reagents or with solutions in organic solvents, involves handling large volumes of liquids. All the liquid streams must be treated by processes that totally destroy the agent and eventually produce mineralized products. Supercritical water oxidation or wet air oxidation combined with biotreatment appears to be a viable option for mineralization.
3. *Solids*: A neutralization system must ultimately produce oxidized solids that can be contained safely in a hazardous waste landfill. Salts such as fluoride, phosphate, and sulfate should be in insoluble forms (such as calcium salts) to reduce the likelihood of leaching into groundwater.

Physical Limitations

Access to Agent

The U.S. arsenals contain chemical agents stored both in bulk containers and in munitions such as projectiles, bombs, rockets, and land mines. In order to employ neutralization as a destruction process, it will be necessary to transfer the agents from their present containers to appropriate chemical reactors. Access to the agent is easiest when the agent is a pure liquid stored in an easily drained bulk (ton) container, although agent drained from munitions can also be treated by hydrolysis. In draining munitions for agent destruction by hydrolysis, one encounters the same problems as those of the baseline system. As a result, a munitions disassembly process is needed as a "front end" to a neutralization-based agent destruction system.

Other Munitions Components

Chemical hydrolysis is difficult to apply to the agent retained in the metal parts of munitions that have been drained after disassembly. Thorough mixing of the hydrolysis reagent with the liquid agent is necessary to ensure complete neutralization, but it is difficult to get good mixing with films of agent adhering to metal surfaces in the confines of projectiles, bombs, rockets, and other munitions. It is extremely difficult to get complete hydrolysis of agent retained in minute cracks in the metal. Neutralization alone is also ineffective in destroying "energetics" such as explosives and propellants that are contained in the munitions. Because of these physical limitations on low-temperature, liquid-phase destruction processes, it is likely that a complete system for munitions destruction must employ a thermal process as a "back end" to the system. The thermal process might be either incineration as in the baseline system or high-temperature baking of the metal parts of a weapon.

Potentially Useful Applications of Neutralization

The chemical and physical constraints listed above help define situations in which a neutralization-based system might be preferred as a way to destroy agents in the U.S. stockpile. Neutralization systems look most attractive when neat liquid agent is easily available. The best situations for its use are arsenals where the agent is stored only in ton containers. These containers are drained easily (apart from gelled agent) and present relatively little metal surface to be decontaminated after draining. If no other chemical munitions are present at such sites, the capital investment for draining, neutralization, and decontamination facilities may possibly be lower than for the baseline system even though development costs will be higher. The two arsenals that seem to meet this criterion are the Newport Army Ammunition Plant, Indiana, which stores only ton containers of VX, and the Aberdeen Proving Ground, Maryland, which stores only ton containers of mustard agents.

Since chemical hydrolysis of agents contained in munitions such as rockets and projectiles requires access and decontamination processes analogous to the liquid incinerator in the baseline system, neutralization-based systems offer little advantage at sites that store several types of munitions, especially if a variety of chemical agents are contained in the munitions. This disadvantageous situation seems to exist at all U.S. arsenals other than Newport and Aberdeen. Chemical hydrolysis could be substituted for incineration of agent drained from munitions in the baseline system, but the substitution would probably not result in cost reduction or in improved worker safety.

Neutralization could be used at Newport and Aberdeen in either of two contexts: (1) it could be used as part of a complete on-site agent destruction and waste treatment facility; or (2) it could be used for preliminary detoxification of agent on-site, with the hydrolysis products shipped elsewhere for incineration, biological treatment, or oxidation by other means. The "stand-alone" facility, option (1), at each site would involve the full set of unit operations described in the following section.

Option (2) is economically attractive because it would require construction of only the facilities needed for neutralization. The hydrolysis products could be sent to other arsenals for final disposal. For maximum advantage, the drained metal ton containers would be decontaminated by treatment with a hydrolysis reagent to render them safe for shipment to another site having the thermal treatment facilities necessary to prepare the metal for final disposal. This approach would eliminate the need for an incinerator and might reduce the capital cost for disposal facilities.

POSSIBLE SYSTEM DESIGNS FOR NEUTRALIZATION

As discussed above, a neutralization process is but one component of the complex integrated system required for safe destruction of chemical agents. A complete system must contain the following elements:

1. a drain station in which containers of liquid agent are opened and emptied in a contained-atmosphere environment, just as in the baseline system;
2. reactors for the hydrolysis and oxidation of liquid agent;
3. thermal treatment to decontaminate metal parts such as ton containers or munitions such as bombs (the treatment might be done either by furnace heating as in the baseline system or by baking in an externally heated oven); and
4. cleanup treatments for each waste stream:

    - gas streams include vapors of the agent from the contained-atmosphere rooms used for munitions handling, gases evolved from the chemical reactors, and combustion gases from the thermal treatments;
    - liquids, primarily the aqueous effluent from the hydrolysis and oxidation reactors; and
    - solids, largely salts from evaporation of the liquids, but also ash from the thermal treatment.

One possible scheme for integration of these elements into a complete system for destruction of chemical agents is sketched in Figure E-1. The postulated system would be better adapted to handling bulk agent than complete munitions. Some of the unit operations (draining and gas cleanup) are similar to those in the baseline system and are well developed. Others are significantly different and would require extensive research and development. Two of these significantly different aspects (agent hydrolysis and treatment of liquid hydrolysate) are discussed in more detail below.

Liquid Agent Destruction

Most neutralization-based schemes for agent destruction involve hydrolysis and oxidation in sequence. For the nerve agent GB, the hydrolysis-neutralization step is largely developed. The oxidation to convert organic products from GB hydrolysis (mostly isopropyl alcohol and methylphosphonic acid) to mineralized products for disposal would require extensive research and development. The processes might be much the same as those required for VX. If the neutralization of GB were chosen for development, it could be useful as a front end for wet air or supercritical water oxidation. The alkaline hydrolysis of GB would give an aqueous solution that would have the reduced toxicity and low corrosivity desirable in a feed for supercritical water oxidation or wet air oxidation. Oxidation of the hydrolysate under the severe conditions of supercritical water should give mineralized products suitable for disposal after precipitation of calcium Salts and evaporation of the water for recycle.

Implementation of hydrolysis processes for VX nerve agent may require extensive research and development because VX is largely insoluble in alkaline solution and because uncatalyzed hydrolysis is slow. As noted earlier, the peroxide-accelerated alkaline hydrolysis is a promising approach. Oxidation of the hydrolysate under the severe conditions of supercritical water oxidation should give mineralized products suitable for disposal after precipitation of calcium salts and evaporation of water for recycle.

An interesting but undeveloped alternative is to combine hydrolysis and oxidation in a single step (Cooper and McGuire, 1993). A major virtue to combining the two processes is that even though the hydrolysis of the P—S bond in VX is slow, it is greatly accelerated if the sulfur is oxidized first:

$$\text{P-SR} + \text{oxidant} \longrightarrow \text{P-SOR} \quad (\text{R} = \text{CH}_2\text{CH}_2\text{N-}i\text{-Pr}_2) \tag{6}$$

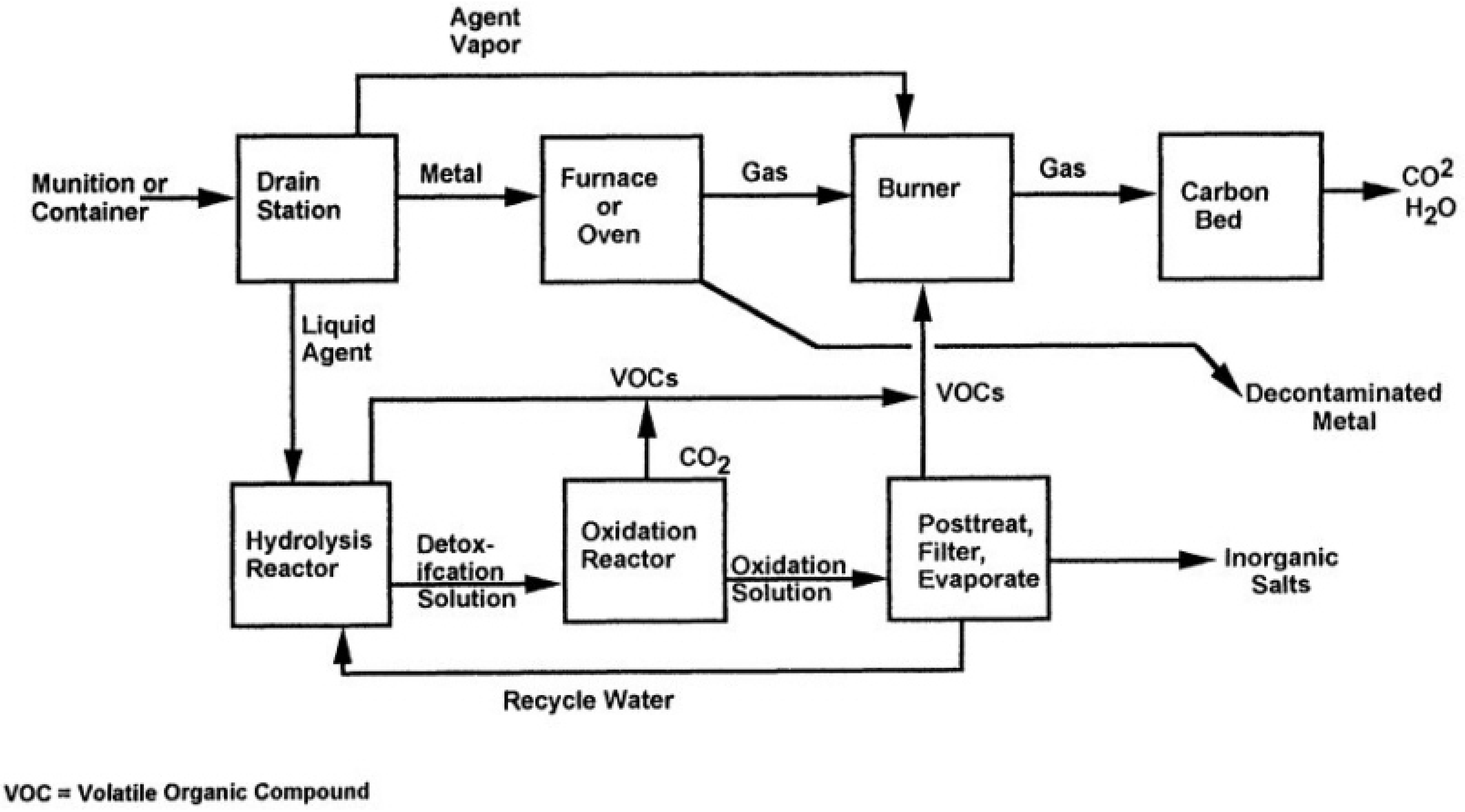


FIGURE E-1 Block diagram of a neutralization-based system for destruction of chemical agents (VOC = volatile organic compound).

The P—SOR product is readily hydrolyzed and oxidized further to give phosphonic and sulfonic acid derivatives. The desired hydrolysis-oxidation can be accomplished with chemical reagents such as oxone ($KHSO_5$) and peroxydisulfate ($S_2O_8^{2-}$). These reactions are being studied at the Army's Edgewood Research, Development, and Engineering Center. If, in fact, the combined hydrolysis-oxidation process can be done without generation of excessive quantities of reagent-derived waste (dilute sulfuric acid), it may be an attractive approach to destruction of bulk VX. Preliminary results indicate that the reagents will convert all of the organic products to carbon dioxide or carbonate salts for easy disposal.

The hydrolysis-oxidation approach to destruction of mustard agents is more difficult than with nerve agents. The mustards are heterogeneous mixtures of chemical compounds and have low solubility in water, either acidic or alkaline solution. The solubility problem can be partially overcome by vigorous agitation, elevated temperature, polar organic solvents, or phase-transfer agents, but it is a technical obstacle that will increase cost as well as adding to development time and effort.

One of the most promising approaches to neutralization of mustard involves hydrolysis with calcium hydroxide (slaked lime) or sodium hydroxide. Both reagents convert mustard rapidly to thiodiethanol and cyclic thioethers (Reichert, 1975; Yang et al., 1993). The products emerge from the reaction as an alkaline solution that may be useful for supercritical water oxidation because it should have low toxicity and reduced corrosivity. It should also be suitable for demilitarization by wet air oxidation or by biological treatment. The oxidation step must be closely linked to hydrolysis because, as noted earlier, TDE is a chemical agent precursor regulated by treaty. Its handling and disposal must be monitored and documented carefully.

An approach to combining hydrolysis and oxidation is to use strongly acidic oxidizing agents such as oxone or peroxydisulfate. These reagents oxidize mustard to carbon dioxide, water, sulfate, and chlorine, but the completeness of oxidation needs to be demonstrated. Oxone and peroxydisulfate generate very large quantities of dilute sulfuric acid as a by-product. To avoid a large sulfate waste stream, it has been proposed that the sulfate by-product be recycled to an electrochemical cell for regeneration of oxone or peroxydisulfate (Cooper and McGuire, 1983). Both the chemistry and the engineering feasibility of this approach need to be demonstrated.

Waste Stream Treatments

The waste streams from a neutralization-based process differ from those generated by the baseline system. The greatest difference is the nature of the liquid generated by the hydrolysis and oxidation steps. The gas and solid waste streams, however, also differ significantly from those in the baseline system. A particular virtue of neutralization is that most of the products of agent destruction are liquids or solids that can be stored easily until analysis and certification are completed.

The gases and vapors generated by a system like that in Figure E-1 resemble those from the baseline system, but there are two significant differences. One major difference is that the low temperatures in the neutralization and oxidation processes should not generate dioxins and furans. The main potential for formation of these materials in the proposed system is in the furnace or oven used to decontaminate metal parts. The small amount of products of incomplete combustion formed in this operation should be handled by the charcoal filter system proposed for the "enhanced" baseline system. In principle, there is little opportunity for formation of chlorinated dioxins or furans in the destruction of VX because there is no significant amount of chlorine in the agent or the proposed reagents. Mustard agents contain chlorine, but they have been burned at the Johnston Atoll Chemical Agent Disposal System (JACADS) without exceeding accepted limits for products of incomplete combustion production.

A second difference between the baseline system and the scheme of Figure E-1 arises if an externally heated oven is used instead of an internally fired furnace to treat contaminated metal parts such as ton containers. The oven baking treatment may drive vapors of unreacted agent into the gas phase along with the products of thermal decomposition and combustion.

The liquid streams exiting from the hydrolysis and oxidation reactors will vary greatly depending on the agent being treated and the reagents used to destroy it. Perhaps the simplest situation is presented by the effluent from supercritical water oxidation of hydrolyzed agents. The effluent should be a slightly alkaline water solution of inorganic salts such as carbonate, phosphate, sulfate, and chloride (also fluoride if GB is treated this way). All these materials except chloride can be precipitated as relatively insoluble calcium salts that can be filtered, calcined, and deposited in a hazardous waste landfill (after proper analysis and certification). The aqueous filtrate containing chloride and traces of other salts can be treated by conventional processes as in the baseline system.

Wet air oxidation (WAO) of the aqueous hydrolysis product, followed by biological oxidation, should produce a result like that obtained with supercritical water oxidation. The combination of wet air oxidation and biotreatment is a common commercial practice.

The aqueous hydrolysis products could also be oxidized chemically. Mild alkaline oxidants such as peroxide or hypochlorite may produce liquid wastes containing significant amounts of partially oxidized organic products. These compounds should have low toxicity, but will require extensive further treatment before they can be released into the environment. Use of chlorine or hypochlorites as oxidizing agents will also lead to high chloride concentrations in the effluents. The liquid effluents from any particular process must be characterized thoroughly in order to develop appropriate posttreatment processes.

Treatment of the agent hydrolysis products with acidic, sulfur-based reagents (oxone, peroxydisulfate) would produce voluminous waste streams because many pounds of oxidant are required to oxidize 1 pound of agent. The oxidizing agent is converted to dilute sulfuric acid, which will be contaminated with phosphate or chloride from oxidation of the agent. These waste streams could be treated with lime to precipitate calcium sulfate, but the sheer volume of this product would be a severe burden on landfills unless the sulfuric acid can be recycled.

One critical aspect to be considered with any neutralization-based process is that large volumes of liquid need to be pumped, piped, filtered, and evaporated. Although these are standard unit operations in the chemical industry, each operation introduces a risk of leaks and spills of liquids, some of which may contain the agent or other toxic compounds. Careful engineering is required to reduce the risks. Considerable forethought is also needed because all of the effluents are eventually released to the environment as carbon dioxide, water, and the solids that go to landfills. The volume of water to be released can be reduced by recycle to earlier steps in the process, but some salt-beating streams need to be "purged" from the system. The volume of these streams can be reduced by evaporation, but the process must be controlled to prevent generation of mists or aerosols that may escape containment.

The solid wastes arise mainly by precipitation of insoluble salts from the oxidation effluent and by evaporation of the salt-beating filtrates remaining after precipitation. The insoluble salts can be deposited in hazardous waste landfills, but characterization and certification of the solids must take place before transportation. The soluble salts, primarily sodium and calcium chlorides, present greater difficulties because of their potential for leaching from a landfill.

HEALTH, SAFETY, AND ENVIRONMENTAL CONCERNS RELATED TO NEUTRALIZATION PROCESSES

Many concerns about the destruction of chemical agents are common to all destruction processes. The greatest risks probably arise from the on-site transportation and handling of munitions or storage containers, the disassembly and draining operations, and the handling of liquid agent before destruction. These sources of risk are shared by the baseline system and nearly all the alternatives. The differences lie in the specific destruction processes and the character of the waste streams that result from them. For neutralization, the unique concerns center on the liquid streams and the solids derived from them.

For neutralization, air monitoring analogous to that recommended for the baseline system must be done to protect workers. Air monitoring also needs to be part of a complete system because the thermal treatment of metal parts has the potential for agent release as well as the emission of non-agent volatile organic compounds (VOCs). Non-agent VOCs from the hydrolysis and oxidation steps are expected to present minimal risks to the workers and the community.

The unique risks in neutralization center on aqueous solutions or suspensions containing incompletely neutralized agent. Spills or leaks should not pose a threat to the neighboring community if properly contained, but they would present serious problems for workers involved in cleanup. Since both VX and mustard act on or through the skin, contact with the liquids must be avoided.

A closely related source of risk is accidental discharge of solutions containing incompletely neutralized agent to the waste treatment systems for salt precipitation, filtration, and evaporation. If such discharges occur, worker exposure and equipment contamination could be severe problems. Careful monitoring of the hydrolysis and oxidation processes will be needed, and may require the development of specialized equipment to analyze aqueous solutions containing agent and its decomposition products. Some of the known hydrolysis products are toxic, and others may reform toxic substances as solution compositions change during the waste treatment processes. Research on analytical procedures and specific solution chemistry will be necessary.

The potential environmental impacts unique to neutralization-based systems also arise from the nature of liquid discharges, whether accidental or as part of routine operations. For example, it is difficult to predict the environmental effects that would occur if dilute aqueous solutions of methylphosphonic acid from hydrolysis of nerve agents were to be released as a result of leaks, spills, or failure of wastewater treatment processes. Acute toxicity to a variety of plants and animals is easily measured, but longer-term effects on ecosystems may be difficult to forecast. A closely related problem is leaching of soluble compounds (e.g., methylphosphonic acid) absorbed on solids sent to landfills for disposal. Given the substantial volume of solids generated by a neutralization process, this potential problem should be considered carefully. Again it points to the need for careful and continuous monitoring of effluents from hydrolysis and oxidation operations.

RESEARCH AND DEVELOPMENT NEEDS

Many of the research and development needs for neutralization-based systems to destroy chemical agents have been mentioned in the preceding discussion. Because these needs will be specific to the system chosen, it may be desirable to prioritize the research activities on the basis of the systems most promising for development. The criteria for selection may include factors such as readiness of a process for development and the potential capital cost savings relative to the baseline system.

Based on the "access" limitations discussed earlier, the most promising sites for use of neutralization-based processes are those that store solely VX and mustard in bulk containers. For VX, the most attractive options appear to be base-catalyzed hydrolysis followed by oxidation or, alternatively, a combined hydrolysis-oxidation in which the two processes occur simultaneously. For mustard agents, the options seem similar—base hydrolysis followed by oxidation or a combined hydrolysis-oxidation process.

Research and Development Needs Specific to Nerve Agent VX

1. Understand the chemical mechanism for hydrolysis of VX and establish the potential to accelerate the process by catalysis.
2. Select and develop a process for oxidation of the hydrolysis products of VX:

    - Evaluate the NaOH or NaOH-peroxide hydrolysis products as feeds for incineration.
    - Evaluate the product of glycol-phosphoric acid transesterification as a feed for supercritical water oxidation. The glycol ester arising from this process should give a product with low toxicity, and even though the catalyst is acidic, the ester should have low corrosivity.
    - As candidates for non-supercritical water oxidation, clean chemical oxidants such as ozone and hydrogen peroxide should be tested because they do not add to the waste burden from the agent destruction process.

3. Analytical techniques must be developed for water solutions of VX and its hydrolysis products.

Research and Development Needs Specific to Mustard Agents

1. Understand the process mechanisms and solubility effects critical to the hydrolysis of mustard agents by NaOH. It will be necessary to deal with partially polymerized sulfonium salts in munitions-grade mustard agent.
2. Evaluate the mustard hydrolysis products as feeds for biological oxidation and for incineration.
3. Evaluate dean oxidants (ozone, peroxide) for posttreatment of the base hydrolysis products. Do they mineralize the products? If not, are the final products suitable for biotreatment?
4. Develop analytical procedures for aqueous solutions containing mustard, TDE, and the oxidation products of TDE. Analyze and characterize the final oxidation products.

Generic Development Needs

1. Apply the preferred destruction chemistries to munitions-grade agents, which may be gelled or highly contaminated with decomposition and corrosion products. These adaptations may involve difficult engineering challenges.
2. Scale up the preferred processes from the laboratory to pilot scale to production scale.
3. Develop process control instrumentation and protocols specific to the chosen process.
4. Evaluate the use of hydrolysis reagents as a means to decontaminate metal to the 3X level for shipment.
5. Develop a system for evaporation of aqueous wastes that minimizes aerosols, mists, and corrosion.
6. Develop an environmentally acceptable treatment for chloride-containing waste.
7. Evaluate the toxicity and ecological impact of all process effluents that will (or might be) released to the environment.

Time Requirements

Development of neutralization systems to the stage at which they are ready for full-scale use will take longer than development of an enhanced baseline system, even for neutralization processes with which we have considerable experience, such as hydrolysis of GB nerve agent. If GB hydrolysis were to be developed, all the topics listed above under generic development needs would require study and testing. Even with concurrent studies of the various needs, the time required to implement the process on a large scale might be three years longer than for implementation of the baseline system at a given site. For processes such as oxidation with oxone or bleach, which have a sound chemical footing but little or no development beyond the laboratory, the development period might be at least a year longer. Speculative or unproven processes, such as peroxydisulfate oxidation with sulfuric acid recycle, would take significantly longer under the best of circumstances.

The extended development times required for alternatives to the baseline system will increase costs and prolong the risks associated with continued storage of chemical agents and munitions. In a few situations, however, the potential reductions in capital costs for disposal (relative to the baseline system) may justify the necessary development costs. A significant factor in proceeding with the development of a particular disposal system may be the availability of pilot facilities in which to evaluate the alternative technology.

SUMMARY OF FINDINGS ON NEUTRALIZATION PROCESSES

Neutralization processes have potential advantages over the liquid incinerator of the baseline system for the destruction of chemical agents because they operate at low temperatures that are less apt to generate troublesome by-products such as dioxins. Neutralization may also incur lower capital costs for destruction of bulk agents, but this advantage is lost in dealing with munitions that also require extensive thermal treatment for decontamination. As a consequence, neutralization-based processes seem most promising for use at sites such as Newport and Aberdeen, where only bulk liquid agents are stored.

Neutralization must be integrated into a total chemical agent and munitions disposal system in much the same way that incineration is integrated into the baseline system. Many aspects of a neutralization-based system will be similar to those of the baseline system (e.g., transport and draining of munitions or storage containers, decontamination of metal parts, and treatment of gaseous effluents).

Neutralization processes will produce smaller amounts of gaseous effluents than the baseline system, but they will involve handling large volumes of toxic liquids. Treatment of the liquid products may generate larger quantities of solids for disposal than would result from the baseline system.

Extensive research and development will be required to provide neutralization-based systems suitable for implementation even in the most favorable situations. Although there are useful leads for the neutralization of chemical agents (especially nerve agents), development must include both laboratory and pilot studies. Demonstration studies must also include the development of new analytical and process control techniques, and the establishment of waste treatment procedures adapted to each specific neutralization process and site.

The time required to develop a neutralization-based process for use at any specific site may be three to five years longer than for the baseline system if a complete on-site system must be developed. The time requirement would be reduced if the hydrolysis products were to be disposed of by incineration at an existing incinerator. The research and development for a stand-alone system will add significantly to the cost, although the capital investment may be reduced in favorable situations. It also prolongs the risks associated with continued storage of chemical agents and munitions at a site.

F

Update on the Status of Biological Processes

INTRODUCTION

The status of biological treatment processes for chemical agents and munitions was reviewed in the report *Alternative Technologies for the Destruction of Chemical Agents and Munitions* (*Alternatives* report; NRC, 1993a). It was determined that biological treatment may be potentially applicable to chemical agents but not to energetics, metal parts, or dunnage for the current stockpile configuration. Additional information indicates that some studies have been initiated for the use of biological treatment for energetics (DOD, 1993). Thus, the applicability of biological processes to chemical agents may include the following scenarios:

1. direct biological detoxification of chemical agent;
2. biodegradation of the products from a primary chemical agent detoxification process; and
3. treatment of extracted energetic materials.

Direct biological detoxification of chemical agents may be based on specific enzymatic processes that would be implemented either as purified enzymes, nonviable whole-cell extracts, immobilized cells, or growing cell systems. Primary chemical agent detoxification processes that may be followed by biological treatment include direct biological detoxification (Bio-Bio), chemical neutralization (Chem-Bio), and wet air oxidation (WAO-Bio). The treatment of energetic materials may involve solubilization of solid material followed by one of the three processes mentioned above.

Considerations for the development and application of each of these potential processes must include the status of current research and the flexibility of the projected process for application to the actual stockpile configuration. The purpose of this appendix is to provide an update on the status of each of these potential applications.

Most of the research discussed in the following material is at an early exploratory and proof-of-concept level aimed at enzyme hydrolysis of GB and

VX. Direct biological treatment of mustard is not possible. Enzyme-based processes for both GB and VX would have to be available for practical application to the stockpile configuration. Currently, proof of concept has been demonstrated only for GB. Engineering development appears premature. Biological treatment of reaction products from chemical agents, including GB VX, and mustard, appears however to have a reasonable chance for early application.

DIRECT BIOLOGICAL TREATMENT OF CHEMICAL AGENTS

Mustard

Mustard (H, HD, HT) is a strong vesicant and DNA mutagen that destroys cellular membranes and enzymes. Development of a biological process for direct treatment of mustard agents is extremely unlikely because of their generic xenobiotic characteristics. No recent information has been reported on biological processes for direct destruction of mustard agents.

GB and VX

Several enzyme systems have been reported that are capable of degrading GB and other neurotoxic fluorophosphonates to varying extents and at differing rates (NRC, 1993a). The initial enzyme-catalyzed hydrolysis of GB results in the production of hydrogen fluoride and monoisopropyl methylphosphonate. In addition, several enzyme and cellular systems have been identified that are capable of cleaving the P—C bond; however, their direct applicability to GB or VX destruction has not been evaluated. At the time of the *Alternatives* report, critical limitations of enzyme systems to date were (1) tentative reported results indicating enzyme degradation activity on VX, (2) the absence of reaction rate data, and (3) lack of demonstration of proof of principle for practical process and reactor designs based on the reported enzyme systems. However, recent enzyme characterization and laboratory development of treatment processes based on specific enzyme systems have been initiated and several positive results reported.

It has been reported that hydrolysis of VX with specific P—S bond hydrolysis was observed with the organophosphorus hydrolase (OPH) enzyme from soil bacteria (Harvey et al., 1993b; Kolakowski et al., 1993). The specific activity of the OPH enzyme in studies at Edgewood Research, Development and Engineering Center (ERDEC), Aberdeen, Maryland, on VX was between 0.5 and 1.0 μmol VX hydrolyzed per minute per milligram of protein.

At the recent ERDEC Scientific Conference on Chemical Defense Research (November 16-19, 1993), Kolakowski reported on OPH characterization and increased turnover numbers as a function of metal-ion cofactor with the OPH derived from *Pseudomonas diminuta.* OPH was evaluated for its effectiveness in P—S bond cleavage of VX and related analogues, most of which are commercially available pesticides. Two forms of the enzyme, one with cobalt and the other with zinc as cofactor, were allowed to react with millimolar concentrations of substrate in dilute aqueous media maintained at pH 8.5 and 25ºC. Hydrolysis rates were determined by following the formation of free SH groups. Small, but measurable rates of hydrolysis were observed for VX and several analogues studied, with the activity of OPH (Co^{2+}) usually being 5 to 10 times greater than that of OPH (Zn^{2+}). Spontaneous hydrolysis was negligible. First-order kinetics were observed in all cases, and turnover numbers ranged from a high of 5 per minute for VX to a low of 0.1 per minute for the analogue IBP[1]. OPH is the only enzyme known that hydrolyzes the P—S bond of VX.

Other researchers have reported on the ability to express OPH activity from promoter 1 from *Cochliobolus heterostrophus* and the *trpC* terminator from *Aspergillus nidulans in* the native soil fungus *Gliocladium virens* (Dave et al., 1993a, b). Various *opd*$^+$ transformants displayed differing levels of enzymatic activity, and Western blot analysis of mycelial extracts from transformants confirmed the expression of a mature processed form (lacking the membrane targeting signal) of the enzyme in the fungus.

Harvey et al. (1993b) reported that purified OPH(Co^{2+}) enzyme was able to hydrolyze 0.77- to 1.4-molar concentrations of munitions-grade GB to less than 6 parts per million (ppm) in 1 hour at room temperature. The initial GB concentration was a 5:1 or 10:1 aqueous dilution of chemical agent directly removed from the stockpile. The major stockpile impurity ethyl-GB (approximately 2 percent of the total) was also hydrolyzed.

The Biotechnology Division at ERDEC is accelerating its search for new enzymes and microorganisms capable of degrading both U.S. and Russian stockpile agents. The research team has recently cloned an *opd* gene that encodes the *Alteromonas* JD6.5 enzyme at highly expressed levels (˜5 percent of cell protein in *Escherichia coli*). This enzyme has excellent hydrolytic activity with GB (˜300 µmol/min/mg; Cheng et al., 1993a). In addition, Cheng et al. (1993b) have purified an even more active enzyme from *Alteromonas undina.* The specific activity on GD (soman)[2] is 1,850 µmol/min/mg at 25ºC, pH 7.2, and GB activity is good. Studies are currently under way to clone the gene for this enzyme into *E. coli.*

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[1] O, O-diisopropyl-S-benzylphosphothiate (insecticide Kitazin P)

[2] GD is O-pinacolyl methylphosphonofluoridate.

In summary, the above results indicate that enzyme-based processes capable of both GB and VX hydrolysis may be developed into practical applications. (However, the reported rate of VX hydrolysis is much too slow for practical application.) The OPH enzyme has been characterized and cloned into various viable host cells. Furthermore, the capability of the enzyme to work directly on stockpile agent has been demonstrated. An immobilized whole-cell reactor would limit required enzyme production and purification, eliminate biomass increase, and reduce permanent complications. Major milestones remaining include increased activity (turnover rates) on VX and reactor engineering and evaluation. The time required for development of enzymes with increased activity on VX is not predictable because of the nature of the basic research required.

BIOLOGICAL TREATMENT FOLLOWING NEUTRALIZATION

Mustard

Chemical hydrolysis of mustard under alkaline conditions results in the formation of thiodiglycol as the primary reaction product and numerous other tentatively identified dechlorinated reaction products. Biological treatment of the reaction products from mustard hydrolysis was indicated in the *Alternatives* report as one of the more promising applications of biological processes to the agent stockpile. Subsequent laboratory investigations have demonstrated biodegradation of hydrolysis products from HD (Harvey et al., 1993c).

Investigations of appropriate reactor design for treatment of mustard hydrolysis products have been initiated using thiodiglycol (TDG) as a model substrate. Theoretical studies evaluating different potential reactor configurations indicated that substantial reductions in required reactor volume can be achieved through the use of a fed-batch reactor rather than a continuous stirred tank reactor with cell recycle or two stirred tanks in series design (Sines et al., 1993). Laboratory studies of biological treatment process design have recently been initiated. Some limited thiodiglycol substrate inhibition was indicated in preliminary experiments at substrate concentrations greater than 120 mM. However, this inhibition was very mild, and cells were capable of growth and degradation at much higher thiodiglycol concentrations. The optimal concentration for a bioreactor may be around 120 mM. Bioreactor studies utilizing cryoimmobilized *Alcaligenes* species capable of degrading thiodiglycol have been initiated at the Edgewood Research, Development and Engineering Center.

GB and VX

Biological treatment of reaction products from chemical neutralization of GB and VX was considered in the *Alternatives* report as a potentially viable process subsequent to chemical neutralization. This is being pursued at the Edgewood Research, Development and Engineering Center, but only very preliminary results have been reported.

Cultures have been isolated that utilize ethylmethylphosphonic acid (EMPA) and pinacolyl alcohol as sole sources of carbon for growth. EMPA is produced in stoichiometric amounts from either enzymatic or chemical cleavage of the P—S bond of VX. Pinacolyl alcohol is the alcohol product of GD hydrolysis. Efforts are under way to identify organisms involved and to characterize these processes.

BIOLOGICAL TREATMENT FOLLOWING WET AIR OXIDATION

Application of wet air oxidation as a primary treatment process for chemical agents would result in the formation of aqueous solutions containing acetic acid and other low molecular weight organic compounds. Biological treatment of waste streams similar to those anticipated from wet air oxidation has been applied broadly at full scale. Process development for the specific wastewater stream produced by wet air oxidation would still be required.

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Biographical Sketches

DR. CARL R. PETERSON, CHAIRMAN

Dr. Peterson has served as Chairman of the Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program since April 1, 1991. He is an Associate Professor, Department of Mechanical Engineering, Massachusetts Institute of Technology, with the primary task of teaching design. Dr. Peterson has extensive industrial and academic experience in designing, testing, and operating mechanical equipment. An original member of the committee from 1987, Dr. Peterson, served as Vice Chairman from August 1, 1989, to April 1, 1991, at which time he was appointed Chairman. He is a Fellow of the American Society of Mechanical Engineers (ASME).

DR. ELISABETH M. DRAKE

Dr. Drake, a member of the National Academy of Engineering, is the Associate Director of the Massachusetts Institute of Technology Energy Laboratory. A chemical engineer with interest and experience in technology associated with the transport, processing, storage, and disposal of hazardous materials, as well as with chemical engineering process design and control systems, she has a special interest in the interactions between technology and the environment. Dr. Drake has served extensively, both as a consultant to government and industry, and as a professor of chemical engineering. She has been very active with the American Institute of Chemical Engineers, and in particular with their Center for Chemical Process Safety. She belongs to a number of environmental organizations, including the Audubon Society, the Sierra Club, and Greenpeace.

DR. COLIN G. DRURY

Dr. Drury is currently a Professor of Industrial Engineering at the State University of New York at Buffalo and Executive Director at the Center for Industrial Effectiveness. He has served in a number of professional capacities including committees of the National Institute of Occupational Safety and Health and the National Institutes of Health. His expertise is in human factors and ergonomics, and he has numerous publications on human factors.

MR. GENE H. DYER

Mr. Dyer was graduated with a bachelor of science degree in chemistry, mathematics, and physics from the University of Nebraska. Over a 12-year period he worked for General Electric as a process engineer, the U.S. Navy as a research and development project engineer, and the U.S. Atomic Energy Commission as a project engineer. He then began a more than 20-year career with the Bechtel Corporation in 1963. First a consultant on advanced nuclear power plants and later a program supervisor for nuclear facilities, he then served as manager of the Process and Environmental Department from 1969 to 1983. This department provided engineering services related to research and development projects, including technology probes, environmental assessment, air pollution control, water pollution control, process development, nuclear fuel process development, and regional planning. He culminated his career at Bechtel by serving as a senior staff consultant for several years, with responsibility for identifying and evaluating new technologies and managing their further development and testing for practical applications. He is a member of the American Institute of Chemical Engineers, and a registered Professional Engineer. He recently served as a member of the National Research Council (NRC) Committee on Alternative Chemical Demilitarization Technologies.

MG VINCENT E. FALTER

General Falter spent more than 34 years in the Army, about half of that time dealing with nuclear weapons. He was once the Director of Nuclear and Chemical Warfare on the Army Staff, and was the single point of contact for all chemical operations for the Department of Defense. He was then responsible for all chemical weapons and their destruction. He initiated funding for the Johnston Atoll Chemical Agent Disposal System and testified on behalf of the system before Congress. He retired from the Army approximately five years ago. Since then, he has been a national security research analyst and consultant for numerous corporations. He has participated in a number of activities, including (1) Joint Strategic Targeting Planning Staff at the Strategic Air Command; (2) Scientific Advisory Committee for Nuclear Weapons Effects; and (3) Department of Defense negotiator for two of the rules for chemical disarmament talks.

DR. ANN FISHER

Dr. Fisher, Senior Research Associate, Department of Agricultural Economics and Rural Sociology, the Pennsylvania State University, has extensive academic experience. She also spent 10 years at the Environmental Protection Agency, where she analyzed the benefits of reducing environmental risks and then managed its Risk Communication Program. She is currently Coordinator of the Risk Communication Specialty Group of the Society for Risk Analysis.

DR. B. JOHN GARRICK

Dr. Garrick, a member of the National Academy of Engineering, is President and Chief Executive Officer of PLG, Inc., an engineering and management consulting firm located principally in Newport Beach, California, and Washington, D.C. His principal accomplishments include his Ph.D. thesis that first advocated quantitative risk assessments for nuclear power plants; the building of the first team to perform the initial comprehensive and quantitative risk assessments for the commercial nuclear power industry; and being a major contributor to the methods employed in risk analysis, as well as a prime mover in elevating risk assessment to a science and engineering discipline. Dr. Garrick is a Fellow of the American Nuclear Society, the Society for Risk Analysis, and the Institute for the Advancement of Engineering. He has published approximately 200 papers and reports on risk, reliability, engineering, and technology. Dr. Garrick received his Ph.D. in engineering and applied science from the University of California, Los Angeles.

DR. WILLIAM E. KASTENBERG

Dr. Kastenberg is Professor of Engineering and Applied Science, Department of Mechanical, Aerospace and Nuclear Engineering, University of California, Los Angeles (UCLA). He has taught risk assessment, risk management, toxic waste control, energy and the environment, and applied mathematics. His research interests include the development and application of risk assessment and risk management methods to nuclear and nonnuclear technologies. He is currently the Director of the Risk and Systems Analysis for the Control of Toxics Program at UCLA and Chairman of the Steering Committee for UCLA' s Center for Clean Technology. He is also Chairman of the Technical Advisory Committee for the Environmental Division at Los Alamos National Laboratory.

DR. CHARLES E. KOLB

Dr. Kolb is President and Chief Executive Officer of Aerodyne Research, Inc. At Aerodyne since 1971, his principal research interests have included atmospheric chemistry, combustion chemistry, chemical lasers, gas/surface methods for advanced materials preparation, and the chemical physics of rocket and aircraft exhaust plumes. He has served on several National Aeronautics and Space Administration panels dealing with ozone in the atmosphere, as well as on two NRC committees dealing with atmospheric chemistry.

DR. DAVID S. KOSSON

Dr. Kosson was graduated with a bachelor of science degree in chemical engineering, a master's degree in chemical and biochemical engineering, and a doctorate in chemical and biochemical engineering from Rutgers, the State University of New Jersey. He joined the faculty at Rutgers in 1986 and was made an associate professor with tenure in 1990. He teaches graduate and undergraduate chemical engineering courses. In addition, he is the projects manager for the Department of Chemical and Biochemical Engineering, where considerable work is under way in developing microbial, chemical, and physical treatment methods for hazardous waste. He is responsible for project planning and coordination, from basic research through full-scale design and implementation. Dr. Kosson is a participant in several Environmental Protection Agency (EPA) advisory panels involved in waste research and is the Director of the Physical Treatment Division of the Hazardous Substances Management Research Center in New Jersey. He is a prolific writer in the fields of chemical engineering and waste management and treatment. He is a member of the American Institute of Chemical Engineers. He recently served as a member of the NRC Committee on Alternative Chemical Demilitarization Technologies.

DR. JOHN P. LONGWELL

Dr. Longwell was graduated with a bachelor of science degree from the University of California, Berkeley, and with a doctor of science degree in chemical engineering from Massachusetts Institute of Technology. His distinguished career in research and engineering with Exxon Research and Engineering Company involved management of several research divisions and culminated with the position of senior scientific advisor for four years. Since 1977, Dr. Longwell has been Edwin R. Gilliland Professor of Chemical Engineering at Massachusetts Institute of Technology (MIT). His research interests for the last decade have been primarily related to his activities as Associate Director of the MIT Center for Environmental Health Sciences, with special focus on generation and health effects of combustion products. He is a member of the National Academy of Engineering, the American Institute of Chemical Engineers, and the American Chemical Society. He recently served as the Chairman of the NRC Committee on Alternative Chemical Demilitarization Technologies.

DR. RICHARD S. MAGEE

Dr. Magee is a Professor, Department of Mechanical Engineering and Department of Chemical Engineering, Chemistry, and Environmental Science and Executive Director of the Center for Environmental Engineering and Science at the New Jersey Institute of Technology (NJIT). He also directs EPA's Northeast Hazardous Substance Research Center, as well as the Hazardous Substance Management Research Center, which is jointly sponsored by the National Science Foundation and the New Jersey Commission on Science and Technology, both headquartered at NJIT. He is a Fellow of the ASME and a Diplomate of the American Academy of Environmental Engineers. Dr. Magee's research expertise is in combustion, with major interest in the incineration of municipal and industrial wastes. He presently serves as Vice-Chairman of the ASME Research Committee on Industrial and Municipal Wastes; as a member of the United Nations Special Commission (under Security Council Resolution 687) Advisory Panel on Destruction of Iraq's Chemical Weapons Capabilities; and as a member of the North Atlantic Treaty Organization Science Committee's Priority Area Panel on disarmament technologies.

DR. WALTER G. MAY

Dr. May was graduated with a bachelor of science degree in chemical engineering and master of science degree in chemistry from the University of Saskatchewan and with a doctor of science degree in chemical engineering from the Massachusetts Institute of Technology. He joined the faculty of the University of Saskatchewan as a professor of chemical engineering in 1943. In 1948, he began a distinguished career with Exxon Research and Engineering Company, where he was a Senior Science Advisor from 1976 to 1983. He was Professor of Chemical Engineering at the University of Illinois from 1983 until his retirement in 1991. There he conducted courses in process design, thermodynamics, chemical reactor design, separation processes, and industrial chemistry and stoichiometry. Dr. May has published extensively, served on the editorial boards of *Chemical Engineering Reviews* and *Chemical Engineering Progress,* and obtained numerous patents in his field. He is a member of the National Academy of Engineering and a fellow of the American Institute of Chemical Engineers, and he has received special awards from the American Institute of Chemical Engineers and the American Society of Mechanical Engineers. He has a particular interest in separations research work. He is a registered Professional Engineer in the state of Illinois. He recently served as a member of the NRC Committee on Alternative Chemical Demilitarization Technologies.

DR. ALVIN H. MUSHKATEL

Dr. Mushkatel, Professor of Public Affairs, School of Public Affairs, and Interim Director, Office of Hazards Studies, Arizona State University, is an expert in emergency response and communications. His research interests include emergency management, natural and technological hazards policy, and environmental policy. He has been a member of the NRC Committee on Earthquake Engineering. His most recent research focuses on the intergovernmental policy conflicts involving high-level nuclear waste disposal and the role of citizens in this policy area.

MR. PETER J. NIEMIEC

Mr. Peter Niemiec, a partner in the law firm of Greenberg, Glusker, Fields, Claman, and Machtinger, in Los Angeles, California, is an expert in environmental law and regulations. His work in the private sector has focused on the regulation of, and liability arising out of hazardous materials, including extensive work on Superfund issues. Mr. Niemiec has also represented federal and state environmental agencies, where he was involved in the development of national enforcement policies, and permitting and enforcement issues for major industrial facilities and landfill disposal sites. Mr. Niemiec currently serves as a Vice-Chair of the American Bar Association's Special Committee on Toxic and Environmental Torts, and on the Steering Committee of the Environmental Auditing Forum. He also served as an Adjunct Professor at the Indiana School of Law (Indianapolis), where he taught environmental law. He has published several articles on the availability of private remedies for environmental cleanup.

DR. GEORGE W. PARSHALL

Dr. Parshall is a member of the National Academy of Sciences; has been with the Central Research Department, E.I. du Pont de Nemours & Company for 39 1/2 years, including 13 years as Director-Chemical Science; and is an expert in conducting and supervising chemical research, particularly in the area of catalysis and inorganic chemistry. He has been a past member of the NRC Board on Chemical Science and Technology, and played an active role in National Research Council and National Science Foundation activities.

DR. GAVRIEL SALVENDY

Dr. Salvendy, NEC Professor of Industrial Engineering, Purdue University, is an industrial psychologist. He is a distinguished expert in human factors and industrial engineering. His current research activities are focused on human-computer interaction and human aspects in advanced manufacturing. Dr. Salvendy is a member of the National Academy of Engineering and recipient of the former USSR's Academy of Sciences Founder Award.

DR. JAMES R. WILD

Dr. Wild was graduated with a bachelor of arts degree from the University of California, Davis, and with a doctorate in cell biology from the University of California, Riverside. Following service as a research microbiologist-biochemist at the U.S. Navy Medical Research Institute, he joined the faculty at Texas A&M University in 1975 as an Assistant Professor of Genetics. He was Associate Professor of Biochemistry and Genetics from 1980 to 1984 and was appointed Professor of Biochemistry and Genetics in 1984. In addition to being an extremely active teacher, he has served the university in various administration positions, currently as Chairman of the Faculty of Genetics, Professor and Head of the Department of Biochemistry and Biophysics from 1986 to 1990, and Executive Associate Dean/Associate Dean for Academic Programs of the College of Agriculture and Life Sciences from 1988 to 1992. Dr. Wild has conducted and directed extensive genetic and biochemical research, and has published more than 70 scientific articles and participated in countless seminars and invited presentations. He has been a member of the Faculty of Toxicology and an NIEHS' Graduate Student/Postdoctoral Training Grant in Toxicology since 1992. He recently served as a member of the NRC Committee on Alternative Chemical Demilitarization Technologies.

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