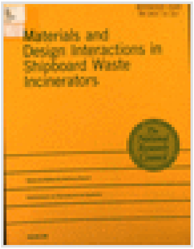


Materials and Design Interactions in Shipboard Waste Incinerators (1979)

Pages
77

Size
8.5 x 10

ISBN
0309332478

Committee on Materials and Design Interactions in Shipboard Waste Incinerators; National Materials Advisory Board; Commission on Sociotechnical Systems; National Research Council

NATIONAL RESEARCH COUNCIL
COMMISSION ON SOCIOTECHNICAL SYSTEMS

NATIONAL MATERIALS ADVISORY BOARD

Chairman

Mr. Julius J. Harwood
Director, Materials Science Laboratory
Engineering and Research Staff
Ford Motor Company
P.O. Box 2053
Dearborn, MI 48121

Past Chairman

Dr. Seymour L. Blum
Vice President
Northern Energy Corporation
70 Memorial Drive
Cambridge, MA 02142

Members

Dr. George S. Ansell
Dean, School of Engineering
Rensselaer Polytechnic Institute
Troy, NY 12181

Dr. Van L. Canady
Senior Planning Associate
Mobil Chemical Company
150 E. 42nd Street, Room 746
New York, NY 10017

Dr. Alan G. Chynoweth
Executive Director, Electronic Device,
Process and Materials Division
Bell Laboratories
Murray Hill, NJ 07974

Dr. George E. Dieter, Jr.
Dean, College of Engineering
University of Maryland
College Park, MD 20742

Mr. Selwyn Enzer
Associate Director
Center for Futures Research
University of Southern California
Los Angeles, CA 90007

Dr. Joseph N. Epel
Director, Plastics Research and
Development Center
Budd Corporation
356 Executive Drive
Troy, MI 48084

Dr. Larry L. Hench
Professor and Head
Ceramics Division
Department of Metallurgical &
Materials Engineering
University of Florida
Gainesville, FL 32601

Dr. Robert E. Hughes
Professor of Chemistry
Executive Director, Materials Science
Center
Department of Chemistry
Cornell University
Ithaca, NY 14850

Dr. John R. Hutchins III
Vice President and Director of
Research and Development
Technical Staff Division
Corning Glass Works
Corning, NY 14830

Dr. James R. Johnson
Executive Scientist and Director
Advanced Research Program Laboratory
3M Company
P.O. Box 33221
St. Paul, MN 55133

Mr. William D. Manly
Senior Vice President
Cabot Corporation
125 High Street
Boston, MA 02110

Dr. James W. Mar
Professor, Aeronautics and Astronautics
Building 33-307
Massachusetts Institute of Technology
Cambridge, MA 02139

Dr. Frederick T. Moore
Industrial Advisor
Industrial Development & Finance Dept.
World Bank
1818 H Street, N.W., Room D422
Washington, DC 20431

Dr. Nathan E. Promisel
Consultant
12519 Davan Drive
Silver Spring, MD 20904

Dr. Allen S. Russell
Vice President-Science & Technology
Aluminum Company of America
1501 Alcoa Building
Pittsburgh, PA 15219

Dr. Jason M. Salsbury
Director, Chemical Research Division
American Cyanamid Company
Berdan Avenue
Wayne, NJ 07470

Dr. John J. Schanz, Jr.
Assistant Director, Center for
Policy Research
Resources for the Future
1755 Massachusetts Avenue, N.W.
Washington, DC 20036

Dr. Arnold J. Silverman
Professor, Department of Geology
University of Montana
Missoula, MT 59801

Dr. William M. Spurgeon
Director, Manufacturing and
Quality Control
Bendix Corporation
24799 Edgemont Road
Southfield, MI 48075

Dr. Morris A. Steinberg
Director, Technology Applications
Lockheed Aircraft Corporation
Burbank, CA 91520

Dr. Roger A. Strehlow
Professor, Aeronautical &
Astronautical Engineering
University of Illinois at Urbana
101 Transportation Building
Urbana, IL 61801

Dr. John E. Tilton
Professor, Department of Mineral
Economics
221 Walker Building
Pennsylvania State University
University Park, PA 16802

NMAB Staff:

W. R. Prindle, Executive Director
R. V. Hemm, Executive Secretary

1/31/79

BIBLIOGRAPHIC DATA SHEET	1. Report No. NMAB-348	2.	3. Recipient's Accession No.

4. Title and Subtitle

Materials and Design Interactions
in Shipboard Waste Incinerators

5. Report Date
1979

6.

7. Author(s) Committee on Materials and Design Interactions
in Shipboard Waste Incinerators

8. Performing Organization Rept. No. NMAB-348

9. Performing Organization Name and Address

National Materials Advisory Board
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D. C. 20418

10. Project/Task/Work Unit No.

11. Contract/Grant No.
DOT-CG-71515-A

12. Sponsoring Organization Name and Address

U. S. Coast Guard
Washington, D. C.

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstracts

The various materials and design problems associated with shipboard waste disposal on U.S. Coast Guard ships is reviewed. An assessment of the present state of the art of several candidate waste management systems is made and suggestions for research and development efforts predicated upon the evolvement of viable shipboard disposal approaches.

17. Key Words and Document Analysis. 17a. Descriptors

Shipboard Incineration
Shipboard Waste Disposal
Ships Wastes
Waste Management Systems
Grinding and Pulping
Spray Drying

Compaction - Waste Materials
Shredding - Waste Materials
Solid Waste Packaging
Control and Monitor Instrumentations for Shipboard Waste Systems

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement This report has been approved for public release and sale; its distribution is unlimited.	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 65
	20. Security Class (This Page) UNCLASSIFIED	22. Price

THIS FORM MAY BE REPRODUCED

Materials and Design Interactions in Shipboard Waste Incinerators

Report of
The Committee on Materials and Design Interactions in Shipboard Waste Incinerators

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council

Publication NMAB-348
National Academy of Sciences
Washington, D. C.
1979

NOTICE

This study by the National Materials Advisory Board was conducted under Contract No. DOT-CG-71515-A with the U. S. Coast Guard.

This report is for sale by the National Technical Information Service, Springfield, Virginia 22151.

NTIS Order No. PB 295 851

Printed in the United States of America.

NATIONAL MATERIALS ADVISORY BOARD

COMMITTEE ON MATERIALS/DESIGN INTERACTIONS IN SHIPBOARD WASTE INCINERATORS

Chairman

WALTER K. BOYD, Senior Research Leader, Corrosion and Electrochemical Technology Section, Battelle-Houston Operation, Houston, Texas.

Members

RICHARD A. ALLIEGRO, Director of Research and New Business Development, Industrial Ceramics Division, The Norton Company, Worcester, Massachusetts.

ORAN L. CULBERSON, Chemical Engineering Department, University of Tennessee, Knoxville.

ROBERT H. ESSENHIGH, E.G. Bailey Professor of Energy Conversion, The Ohio State University, Columbus.

HARRY JACKSON, Consultant, Groton, Connecticut.

ROBERT A. RAPP, Metallurgical Engineering Department, The Ohio State University, Columbus.

CHARLES O. VELZY, President, Charles R. Velzy and Associates, Inc., Armonk, New York.

RICHARD A. WYNVEEN, Life Systems, Inc., Cleveland, Ohio.

Liaison Representative

THOMAS SCARANO, Office of Research and Development, U.S. Coast Guard, Washington, D.C.

NMAB Staff

DONALD G. GROVES, Staff Engineer.

PREFACE

The study documented in this report was requested in 1977 by the U.S. Coast Guard to assist in a shipboard solid waste incinerator development program. This program, which is part of an extensive pollution abatement systems effort, was initiated in response to legislation that prohibits the pollution of the ocean within coastal regions. Both the U.S. Navy and Coast Guard must comply with the provisions of this legislation, and both agencies are pursuing solid waste management investigations.

A committee of the National Research Council's National Materials Advisory Board (NMAB) was appointed to conduct the study. This committee was charged: to assess the current and near-term state of technology for small waste incinerators; to investigate alternative techniques for waste disposal; to determine the feasibility of initiating a full-scale incinerator development effort instead of attempting to modify existing incinerators to meet Coast Guard needs; and to recommend approaches for research and development.

As its study progressed, the committee identified the following specific items for study and evaluation:

- Shipboard and marine environment
- Stack emissions control
- Segregation of solid wastes
- Energy conservation
- Waste heat recovery
- Pretreatment of solid wastes
- Alternatives to incineration
- Retrofit and new construction
- Potential for discharge of solid waste (plastics)

- Waste characteristics
- Volume and weight trade-offs
- Source control of solid wastes
- Single vs. multiple system trade-offs
- Scaling up or down vs. single size
- Fully automatic vs. manual control (sophistication vs. simplicity)
- Performance vs. cost trade-offs
- Time constraints (development time vs. need)
- Cost (development, manufacturing, acquisition, installation, operation, maintenance)
- Market assessment
- Manufacturing methods and costs
- Cyclic operation
- Materials (cost, performance, weight)
- Occupational Safety and Health Administration requirements
- Ash disposal

In assessing the various systems, reliability, habitability, performance, maintainability, operability, and personnel safety were considered. With all these factors in mind, the committee formulated this final report.

Walter K. Boyd, Chairman
Committee on the Materials and
Design Interactions in Ship-
board Waste Incinerators

ACKNOWLEDGEMENTS

The NMAB committee was assisted by various authorities who contributed perspectives from their experience. These authorities, whose contributions the committee gratefully acknowledges, were:

Martin Bell, Consultant to the Royal Canadian Navy
Frank Budininkas, Gard, Inc. (GATX), Niles, Illinois
G. L. Colton, U.S. Coast Guard, Washington, D.C.
William Durnin, National Defense Headquarters, Ottawa, Canada
R. B. Engdahl, Battelle-Columbus Laboratories, Columbus, Ohio
T. E. Jones, Environmental Engineering Test Establishment, Montreal, Canada
P. Klaamas, Department of Fisheries and Environmental Protection Services, Halifax, Nova Scotia
John McKay, Canadian Defense Liaison Staff, Washington, D.C.
Giffen Nickol, David W. Taylor Naval Ship Research and Development Center, Annapolis, Maryland
W. J. Pearson, National Defense Headquarters, Ottawa, Canada
Philip A. Saigh, Gard, Inc. (GATX), Niles, Illinois
Dale Schell, Gard, Inc. (GATX), Niles, Illinois
Robert Schwartz, Executive Officer, United States Coast Guard Cutter, CHASE
John Tozzi, Engineering Officer, United States Coast Guard Cutter, CHASE
William van Hees, David W. Taylor Naval Ship Research and Development Center, Annapolis, Maryland
W. O. Wiley, Consumat Systems, Inc., Richmond, Virginia
Don Wilson, Canadian Armed Forces, Ottawa, Canada
R. J. Wilson, Naval Engineering Test Establishment, Montreal, Canada

Patrick Wright, Consultant to Royal Canadian Navy
Sam Wyatt, Naval Ship Engineering Center,
   Washington, D.C.

CHAPTER I

INTRODUCTION

A. The Problem of Shipboard Waste

A ship and its crew can be considered to have the same sanitary liquid and solid-waste management problems as a land-based community but not the same disposal options. Until quite recently, shipboard wastes generally were disposed of indiscriminately at sea and on the land near ports and waste disposal was not a major consideration in ship design. The environmental movement of the 1960s, however, focused attention on the pollution of the sea, and special shipboard waste disposal techniques now are required.

One of the most difficult-to-handle components of shipboard wastes is trash (i.e., paper, cans, bottles, and food wastes). The normal procedure is to store this trash on the fan tail of the ship as shown in Figure 1a.

B. Legal Background

Included in the environmental protection legislation enacted in recent years are requirements that prohibit the discharge of waste products from vessels in the nation's navigable waters and coastal zones. In response, the U.S. Coast Guard initiated an extensive program to equip its vessels with pollution abatement systems and to develop new systems when existing equipment was inadequate.

With regard to the abatement of wastewater discharges from Coast Guard vessels, the Federal Water Pollution Control Act Amendments of 1972 (1972 FWPCA) state that:

> "...the Administrator...shall promulgate federal standards of performance for marine sanitation devices...which shall be designed to prevent the discharge of untreated or inadequately treated sewage into or upon the navigable waters from new and existing vessels...."

The Act further defines "sewage" as "human body wastes and the wastes from toilets and other receptacles intended to receive or retain body wastes."

Pursuant to this requirement, the U.S. Environmental Protection Agency (EPA) issued performance standards for marine sanitation devices that limit no-discharge and discharge devices and establish effluent quality standards. These performance standards require that:

> ...in freshwater lakes, freshwater reservoirs, or other freshwater inpoundments whose inlets or outlets are such as to prevent the ingress or egress by vessel traffic,... marine sanitation devices... installed on all vessels shall be designed and operated to prevent the overboard discharge of sewage, treated or untreated, or of any waste derived from sewage.
>
> ...In all other waters, ... marine sanitation devices installed on all vessels shall be designed and operated to either retain, dispose of, or discharge sewage. If the device has a discharge,... the effluent shall not have a fecal coliform bacterial count greater than 1000 per 100 milliliters nor visible floating solids....

Recently, the Clean Water Act of 1977 amended the 1972 FWPCA to include "grey water" wastes in the definition of sewage for specific application to commercial vessels operating on the Great Lakes. In addition, discharge standards were raised to a level comparable to secondary treatment standards for shore-based facilities.

The Coast Guard's policy with regard to the disposal of solid waste materials generated during the normal operation of Coast Guard vessels consists of enforcement of the provisions of the Rivers and Harbors Act (Refuse Act) of 1899 and Annex V of the 1973 International Convention for the Prevention of Pollution from Ships convened by the Intergovernmental Maritime Consultative Organization (IMCO). Both the Refuse Act and the Convention prohibit the shipboard disposal of garbage into U.S. navigable waters. For purposes of Coast Guard policy, garbage includes solid food wastes as well as paper products, plastics, rags, glass, metal, bottles, crockery, dunnage, packing and lining materials, and similar refuse generated during the normal operation of a vessel.

FIGURE 1a. Less than a one-day accumulation of trash stored on the fan tail of a typical Coast Guard cutter.

FIGURE 1b. Photograph of typical Coast Guard cutter.

In addition, the Coast Guard prohibits the shipboard disposal into any waters of any plastics, including synthetic ropes, styrofoam, and plastic garbage bags.

The disposal of garbage (with the exception of plastics) outside of U.S. navigable waters is permitted. Such disposal is to be made into the sea as far as practicable from the nearest land, but not less than 25 miles for dunnage and lining and packaging material that will float and not less than 12 miles for solid food wastes and all other garbage.

C. Coast Guard Vessels

The Coast Guard is engaged in a major program to install engineering waste management systems on all its vessels 65 feet in length or longer. These vessels are described briefly in Table 1.

TABLE 1 Coast Guard Vessels

Class	No. of Vessels	Crew Size	Length, ft
Ice Breakers	5	165-225	269-400
High-endurance cutters	17	150	327-378
Medium-endurance cutters	22	55-75	205-230

In designing and installing any waste management system on such vessels, the following system and vessel requirements have been defined by the Coast Guard:

1. Shipboard space available--6 ft long by 7 ft wide by 7½ ft high (including access)

2. Weight of equipment--5000 lb maximum

3. Power requirements--400 V, ac, 3 phase, 60 Hz; 115 V, ac, 1 phase, 60 Hz for 15 A or less; 20 kw peak demand (less is desirable); meet IEEE 45 specification requirements

4. Fuel--No. 2 fuel oil (low-sulfur marine diesel)

5. Stack emissions limitations--less than No. 1 Ringelmann (20 percent opacity) for smoke; 0.2 gr/ft^3 corrected to 12 percent CO_2 maximum and 0.1 gr/ft^3 corrected to 12 percent CO_2 desirable for particulates

6. Ash--2 percent by weight unburned organics maximum

7. Capacity--110 to 450 gal/day for sewage systems; 83 to 338 gal/day for garbage grinder systems; 167 to 684 lb/day or 17 to 68 ft^3/day (uncompacted) for solid waste systems

8. Time between major overhauls (liner life) for incinerators--6000 burn hr (3 yr) minimum and 10,000 burn hr (5 yr) desirable

9. Same deck, horizontal--no vertical deck penetrations

10. Same deck operation--loading, etc.

11. More horizontal space than vertical clearance

12. Operating profile--12 hr/day maximum desirable

13. Materials--suitable for salt water and air marine environment

14. Freshwater carrier for vacuum collected sewage and garbage grinder drains

15. Vibration--first order, 50 mils at 4 cycles/sec vertical and 30 mils at 3 cycles/sec horizontal; second order, 25 percent of first order

16. Skin temperature--120 °F maximum

17. Safety requirements--meet Occupational Safety and Health Administration (OSHA) requirements concerning loading arrangement, etc.

18. Pressure--continuous or transient pressure differential between interior spaces and atmosphere of 3/4 in water column (either positive or negative)

19. Service air--100 psi not to exceed 2 ft^3/min

20. Operation--automatic or semi-automatic (no full-time operator) when underway (waste discharged on shore when in port)

The characteristics of the wastes to be treated are discussed in Chapter III.

CHAPTER II

EXECUTIVE SUMMARY

INCORPORATING CONCLUSIONS AND RECOMMENDATIONS

The Federal Water Pollution Control Act Amendments of 1972 states that most, if not all wastes generated on board ship after 1980 must be treated in some manner as to make them noncontaminating when released into the sea. As part of its effort to meet this requirement, the U.S. Coast Guard asked the National Materials Advisory Board (NMAB) to assess the current and near-term state of the technology for small waste disposal systems suitable for shipboard installation. Incineration was to be given special attention, but alternate systems (e.g., evaporation, spray drying, and compaction) also were to be considered. The committee also was charged to develop a technical program management plan for any research deemed necessary to develop reliable and cost effective waste handling systems. In this respect, the committee concerned itself with near-term (1-3 years), mid-term (2-5 years), and long-term (5-10 years) development programs.

In its assessment of waste management and disposal systems, the committee considered single unit incineration, separate sludge and solid waste incineration, and volume reduction including such processes as evaporation, spray drying, pulping and compaction. Problems of design, reliability, scale-down, maintenance of combustion, and the performance of both metallic and nonmetallic structural materials also were reviewed in detail. On the basis of the data available to it, the committee reached the conclusions and formulated the recommendations presented below.

A. Conclusions

1. At the present time, no satisfactory solution has been developed for the disposal of shipboard wastes regardless of the size of the vessel.

2. No single commercially available incineration system is capable of incinerating all types of waste either simultaneously or on a programmed basis and of meeting the size, weight, reliability, and safety requirements of the Coast Guard. A long-range development and engineering effort would be needed to produce such a system, and there is little or no incentive for industry to underwrite even a portion of the development costs in view of the limited market.

3. The development of individual units for the incineration of either solid (trash) or liquid (sanitary) wastes and pulped galley wastes appears feasible within 3 to 5 years. If solid waste incineration is used, it will be necessary to separate the noncombustibles (e.g., glass, metallic containers, and damaged metal parts) from the trash.

4. The environment in waste incinerators is highly corrosive to metals and ceramic materials. Although materials performance data are limited, high-chromium nickel-base alloys appear to be satisfactory for use in sewage incinerators. Ceramic materials are prime candidates for multipurpose incinerators; however, a considerable effort will be required to identify the optimum specific materials.

5. Compaction is a practical method of reducing the volume of loose trash and has been used on land and sea with varying degrees of success. Reliable systems for Coast Guard applications could be available within 2 to 5 years. The compaction of both loose trash and garbage will require more development effort than the compaction of dry wastes only.

6. Evaporation is a practical and feasible means of reducing the volume of liquid waste that needs to be stored on shipboard, particularly if it is used with a reduced volume sanitary collection system. The scaling up of present systems for possible use on larger Coast Guard ships appears to be feasible within 3 years.

7. Spray drying appears theoretically as a means for disposing of liquid shipboard wastes; however, because of requirements for small particle size and the complexity of the systems, it does not warrant development for shipboard use at this time.

8. Systems for the grinding and pulping of galley wastes have been demonstrated to be feasible; however, they require large quantities of water, and this limit may limit their application by the Coast Guard. Grinding, shredding, or pulping of other types of waste does not appear to be practical for shipboard use.

9. Studies sponsored by the U.S. Navy indicate that controlled packaging can significantly reduce the amount of shipboard solid waste. The Coast Guard's decentralized food supply system will limit applications of controlled packaging, but it should be used whenever possible.

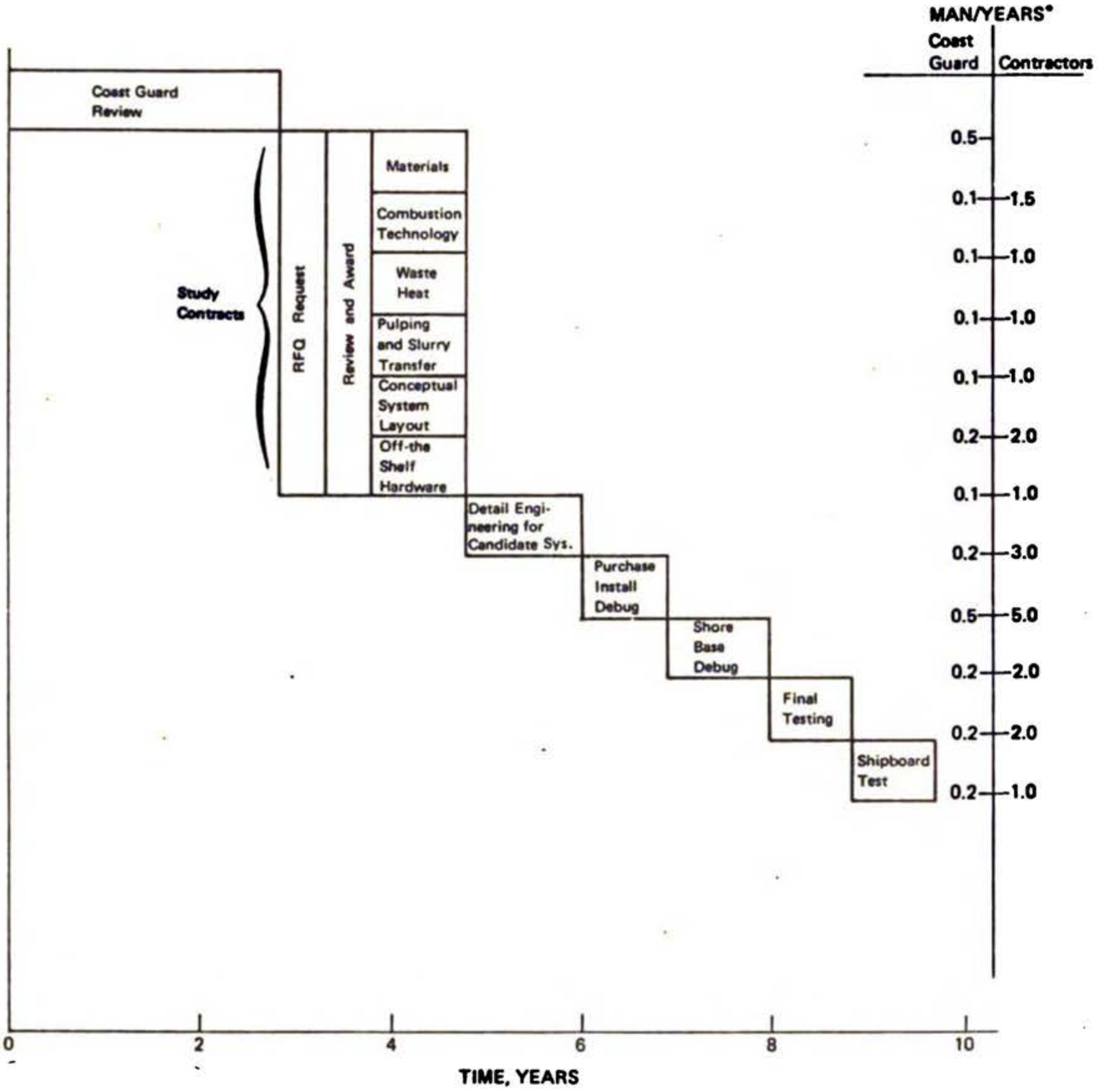
B. Recommendations

1. The Coast Guard should not now undertake a program to develop multipurpose incinerators for shipboard use as shown in Figure 2. Such a development would require considerable effort over a 10-year period with a low probability of success. However, the Coast Guard should continue to monitor waste incineration technology so that a development program could be initiated with a minimum of delays if advances in technology warrant such an activity.

2. The Coast Guard should continue its shipboard evaluation of vortex sewage incinerators under cooperative development by the Navy and Coast Guard. This is a mid-term development program that should be completed within 3 to 5 years.

3. The Coast Guard should initiate a modest effort to develop a pulper and transport system for galley wastes that will permit these wastes to be disposed of with sanitary wastes. This mid-term development program might best be conducted in cooperation with the Navy as indicated in Figure 3a.

4. The Coast Guard should initiate a significant compaction development effort immediately. For the near term only the compaction of solid wastes should be considered. This effort can result in an operable first generation compactor for the new class of vessels scheduled for 1981. The estimated rate of effort is described in Figure 3b.



*100,000 Men/Yrs. (This 100,000 figure includes machining and fabrication costs.)

FIGURE 2 Multipurpose system.

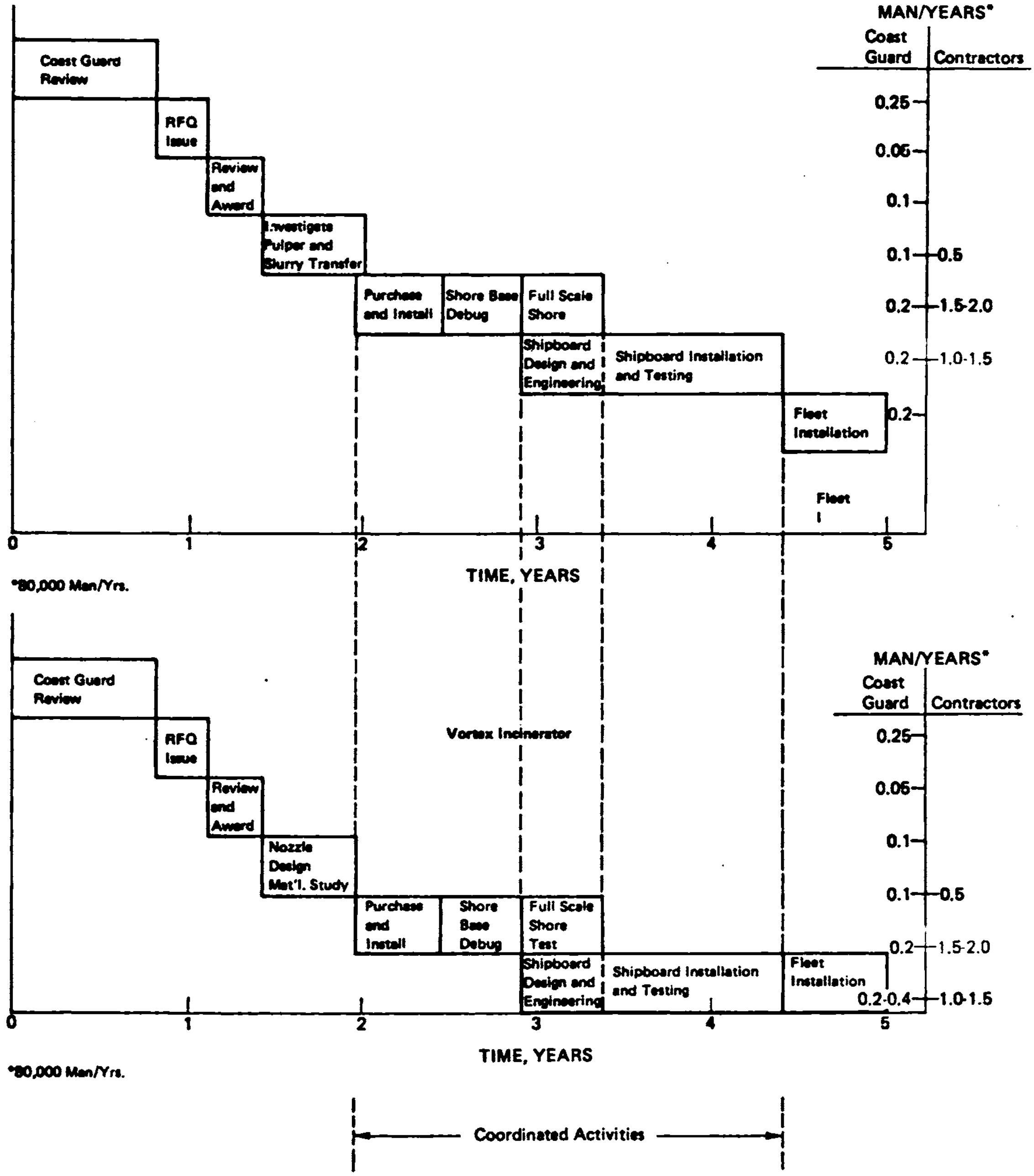
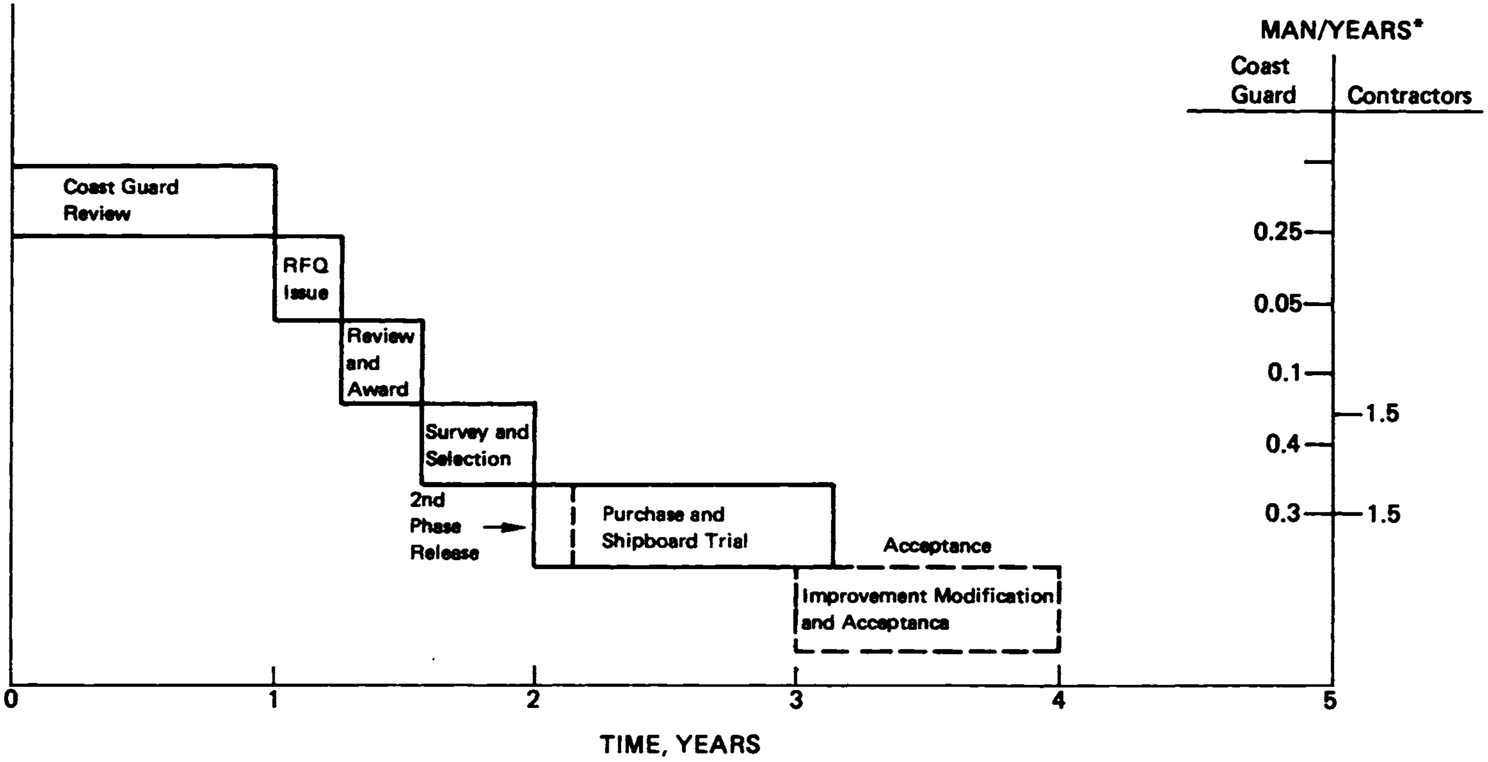


FIGURE 3a. Development of pulper and slurry transporter.



*80,000 Man/Yrs.

FIGURE 3b. Development of compactor.

5. The Coast Guard should initiate studies to determine the feasibility of scaling-up evaporation systems that have given satisfactory service on small Coast Guard vessels. The estimated rate of effort for such a program is described in Figure 4.

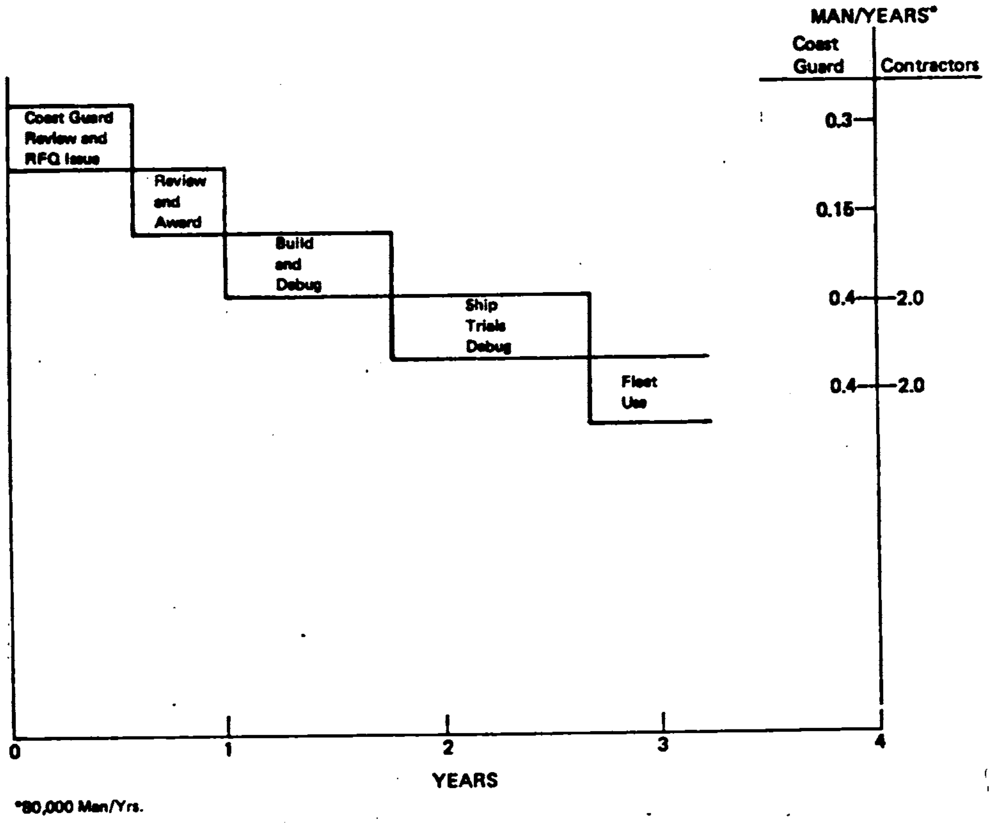


FIGURE 4. Scale-up of evaporator system.

6. The Coast Guard should establish a modest size group within its present research and development structure to concentrate solely on the development, testing, and application of shipboard waste management systems per se. This group should be composed of individuals with expertise in ship system design, process engineering, and materials engineering so that a multidisciplinary team effort can be put forth. Any additional specialized expertise necessary should be available from the National Laboratories of the Department of Energy (DOE) and from the private sector and academia.

7. The Coast Guard should utilize the waste management research facilities of the DOE National Laboratories and the Navy whenever possible but also should consider establishing some modest research at either the Coast Guard Academy or at the Coast Guard Shipyard at Curtis Bay, Maryland. These facilities should be sufficient to allow the testing and evaluation of systems developed for shipboard use.

8. The Coast Guard should initiate an education program to acquaint crewmen and officers with the importance of waste management.

CHAPTER III

CHARACTERISTICS OF SHIP WASTE

A brief discussion of the characteristics of shipboard wastes is presented below. For a more definitive characterization of shipboard wastes the reader is referred to a previous NMAB study entitled Materials of Construction for Shipboard Waste Incinerators (1977).

A. Liquid Waste

1. Sewage (Black Water)

Sewage is the human waste matter from commodes and urinals mixed with salt or fresh water from the flushing system. The volume generated is calculated to be 30 gal/man-day with a normal flushing system and 2 gal/man-day with a reduced volume flushing system.

2. Waste Water (Grey Water)

Waste water on ships originates from showers, wash basins and laundry, galley and scullery sources that utilize fresh water. If garbage grinders are not used the waste water will contain only a small amount of solids composed mostly of particulates, soap, and detergents. The amount of waste water resulting from all domestic services is about 30 gal/man-day; garbage grinders would add an additional 1.5 gal/man-day.

B. Solid Wastes

Solid wastes are much more difficult to characterize than liquid wastes because they vary widely depending on ship type. The information presented in Table 2 was developed during a study of a number of U.S. Navy ships and seem to be a reasonable estimate of the amounts involved.

TABLE 2 Shipboard Solid Waste

Material	Amount, lb/capita/day
Wood	0.25
Paper	0.93
Ceramic	0.02
Cloth	0.08
Metal	0.52
Rubber	0.01
Plastic	0.01
Others	0.08
Garbage	1.14
Total	3.04

Source: Private communication from Willem van Hees, David W. Taylor Naval Research and Development Center, January 16, 1978.

The uncompacted bulk density of this combined solid waste is approximately 10 lbs/ft^3 with garbage and 7 lb/ft^3 without garbage.

CHAPTER IV

DESCRIPTION OF PRESENT AND PLANNED COAST GUARD SHIPBOARD WASTE MANAGEMENT SYSTEMS

A. Waste Water

The Coast Guard currently is engaged in a major program to install new waste water management systems on all its vessels 65 feet in length or longer in order to comply with existing regulations concerning vessel waste discharges. This program is scheduled for completion in 1980. Some vessels now are equipped with new systems while others are operating with old systems.

The system being replaced is a collection, holding, and transfer (CHT) system in which waste water is collected by gravity drainage through three segregated piping systems (i.e., sanitary lines for the wastes from commodes and urinals; galley lines for the wastes from kitchen areas including the discharge from garbage grinders where installed; and turbid lines for the wastes from the laundries, showers, sinks, and certain deck-drains below the water line). Sanitary wastes are collected in a holding or retention tank for transfer ashore when in port, stored during operation in restricted waters, or are disposed of overboard when operating beyond the 3-mile limit. Galley and turbid wastes normally are routed to a small collector-ejector tank from which they are pumped ashore or overboard depending on the operational mode of the vessel. Because the volume of waste water produced is large and the onboard space available for storage is limited, the capability of vessels to operate for extended periods in restricted waters is limited by this system.

The new system being installed handles galley and turbid wastes in the same way as the CHT system (i.e., the galley and turbid lines are segregated, collection is by gravity drainage, and disposal is accomplished via pump-out from a relatively small collector-ejector tank) but uses different methods for the collection of sanitary wastes and garbage grinder discharge. The sanitary wastes are moved by vacuum transport through small diameter lines to a relatively small vacuum collection tank, which also serves as a vacuum reservoir. Vacuum pumps maintain the system vacuum at approximately 15 to 18 inches of mercury. Periodically, the wastes in the vacuum collection tank are pumped to the ship's main holding/retention tank for storage and subsequent disposal ashore or overboard. The sanitary vacuum collection system requires the installation of special commodes and urinals and of small diameter piping to minimize the size of the vacuum pumps

With the new system, sink drain garbage grinders are replaced by heavy-duty grinders that are installed as separate counter-top fixtures in the galley space. The food waste and water slurry discharged from the grinder is stored in a small collection tank mounted below the grinder. This tank is connected to the ship's main holding tank via a vacuum line and vacuum interface valve. When the slurry level in the tank reaches a preset height, the vacuum interface valve opens and the slurry is transported by vacuum to the central holding tank for storage and disposal with the vacuum-collected sanitary wastes. As with the old CHT system, the new system has provisions to route the galley and turbid gravity drains to the sanitary holding tank as operational conditions warrant.

The major advantage of the new system is that the volume of waste water generated by the sanitary vacuum collection system is approximately one-tenth that generated by the standard gravity drainage system. Thus, the retention time in a holding tank of a given size is significantly increased and the length of time that a vessel can operate in restricted waters is increased. In addition, the use of smaller diameter piping (2 in. for the vacuum versus 4 in. for the gravity system) reduces the material costs for new construction applications. The major disadvantages are the additional costs for the special fixtures and repiping required in retrofit application. In addition, the system does not address the problem of the collection and disposal of the galley and turbid waste waters.

B. Solid Wastes

Many Coast Guard vessels operate for extended periods of time in waters where overboard discharge of solid wastes (especially plastic materials) is prohibited. The current handling method involves the collection of solid wastes in cans at various locations and the storage of these materials in plastic trash bags in whatever space is available. The bags are transferred ashore for disposal when the vessel returns to port or are disposed of overboard if the vessel is beyond restricted waters. Little if any attempt is made to separate combustibles or to classify the wastes by other methods. This method requires considerable storage space, is aesthetically offensive, and encourages the proliferation of vermin and other disease factors.

The Coast Guard does not now plan to install solid waste handling equipment on its vessels on a fleet-wide basis. Off-the-shelf equipment such as compactors and incinerators has proven to be too unreliable and/or too large for most Coast Guard vessels. Household-type, undercounter trash compactors have been installed on a few ships, but these systems generally did not perform satisfactorily under continuous, heavy duty use. Thus, solid waste management on Coast Guard vessels is a major unresolved problem.

CHAPTER V

ASSESSMENT OF THE STATE OF THE ART OF WASTE MANAGEMENT SYSTEMS

The handling and disposal of wastes generated in the course of normal activities has received much study from both government and industry. On land, the traditional method of disposing of wastes of all kinds has been to burn them or to bury them in a landfill. More recently, attention has been given to other techniques such as chemical processing, separation, grinding, and compaction, and many of these techniques may be useful in shipboard applications.

In this section, the state of the art of waste management systems is reviewed in terms of their potential for shipboard use. Attention is focused on incineration; evaporation; spray drying; grinding, pulping and shredding; mechanical compaction; and packaging. Wet oxidation and biomass conversion also are recognized as being used in waste disposal, but are not reviewed here since they are not considered to be applicable to the waste disposal problems of the Coast Guard.

A. An Overview of Waste Combustion

Incineration is a complex combustion process whose understanding simultaneously involves the disciplines of reaction kinetics, combustion aerodynamics, and heat transfer. The problem is aggravated by the nature of the fuel whose composition is usually imprecisely known and is often subjected to wide fluctuations. Classic texts on combustion fundamentals (Frestrom and Westenberg, 1965; Gaydon and Wolfhard, 1960; Lewis and von Elbe, 1961; Strehlow, 1968; Williams, 1965) generally are not relevant to the solid waste problem.

The more engineering-oriented texts on furnaces (Brame and King, 1955; Griswold, 1946; Trinks and Mawhinney, 1955 and 1961; Smith and Stinson, 1952) treat kinetics, fluid flow, and heat transfer only superficially. Specific air pollution texts and handbooks (Hesketh, 1972; European Protection Agency, 1973; Cheremisinoff and Young, 1975; Perkins, 1975) also lack an in-depth review of the fundamental topics of concern. The only fundamental text or handbook on design relating to incineration is the Shell Development Company's Afterburner Systems Study (Rolke et al., 1971) but, as the title indicates, this document is restricted to afterburners. Only the Principles and Practices of Incineration (Corey, 1979) is specifically concerned with incineration but, again, quantitative design is not emphasized. Niessen's Systems Study of Municipal Incinerators (1970) presents quantitative design information but it is largely empirical in nature and is based on historical municipal incineration experience. Mention also should be made of a recent American Society of Mechanical Engineers (ASME) publication, Combustion Fundamentals for Waste Incineration (1974), but this report is concerned exclusively with thermodynamic equilibria and has no bearing on the kinetic, aerodynamic, and heat transfer aspects of incineration.

In incineration, it generally is necessary to satisfy, almost simultaneously, two mutually exclusive temperature requirements, and this is the major cause of the materials problem. First, temperatures in some part of the flame must be in excess of about 1250°C (2300°F) to maintain ignition (flame holding) and to accelerate burn-out. Second, the temperatures of the combustion chamber walls must be lower than those in the flame-holding flame ball.

These two conflicting requirements, in turn, dictate many of the design and operational requirements. Specifically, without affecting flame stability, sufficient heat must be extracted from the flame gases (thermal loading) so that they will be at roughly the same temperature as the walls when they reach the flue. Cooling of the gases is mainly achieved by adding high excess air or water (this latter can be a large natural component of some of the liquid wastes), which requires an increase in combustion chamber volume and, hence, increases the space requirements for the incinerator. At the same time, the normally preferred atmosphere adjacent to the walls should be oxidizing rather than reducing. However, this is not necessarily easy to achieve at all points even at high overall excess air. If significant sulfur is present, the preferred method of cooling may be by water rather than air to suppress SO_3 formation. This, however, may introduce problems of salt emissions if sea water is used for the cooling. Overcooling also can create particulate emissions and odor problems. Odor destruction requires oxidation at a temperature in excess of about 800°C (1500°F) for a period exceeding 0.5 sec and, therefore, imposes a critical constraint on cooling design.

The size of an incinerator (or any combustion chamber) for any specified firing rate is determined principally by the rate of chemical reaction of the fuel and other combustibles. Since the reaction must be completed within the combustion chamber, the total reaction time must be less than the residence time of the combustion gases in the combustor. Clearly, the less reactive the fuel or wastes, the larger the combustion chamber must be for a given firing rate. Likewise, if a chember is fired at capacity with a reactive fuel or waste, the introduction of a less reactive fuel or waste will require a reduction in firing rate, which means reduced capacity. In normal circumstances this is not a problem since the same fuel is used, with specifications kept between predetermined limits. However, when firing waste by itself or when added to a fuel system, if the waste is the main fuel, the fuel specifications can sometimes vary widely, usually with periodic opportunity for upset conditions resulting in excess emissions of various sorts. Even if the waste is added to a stable burning fuel or flame, it can still cause problems if there are significant interactions between the waste components and the fuel. Notably, chlorides tend to affect gas-phase reactions, in many cases acting as reaction inhibitors. Consequently, the effective reactivity of the supporting fuel is reduced, thus effecting firing rate or capacity of the unit.

The above discussion reveals that design of any combustion chamber from first principles is not impossible. Instead, approximate sizes and quantities are determined on the basis of combustion intensity, which is defined as the average thermal loading rate per unit volume of the combustion chamber. Combustion intensity is calculated by dividing the Btu supply rate from all combustible sources by the combustion chamber volume. Typical combustion intensity values for the gaseous, liquid, and solid fuels burned in furnaces are listed in Table 3. The various categories of solid wastes

TABLE 3 Comparisons of Combustion Intensities Obtained with Different Fuels.

Combustion Intensity (Btu/hr cu ft atm)	Fuel Type		
	Gas	Liquid	Solid
4×10^9	Mullins theoretical upper limit		
10^9			
10^8	Longwell bomb (80% combustion) (Special research reactor)	Liquid fuel rockets	
10^7	Premixed gas burners (intensity defined on <u>flame</u> volume)	Ram jet Gas turbines using pressure atomized oil	Solid fuel rockets
10^6	Premixed or turbulent diffusion gas flames with intensity defined on furnace volume	Medium fuel oils (pressure and air atomized)	Pulverized fuel (experimental for MHD). Also cyclone burners alone (excluding radiant chamber)
10^5		Heavy fuel oils (air and steam atomized)	
10^4		Household oil burners	Pulverized fuel and stoker firing (industrial)
10^3			
10^2	ALL FUELS - for drying and baking ovens		

NOTE: Industrial furnaces usually are operated at 1 atm and normally are operated under pressure.

SOURCE: Essenhigh, 1974

defined by the Incineration Institute of America (IIA) are described in Table 4 and the combustion intensities of Types 0-4 are estimated in Table 5.

TABLE 4 Incinerator Institute of America (IIA) Classification of Wastes to be Incinerated.

Classification of Wastes		Principal Components	Approximate Composition (% by Weight)	Moisture Content (%)	Incombustible Solids (%)	Btu Value/lb of Refuse as Fired	Btu of Aux. Fuel per lb of Waste to be Included in Combustion Calculations	Recommended Min Btu/hr Burner Input per lb Waste
Type	Description							
0*	Trash	Highly combustible waste, paper, wood, cardboard cartons, including up to 10% treated papers, plastic or rubber scraps; commercial and industrial sources	Trash 100%	10	5	8500	0	0
1*	Rubbish	Combustible waste, paper, cartons, rags, wood scraps, combustible floor sweepings; domestic, commercial, and industrial sources	Rubbish 80% Garbage 20%	25	10	6500	0	0
2*	Refuse	Rubbish and garbage; residential sources	Rubbish 50% Garbage 50%	50	7	4300	0	1500
3*	Garbage	Animal and vegetable wastes, restaurants, hotels, markets; institutional, commercial and club sources	Garbage 65% Rubbish 35%	70	5	2500	1500	3000
4	Animal Solids and organic wastes	Carcasses, organs, solid organic wastes; hospitals, laboratories, abattoirs, animal pounds, and similar sources	100% Animal and human Tissue	85	5	1000	3000	8000 (5000 primary) (3000 secondary)
5	Gaseous, liquid or semi-liquid wastes	Industrial process wastes	Variable	Dependent on predominant components	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey
6	Semi-solid and solid wastes	Combustibles requiring hearth, retort, or grate burning equipment	Variable	Dependent on predominant components	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey

* Moisture content, ash, and Btu value/lb of refuse fired have been determined by analysis of many samples. The values presented are recommended for use in computing heat release, burning rate, velocity, and other details of incinerator designs. Any design based on these calculations can accommodate minor variations.

SOURCE: Incinerator Institute of America, 1968.

TABLE 5 Estimated Values of Waste Factor (K) and of Combustion Intensities (I)

Waste Type	0	1	2	3	4
Logarithmic Waste	13	13	10	8	----
Factor (K_L)	13	1 13	10	8	-----
Ash, %	5	5	5	5	5
Moisture, %	10	25	50	70	85
Heat of Combustion, Btu/lb	8500	7000	4500	2500	1000
Auxiliary Fuel, Btu/lb	----	----	----	1500	3000 to 8000
Average Volumetric Reaction Rate ($\bar{R}_V$), lb/hr/ft^3	4.53	4.53	3.06	2.17	1.41
Waste Factor (K)	4.33	4.33	3.33	2.67	2.0
Combustion Intensity (I), Btu/ft^3/hr	38,500	31,750	13,750	5425	1405

SOURCE: Essenhigh, 1968.

1. Solid Waste Incineration

The incineration of solid waste in special units designed specifically for that purpose is a technique that has been utilized for over 100 years. The original units were large boxes fabricated of refractory materials intended to confine the combustion process. Over the years some reduction in the massive size of the combustion chamber was achieved by use of integrated refractory-lined metal construction systems, but these units are quite heavy since extensive use of refractory materials is relied on to maintain safe skin temperatures. Recently established air pollution control requirements stimulated some modifications (e.g., addition of a secondary chamber and burner to assure completion of burn-out, an afterburner, combustion air fans, an induced draft fan, and air pollution control equipment and mechanization of charging, grate systems, and ash removal systems, especially in the larger units) in incinerator design that make contemporary units more complex to operate and bulkier and heavier than earlier models.

Solid waste incineration systems have been utilized for some time on shipboard. The earliest units consisted of metal drums placed on deck in which trash was burned under largely uncontrolled conditions. Later, simple refractory-lined natural draft units installed below deck were employed. These units, although simple in concept, were large and heavy, were hazardous to personnel, were a source of gross air pollution, and required much operator attention. In addition, these incinerators generally were capable of burning only relatively dry solid waste material. These units can be modernized by the inclusion of fans and air pollution control equipment to achieve a reduction in air pollution emissions, but their basic shortcomings cannot be overcome.

Coast Guard requirements for waste handling systems were listed in Chapter 1. The size of an incineration unit capable of burning 14 to 57 lb/hr (17 to 68 ft^3/day) of solid waste is limited to 6 feet long by 7 feet wide by 7½ feet high. The height requirement cannot be exceeded because no vertical deck penetrations are permitted. Operation is to be limited to no more than 12 hr/day and must be automatic or semi-automatic. The smallest off-the-shelf units designed for land-based installations burn 60 to 100 lb/hr, depending on the type of waste; would just barely fit the deck space available without provision for ram feeding of the unit or give adequate access around the unit for maintenance; and normally require manual feeding through doors approximately 2 feet by 2 feet. On many of these units, the height requirement is exceeded in normal configurations by the afterburner or secondary emission control chamber. Although it might be possible to move this chamber to the side of the unit, the length criterion probably would be exceeded.

Other Coast Guard requirements for shipboard units considered in this study were: a weight limitation of 5,000 lb maximum; skin temperature of 120°F; 20 kw peak power demand; ash containing not more than 2 percent by weight of unburned organics; and a miminum of 6,000 burn hours (3 years) between major overhauls with a goal of 10,000 burn hours (5 years). Materials of construction must be suitable for the salt water/marine air environment. The first-order vibration limits were 40 mils at 3 cps horizontal, with second-order vibration limitations 25 percent of first-order. The incinerator must be able to maintain satisfactory operation under continuous or transient pressure differentials between the interior compartment in which the incineration unit is located and with an atmosphere of plus or minus 3/4 inch water column. Operation must also be maintained during severe ship roll conditions when under way.

Off-the-shelf solid waste incineration units with a capacity of 60 to 100 lb/hr weigh from 2,400 to 5,700 lb without a ram feeder. Thus, it seems unlikely that the 5,000 lb weight limitation can be met with present designs and materials of construction. Requirements for temperatures measured 12 inches from incinerator exterior surfaces, as stipulated in Incinerator Institute of America (1968) criteria for this size unit, were less than 90°F above normal room temperature, which is substantially in excess of the Coast Guard's limit. One supplier of incinerators for Navy shipboard use has indicated that the maintenance experience exists to evaluate maintenance requirements of the newer, more complex units (Marks, 1976). Also, these units apparently are of substantially larger size than those required for Coast Guard service. A report on noise levels and corrective action taken in the development of the Navy's multi-use shipboard incinerator indicates that off-the-shelf incineration equipment might have to be modified in order to meet noise criteria (Vent-O-Matic Incinerator Corp., n.d.). Little or no information on the following requirements is available for off-the-shelf units: typical peak power demands; unburned organics in the ash; suitability of special materials for the salt water/marine air environment; vibration criteria; resistance to vibration-induced stresses; controls to maintain operation under substantial swings in pressure conditions; and maintenance of operation under ship roll conditions.

Coast Guard criteria for stack emissions are: less than No. 1 Ringelmann (20 percent opacity) for smoke and 0.2 ft^3 corrected to 12 percent CO_2 desirable for particulates. A well designed and well operated package incineration unit with an afterburner burning shipboard solid waste should be able to achieve the desired goal and operate well within the indicated opacity limit. Although the Coast Guard criteria do not cover gaseous emissions, this matter also should be considered. Published information regarding these emissions (Corey, 1969; National Center for Resource Recovery, 1974; Velzy and Velzy, 1978; Lund, 1971) indicates that carbon monoxide, sulfur dioxide, nitrogen oxides, hydrocarbons, and heavy metals should not be of concern if the solid waste combustion units are designed to modern standards and are well operated and maintained. On the other hand, hydrogen chloride emissions may be of concern if no flue gas treatment is provided depending on the composition of the waste being burned. For those installations in which excessive hydrogen chloride is generated, a wet scrubber will be required. (Adequate emission control cannot be expressed numerically at this time since no requirements have been established by regulatory agencies.)

Thus, it appears that many Coast Guard requirements preclude the application of land-base incineration systems on shipboard without an extensive program of development and demonstration under anticipated shipboard service conditions.

2. Sludge Incineration

Two basic units have been used for sludge incineration at land based installations--fluidized-bed incinerators and multiple-hearth incinerators. These combustion systems are large, heavy units since sludge burning requires the use of rather substantial amounts of auxiliary fuel unless the moisture content can be reduced below approximately 65 percent.

With the fluidized bed incinerator (Kwon, 1978), dewatered sludge is introduced into a bed of sand that is fluidized with air at the bottom of the bed and heated to a temperature of 1400-1500°F. The bed of sand, and a freeboard volume above the sand bed, is contained within a refractory-lined steel vessel. Combustion of the sludge particles takes place in and on the surface of the bed of sand. Ash particles carried out of the vessel with the exhaust gases are removed by a scrubber. The advantage of this type of unit is that the bed of sand provides an enormous heat reservoir capacity allowing for rapid start-up after short shut-down periods. The unit consists of a number (usually four or more) of refractory lined hearths housed within a refractory-lined steel shell. Rotating plows attached to an air-cooled center shaft move the sludge on alternate grates towards the outer shell and then back towards the center shaft to discharge ports. The sludge is dried on the upper hearths, burned on the middle combustion hearths at 1400-1800°F, and then cooled on the lower hearths. The exhaust gases are passed through scrubbers for removal of particulate matter. Use of auxiliary fuel is dependent on the volatile matter content of the sludge and moisture content of the sludge cake. The disadvantages of this type of unit for shipboard use are its relatively large weight-to-capacity ratio and the need for sludge dewatering equipment to limit the amount of fuel required.

The Navy's attempts to develop an air-cooled vortex sludge-burning unit show promise. This unit consists of an air-cooled incineration chamber constructed of metal, an oil-fired burner, a fuel pump and centrifugal blowers, an electrical control panel with associated flame scanner and pressure switches, fuel and combustion air valves, and effluent injection nozzle, and an air pressure reducing valve for nozzle low-pressure aspirating air. A blower supplies combustion air to the oil-fired burner and cooling air to the incinerator combustion chamber jacket, access door, and exhaust stack. All cooling air and combustion gases exit through the exhaust duct. The oil burner is mounted to fire downward along one side of the cylindrical incineration chamber. The hot gases follow the inner surface of the chamber creating a spiraling flow as they move towards the chamber exit. Sewage is introduced at the oil burner end of the incineration chamber through a specially designed, nonclogging waste injection nozzle. The sewage is directed into the hot gases discharging from the oil burner by low-pressure air passing through a group of jets at the tip of the nozzle. The liquid in the sewage is converted to steam while the volatile solids are combusted. Noncombustible particles and fly ash are collected within the incineration chamber in the particulate trap at the exit from the chamber. Exhaust gases, water vapor, and a very small amount of fly ash exit the incineration chamber where they are immediately mixed with cooling air to reduce their temperature to 850°F or less before being discharged to the atmosphere through the ship's exhaust duct system.

Although field tests of this system by the Navy and the Coast Guard have been limited, those tests that have been conducted identified several problems. For example, liner corrosion was experienced in the initial field trial units of both the Navy and the Coast Guard after 650 to 680 burn hours (NAS Solid Waste Incinerator Seminar, 1977; White, 1976). A replacement liner of 309 stainless steel has given better service, and Inconel 671 and 690 appear capable of increasing liner life to the desired 10,000 burn hours. Another problem involves the lack of automatic damper controls on the original units. Several burner and burner component modifications have been made to eliminate problems encountered during the initial operation of these units. Surface metal temperatures to which personnel were exposed were found to be excessively high in some areas. Several other relatively minor operational problems were identified and have either been corrected or appear to be readily correctable. The units are considered to present no fire hazard.

Such units also were laboratory tested and their capability to handle other types of waste, such as a simulated pulped galley waste, were explored (Raupuk, n.d.). Several problems were noted during these tests. When the waste water contained high concentrations of fibrous material, combustion was not complete and waste impinged on and ran down the liner side. This problem was attributed either to overly large waste droplet size or to insufficient droplet residence time prior to hitting the wall of the liner. Problems also were encountered at the feed pumps in handling paper and sawdust synthesized slurries. In all cases, investigations and development are continuing in an effort to overcome these problems.

Since the sludge disposed of in these units has a relatively high moisture content (1 to 7 percent dry solids), the requirement for auxiliary heat input from fossil fuel is relatively high. However, these units, which are of metal construction, air cooled and sized for a personnel complement of 200, are lighter and more compact than the fluidized-bed and multiple-hearth sludge burning units developed for land-based application. Thus, they may have some application in the future on shipboard if the current problems of sludge feed and materials of construction can be satisfactorily resolved.

3. Combined Incineration

No single incineration units currently available are capable of disposing of all shipboard wastes. Such wastes range from relatively dry, highly combustible paper materials and plastics to wet kitchen wastes, sewage solids, sludges, and oily wastes. The consistency, together with the heat content and heat release characteristics, of the wastes vary so greatly and unpredictably that changes in equipment configuration and/or capability are required. Such flexibility of application has been required of land based installations in the past.

The Navy presently is developing a unit to solve the shipboard waste disposal problem for ships with a personnel complement of 320 and larger (Wyatt and Hagedorn, 1975). The waste streams expected for this size ship are 1,100 lb of solid waste (approximately half trash and half garbage), 160 lb of sewage sludge (15 percent total solids) or 3,200 lb of raw sewage (total solids less than 2 percent), and up to 800 lb of waste oil daily. An initial contract effort, in which incinerator concepts were developed for excess air, controlled excess air, and controlled or starved air, resulted in selection of the controlled excess air type for further development.

The controlled excess air unit is designed in modular components, and after early rigid physical testing and some rebuilding, it now is being tested extensively at a Navy shore-based installation using simulated shipboard wastes. Problems experienced with portions of the system have been corrected. The induced draft fan has been modified to increase its capacity and solve an overheating problem. Smoke emissions were reduced and feed control was improved by operational changes. External casing temperatures in some localized areas were in excess of the specified (140°F) limit, and this problem still has not been solved. The unit weighs approximately 12,000 lb (about 40 lb/person served). Before complete assurance can be given that this unit has overall fleet-wide application, it must be subjected to extensive shipboard testing. This unit also is substantially larger in size and capacity than units that might have application in the largest Coast Guard ships (maximum crew complement of 165 to 225 men), and it is questionable whether such a combined unit can be sufficiently scaled down in size to be usable on the smaller Coast Guard vessels.

B. Evaporation

During the past several years the Coast Guard and the Navy, in cooperation with industry, have engineered, developed and evaluated advanced toilet waste treatment systems based on evaporation. The system developed is referred to as the evaporative toilet system (ETS). To date, approximately 40 of these systems have been or are being installed on vessels operated by various government agencies.

Basically, the ETS reduces the volume of waste production by reducing the hydraulic load (volume of flush water) and by evaporation of the flush and waste liquids. The system (Figure 5) consists of four components or subsystems:

1. Controlled volume flush commodes and urinals,

2. Macerator-transfer pump,

3. Evaporation-holding tank equipped with a catalytic vapor treatment column, and

4. Operational controls

Each time a commode or urinal is used, the macerator-transfer pump is automatically activated for a short period of time (approximately 10 seconds); it macerates the solids and transfers the waste slurry to the evaporator tank.

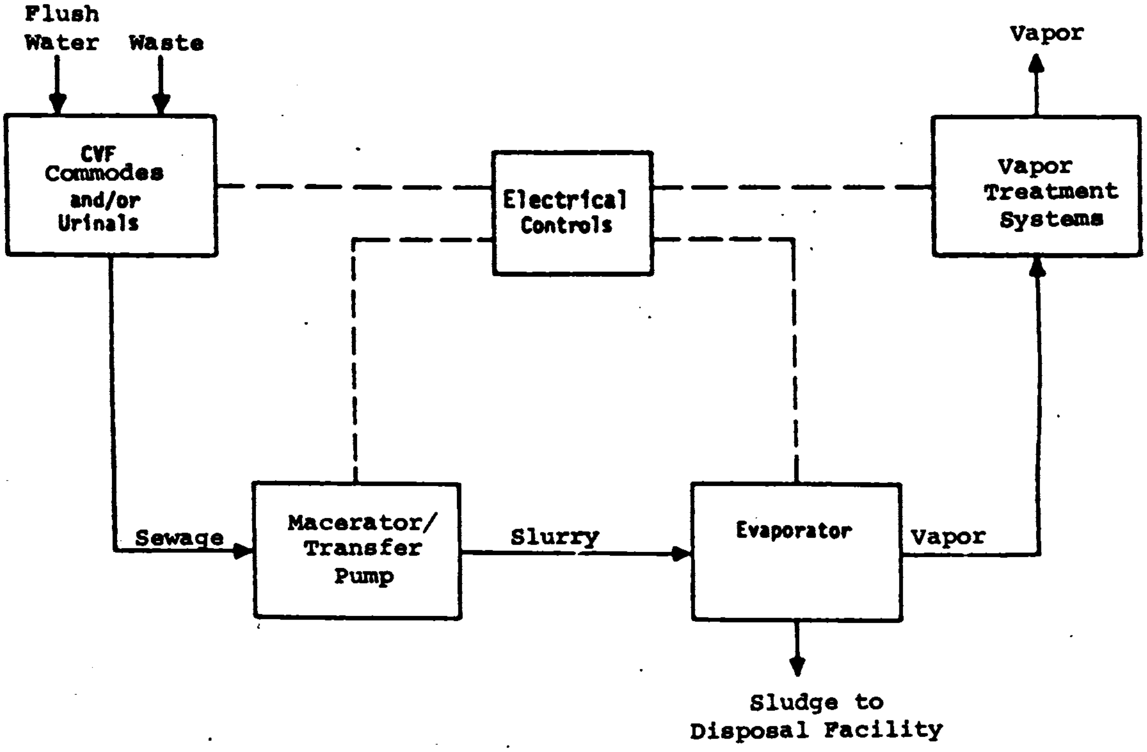


FIGURE 5. The evaporative toilet system.

The evaporator (Figure 6) stores and processes the sewage slurry delivered to it by the pump. It is an electrically heated process vessel fabricated of stainless steel with a thin fluorocarbon polymer coating on the inside surface. A gasketed cover provides access for cleaning and maintenance.

The evaporator is filled with a preset volume of water after each service interval. When this preset volume is exceeded, a level sensor activates electrical heaters that initiate the evaporation process. This sensor also turns off the heater when the liquid level fills below the preset volume. Solids accumulate as a result of the evaporation process.

Cyclic heating and evaporation continue until the slurry level activates a high-level sensor that shuts down the macerator-transfer pumps and prevents further addition of wastes to the evaporator. At this point, a signal light is activated on the control panel to indicate the need for evaporator cleanup. The water vapors evolved are treated catalytically to remove various odors before they are vented to the atmosphere.

The capacity of the evaporator depends on two factors--the number of men using the system and the length of the ship's service interval. For example, with a crew of 25 and a 15-day service cycle, an 80 gal evaporator tank is needed if saltwater flush is used. If a freshwater limited-flush system like that being installed on Coast Guard vessels is used, the system would not require dumping for approximately 50 days. With a 100 man crew, an evaporator capacity of 85 gal would be required on a 7-day duty cycle and of 315 gal on a 30-day duty cycle.

The limiting factors that govern the number of crew the system will serve are evaporator boil-off rate and salt precipitation and sludge accumulation rate. The boil-off rate is directly related to the power input. In the present system, 3 electric heaters provide a total of 5.5 kw. This corresponds to a boil-off rate of approximately 48 gal/day or 2 gal/hr after the evaporator reaches temperature. The power requirement would be approximately 18 kw for a 100 man crew and 35 kw for a 200 man crew (private communication from Willem van Hees, David W. Taylor Naval Ship Research and Development Center, Annapolis, Maryland, January 16-17, 1978). With regard to salt precipitation and sludge accumulation, Figure 7 illustrates that use of a saltwater flush

FIGURE 6 The ETS evaporator as installed on a U.S. Coast Guard vessel.

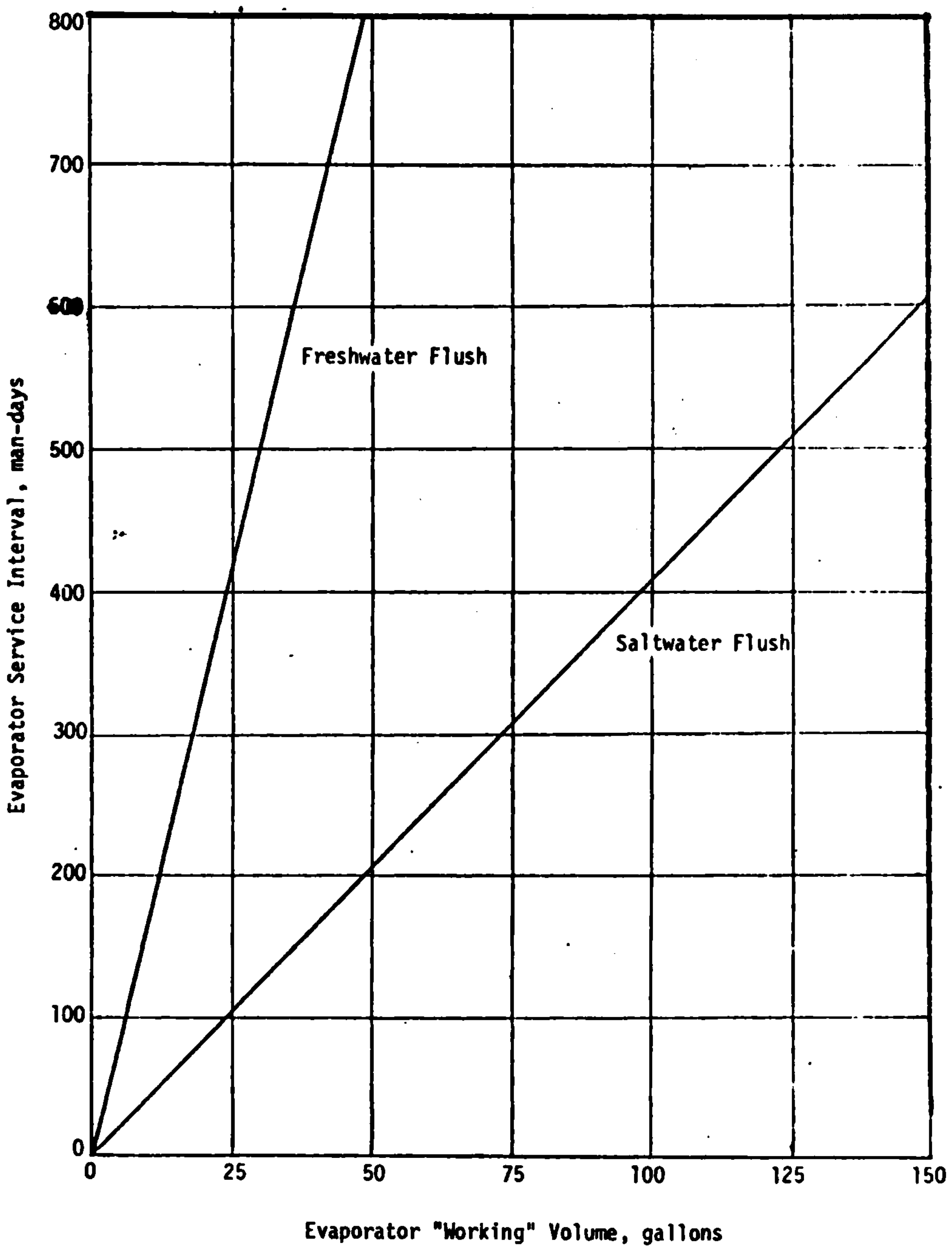


FIGURE 7 Evaporator service interval vs. working volume (based on total sewage volume of 1.5 gal/man-day).

increases evaporator service intervals by a factor of about 4. The bulk of the Coast Guard installations use fresh water reduced volume collection systems, and this will ensure longer service intervals before the evaporator must be cleaned.

None of the evaporation systems evaluated on Navy and Coast Guard ships has included treatment of either galley or grey water wastes. From the standpoint of mechanics, it is feasible to feed such wastes to the evaporator but the amount of power required to handle the increased volume of water would be prohibitive. Galley wastes have been pulped and ground to a sufficiently fine consistency to be burned in a Vortex incinerator (Figure 8).

Thus, evaporation has been demonstrated to be a satisfactory means of reducing the volume of liquid sanitary shipboard wastes; however, no effort has been made to introduce galley and grey water wastes into the evaporator. Scale-up of the evaporator systems for larger ship use appears feasible.

C. Spray Drying

Spray drying is a particular kind of evaporation in which a slurry of fine-ground solids in a liquid is atomized into droplets that are then exposed to a stream of hot gas to vaporize the liquid and leave the solid in dry powder form. Spray drying has an advantage for the disposal of shipboard wastes since it completely rids the ship of the aqueous portion of the slurry and leaves the solids in a form that readily can be burned or compacted to extremely low volume. However, no workable spray drying systems for shipboard use are available and only one manufacturer has made a study of spray drying systems for ships (Gard, Inc., 1978). A schematic of a spray drying system is shown in Figure 9.

The conceptual aspects of the spray drying system which was operated on sanitary wastes are as follows: sanitary wastes from reduced flush urinals and commodes containing about 2 percent by weight solids are collected in a holding tank. The wastes are continuously withdrawn from the tank by a macerator-transfer pump. This pump reduces the solids to a very small particle size and generates a large head for introduction of the slurry into the dryer. In the dryer, the jet of slurry impinges upon a disc rotating at high

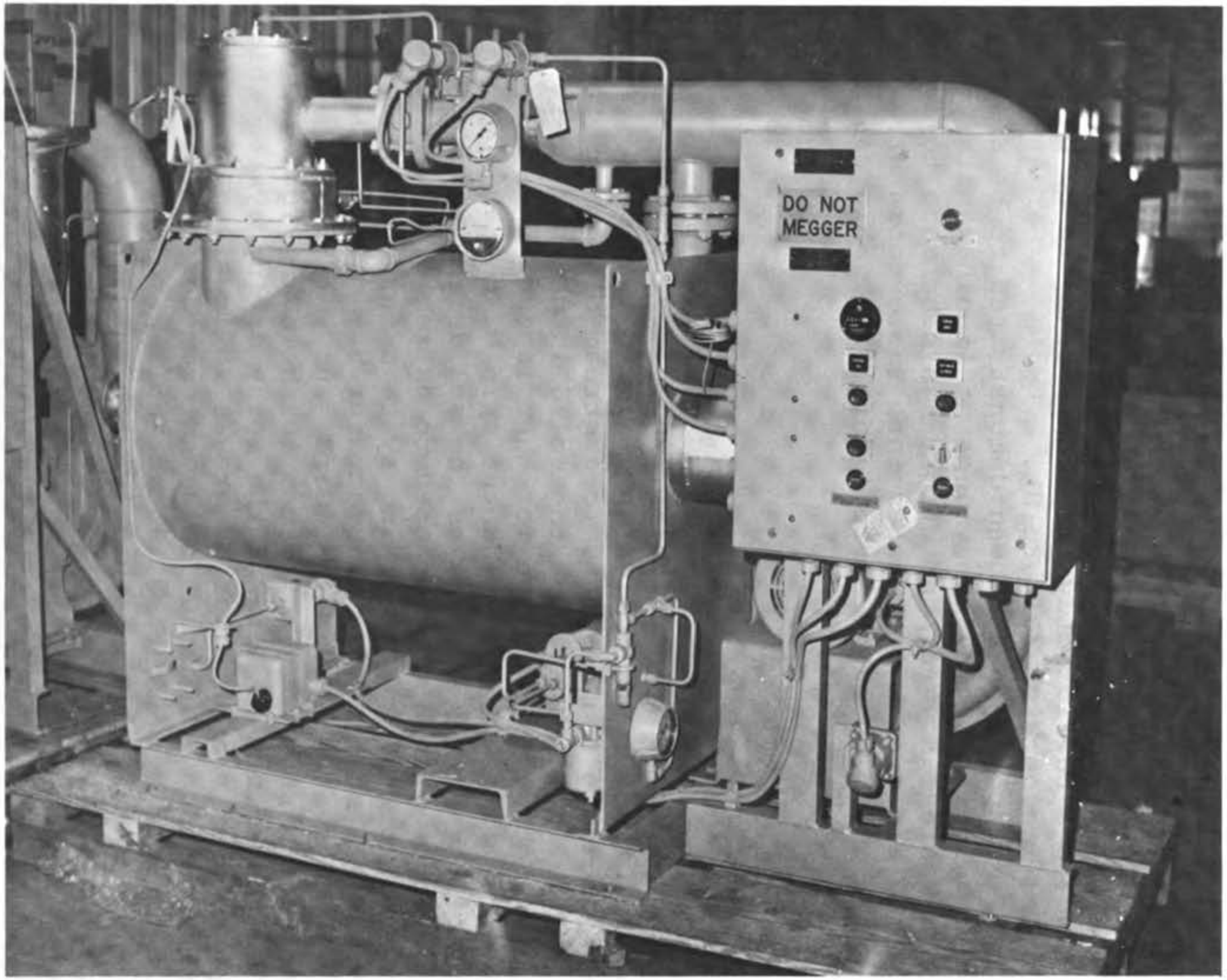


FIGURE 8 Vortex incinerator.

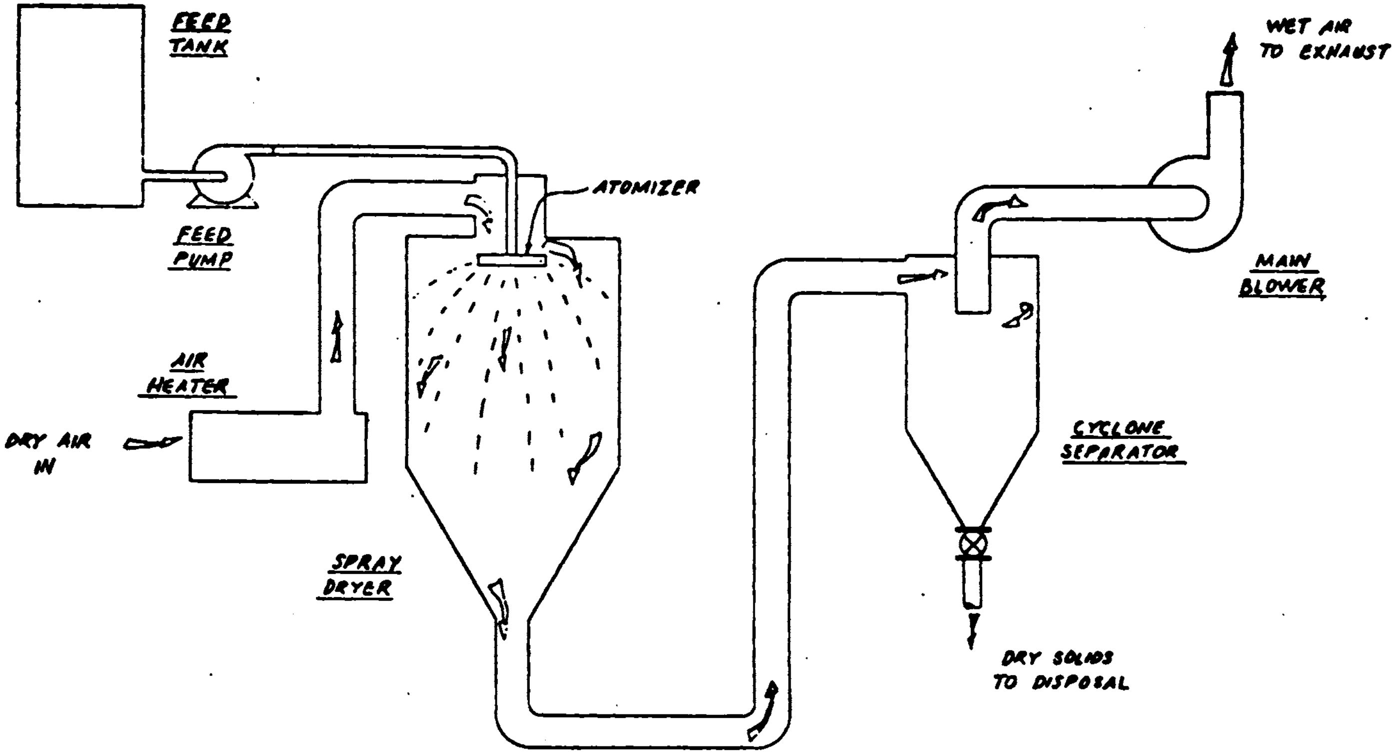


FIGURE 9 Typical spray drying system showing cocurrent operation (GARD, Inc.).

velocity. The jet is dispersed into small droplets having a velocity of 250 to 600 ft/sec and a desired diameter of 10 to 60 microns. These droplets are exposed to air heated to 660°F by electrical heaters. The water evaporates in 5 to 30 sec, and the resultant solid particles are essentially dry. The stream of air, water vapor, and solid particles then is passed into a cyclone separator by an induced-flow blower downstream of the cyclone. The particulates collected at the bottom of the cyclone are fine and free blowing. The vent stream is odorous, but this situation probably can be corrected by passing the gas stream through a catalytic oxidation unit. The dry solids were found to contain viable bacteria, which suggests the need for a pretreatment of the spray drying feed through a sterilizer system.

Although spray drying has many attractive features (e.g., single step operation from liquid to a by-product, low maintenance since there are few moving parts, and relatively clean operation), it has several disadvantages that may preclude its use for shipwaste systems. For example, feed stocks must be ground or macerated to prevent plugging of the atomizing device. Proper atomization is the key to successful spray drying. Although it may be possible to macerate the sanitary waste, it seems unlikely that such a system could operate with a feed that includes galley wastes. In addition, the energy requirements are very high. It has been estimated that air and heat requirements for sewage spray drying will be as follows:

Air	200 lb/man-day
Heat energy	29,500 Btu/man-day or 8.6 kw/man-day
Continuous power	0.36 kw/man-day

Thus, the spray drying of shipboard wastes offers no advantage so outstanding that it would warrant the effort necessary to develop a system for shipboard use. In addition, there is no experience to suggest that systems could be designed to meet the size constraints imposed by shipboard use.

D. Grinding and Pulping

This topic is significant to a study of the disposal of shipboard wastes because most systems for disposal require the reduction of solids to a small size (ranging from about ¼ in. for Vortex-type incinerators to 100 microns for spray dryers). This discussion, however, is limited to size reductions which give maximum dimensions pumpable as aqueous slurries in normal-size piping.

The two shipboard sources of aqueous wastes are sanitary wastes from commodes and urinals and galley wastes. Experience with Vortex-type incinerators and spray dryers using macerators reveals that sanitary wastes normally present no size reduction problems since they contain, at worst, only fecal matter and paper. There is, however, the possibility that material which is difficult to comminute will inadvertently or maliciously be introduced into the sanitary waste stream, and it may be desirable to provide a device in the sanitary waste line that is capable of comminuting "worst case" material. That worst case material would probably fall in the domain of the materials which conceivably could enter the system via the galley. Therefore, it is assumed that any device capable of comminuting the waste would also be capable of handling any solid object which appeared in the sanitary waste, if such a device is used at all in the sanitary waste line.

Probable candidates for entry into the galley waste stream include paper, glass, cloth, rubber/leather, plastics, food, bones, and metal tableware. Among these items, cloth, rubber, and metal tableware are likely to be the most troublesome. The David W. Taylor Naval Ship Research and Development Center, Annapolis, Maryland (NSRDC) has probably done more work in the comminution of these materials than any other organization, and they believe that a pulper exists which is capable of handling these galley wastes to create an aqueous slurry amenable to pumping, incineration, evaporation, etc. (private communication from Willem van Hees, NSRDC, April 12-13, 1978). The NSRDC group reports that this pulper is reliable and effective and can deal with metal tableware in that it can reject it in an "inactive bin." The only negative NSRDC comment about the pulper is that it is "too large" for a destroyer and, hence, would also be too large for Coast Guard vessels.

The pulper itself fits under a galley table that is 34 ± 0.75 in. high, an acceptable size (Figure 10). However, it requires a large amount (50 gpm) of water which limits its usefulness on small ships. The pulper manufacturer offers an optional water extractor as an integral part of the installation. This extractor separates most of the pulping water from the solids and recycles it to the pulper, thus limiting the makeup water to 12 gpm. The integrated assembly weight 450 lb and energy consumption is 5 HP.

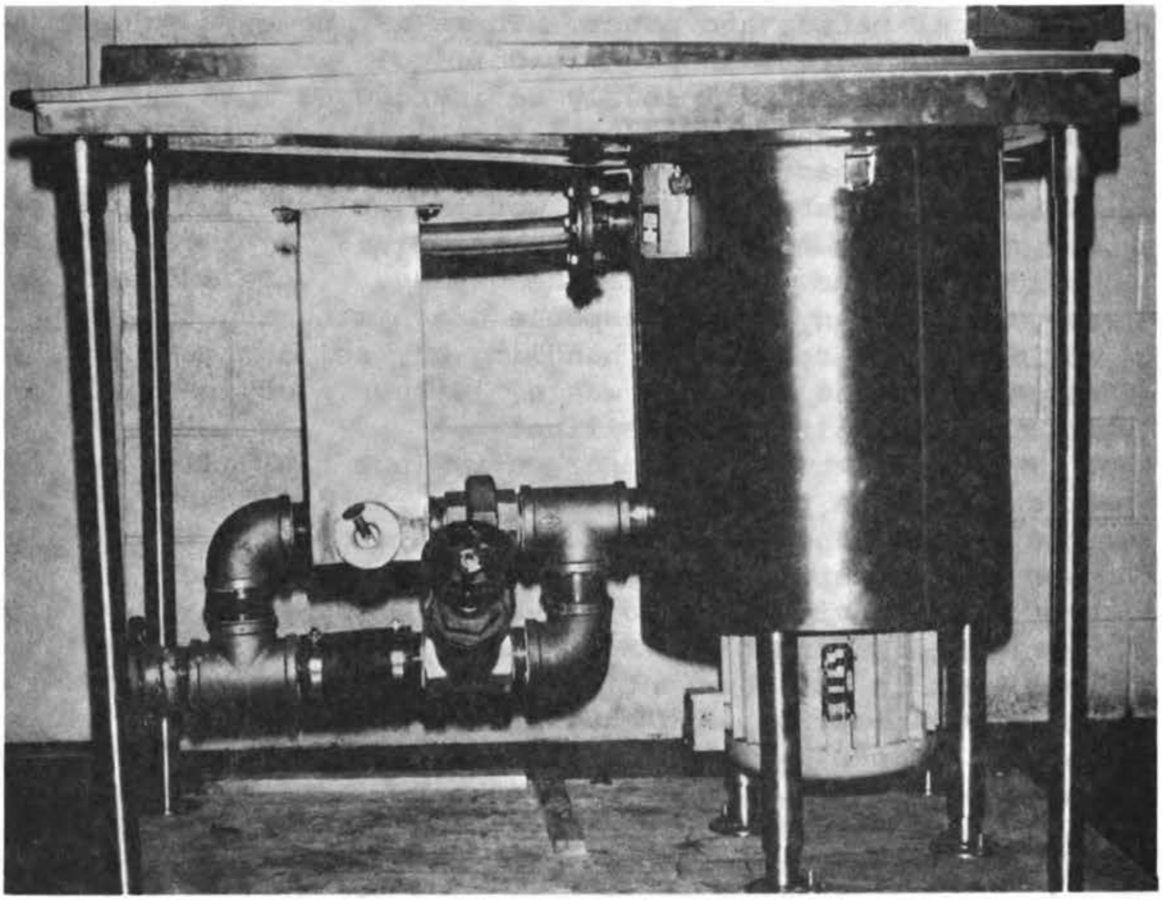


FIGURE 10 Photograph of a pulper installed under a galley table.

E. Compaction and Shredding

The volume of loose trash and garbage presents a major handling, storage, and disposal problem on board a ship. Compaction and shredding are methods to reduce the volume of wastes.

For the most part, shredding of refuse has been used by municipalities to reduce the volume of wastes and to produce a product that can be incinerated easily. As would be expected, the equipment used is designed to handle large volumes of wastes and therefore is much too large and heavy for shipboard applications.

Although shredders generally perform satisfactorily, they are not without problems. Experience has shown that periodic jamming may occur, necessitating extra attention. Blades and cutters also require frequent attention and maintenance, and fires and/or explosions occasionally occurred.

The development of small shredders suitable for use on Coast Guard vessels has been stimulated primarily by the waste handling problem on offshore drilling structures. Commercial shredders are available; however, their performance on offshore structures is not well documented. These shredders are approximately 4 ft long, 3 ft wide, and 6 ft high and weigh about 1,300 lb. The shredder area is small (15 to 18 in. by 14 to 16 in.), thus limiting the size of cans and bottles that can be handled. Capacities vary, depending on the arrangement and speed of the cutters in the unit, and the particular size of the shredder wastes. The machines have controls that provide for a forward-reverse cycle designed to minimize jamming and reduce power requirements.

Both the Coast Guard and the Navy have experimented with refuse compaction. All units installed on surface ships were off-the-shelf items ranging from small household compactors to large systems 8 ft by 3 ft that weighed up to 3,800 lb.

In addition, the Navy traditionally has used compaction as a means of handling and disposing of wastes on submarines. Loose trash and garbage are collected in a trash compartment and loaded into metal cans formed onboard from precut sheet stock. The compactor presses the wastes into high-density cylinders that sink when ejected. Thus large quantities of liquid residue are drained to a collection tank. The main problem with this system is that it is considered to be "messy" and rather unsanitary and, as such, is not favored by the crew. There also have been some problems with reliability and maintenance. Nonetheless, compaction has proved to be a viable waste management method for use on submarines.

Experience with compaction on surface ships has been less than satisfactory. For example, the Navy installed a commercial compactor on the Nimitz. The compactor weighed 3,800 lb and required a 9 ft by 16 ft compartment. The compactor was designed to handle 1,000 lb of solid waste/hr on a 6 hr/day operating cycle. Waste was compacted into a "slug" weighing approximately 75 lb. The size and weight of the compactor is such that it can be installed only on the largest ships of the Navy and, thus, is quite impractical for Coast Guard applications. In addition, the compactor requires frequent washdowns and operates in a horizontal rather than a vertical mode.

In spite of this rather unsatisfactory experience, compaction is still of interest and the Navy presently is developing a small (3½ ft by 3½ ft) vertical compactor capable of processing 500 lb of trash/day. Such a compactor could be of interest to the Coast Guard; however, development of the compactor to the fleet deployment stage is expected to require up to 5 years.

Coast Guard experience with compaction has been limited to the use of units designed for single-family dwellings, and the experience has varied. In instances where control has been exercised as to what is fed into the compactor, satisfactory results have been obtained. However, in general, the household compactor construction has proved to be less rugged than that required for the continuous and heavy duty shipboard use.

European compactors under development or commercially available for offshore structures are of two types:

1. A unit that crushes, compacts, and stores waste in a sealed box-type structure that can be removed periodically and emptied on shore, and

2. A permanently installed unit having a box volume of about 8 ft^3 and weighing 1,000 lb.

Neither of these types of compactor appears to have been designed for shipboard service, but the technology can be expected to be of interest to the Coast Guard. The small permanently installed unit appears to be most practical for Coast Guard applications since a removable unit capable of handling a sufficient volume of waste may be too large and heavy for storage on the fan tail of a Coast Guard vessel.

In general, shredding does not appear to be a practical means of reducing the volume of shipboard solid wastes, and experience with small-scale units suitable for Coast Guard use is limited. Shipboard experience with presently available waste compactors has been less than satisfactory; however, with further development, systems capable of satisfactory operation on ships could result. Compaction is an attractive method of reducing the volume of solid wastes on Coast Guard vessels, and efforts to develop appropriate equipment may offer the greatest short-term payoff.

F. Packaging and Solid Waste Control at the Source

An obvious method to reduce shipboard wastes is to avoid the loading of unnecessary solid packaging at the port. In this regard, studies (Mansur, 1972 and 1975) have been conducted to determine the feasibility of reducing the weight and volume of galley items. This, in turn, would reduce the volume of solid wastes generated on a ship.

Solid waste packaging materials include glass jars and bottles, wooden pallets, steel cans, paper cartons, rags, polystyrene foam, fiberboard boxes, polyethylene bags, PVC containers, and steel wire and bands. Each of the materials can be rated in terms of disposability. For example, paper and fiberboard burn readily but are difficult to sink. Similarly, plastics burn, but release toxic and corrosive gasses and sink with difficulty. Cans and glass bottles can be compacted and sunk, and wood, steel wire and bands, and cloth jam up shredders and compactors. Thus, the optimization of packaging materials is directly related to the methods available for waste disposal.

Nonperishable items account for two-thirds of total galley packaging wastes and perishable items for the remaining one-third. This solid waste is made up mostly of metal cans, bottles, and fiberboard boxes. Studies have revealed that some 20 of 254 nonperishable items and 18 of 180 perishable items are responsible for 50 percent of the total packaging material weight; therefore, emphasis has been placed on reducing the weight of packaging. For example, the use of No. 10 cans instead of small bottles or No. 303 cans for some vegetables and fruits can decrease the weight of the waste by 40 percent and the volume by 13 percent. Similarly, the use of No. 2.5 cans instead of No. 2 jars for such items as jams, jellies, peanut butter, and mustard results in a weight and volume reduction of 65 and 25 percent, respectively. Other packaging design changes (e.g., the use of shrink-wrapped canned items and the substitution of dehydrated, prefried, and concentrated food items) also have been considered.

The results of these studies indicate that savings can be made in the weight and volume of shipboard-generated wastes; however, industry has shown little interest in providing specially designed packages to suit military needs. Thus, if reduced volume waste is to be obtained through management of packaging materials taken on board, it appears that the Coast Guard will have to repackage items themselves. From the standpoint of economics and operational considerations, such an approach would be difficult to justify.

Another factor that makes management of packaging difficult is that the stores for most Coast Guard vessels are purchased locally at ports where the vessels dock. In addition, it is well established that morale can be influenced significantly by the type of food offered onboard. Since food preferences may vary from crew to crew, the purchase of standard packages and food forms is impractical, at least at this time. Nevertheless, because a few items account for the bulk of packaging material weight, it may be possible to package wastes by concentrating only on these items.

At the present time there is no attempt to provide for separation of waste forms, i.e., paper from cans, onboard Coast Guard vessels. The practicability of implementation of this is recognized to be a function of the ship's mission and its crew. However, classification can play an important role in disposal. For example, the simple separation of cans and bottles from burnable solid wastes such as paper and plastic has been shown to markedly improve efficiency of compactors and incinerators for homes and apartments. A similar effect can be expected for such waste disposal equipment installed aboard ship. Discussion with Coast Guard ship officers indicated that such a separation is feasible and could be instigated with a minimum effort. Accordingly, it is recommended that specific space and procedures for classification and storage of wastes should be further studied and developed.

G. Control and Monitor Instrumentation for Shipboard Waste Handling Systems

This section focuses on the control and monitor instrumentation (CMI) aspects of a shipboard waste handling system in an attempt to identify the states of technology, the directions for the future, and available options. Such a discussion must be qualified in view of the following:

1. No specific mechanical system has been designed with the CMI; therefore, the discussion is general in nature.

2. No specific time frame has been specified over which the system is to evolve, but the discussion assumes a 3 to 6 year period.

3. CMI is basically independent of the system's waste handling capacity; however, if capacity is very small, any form of CMI becomes unnecessary. Conversely, the larger the capacity and the more varied the unit processes of the system, the more important the CMI becomes.

4. The technology assessment factors specified by the Coast Guard include: reliability (potential for failure-free operation); habitability (noise, odor, heat, and aesthetics); performance (effective accomplishments of intended functions); maintainability (ease of correcting failure and people, power and logistic requirements); operability (ease of operation, burden on crew, and operational expendables); and personnel safety (likelihood, severity, and ease of correcting hazards).

Historically, CMI was treated as something to be avoided in system development. Minimal controls were provided and automatic shutdowns were to be effected only when conditions would cause safety hazards. Generally, the CMI was designed without the aid of electronics and control specialists. Lowest first cost, not lowest life-cycle cost, was the goal. Additionally, the electronic logic provided for startup and shutdown often involved considerable manual intervention and little system protection was provided.

The CMI for a shipboard waste handling system is a service to the system, not a function of the system. Minimum instrumentation is always the goal.

Control instrumentation is needed to maintain operating parameters at desired levels and within preset limits, generally using feedback control circuits. Monitor instrumentation is needed to protect personnel and equipment; to prevent failures and shutdowns; to predict, detect, and isolate faults; and to aid in system maintenance. The prevention of shutdowns that cause perturbation in vessel operation as well as stress on the equipment (e.g., incinerator liners) is one of the most important functions.

Major considerations in the design and selection of CMI are:

1. Operator skill level,

2. Volume of the end item production run, and

3. Protection of the materials of construction (specifically the incinerator liner) against deterioration.

Given the state of the art of waste handling technology, failures are most likely to occur in auxiliary equipment (e.g., pumps, blowers, controls, strainers, regulators, valves, fittings). The use of redundant auxiliaries to ensure continuity of operation, however, is prohibited by weight, space, and cost considerations. Thus, selection of auxiliary equipment for a waste handling system warrants as much designer attention as the major component (e.g., an incinerator). Typical instrumentation problem areas to be given special attention in design include:

1. The need for sensor calibrations,

2. The need for equipment repair when the vessel is at any location throughout the world,

3. The lack of knowledge of system control dynamics until considerable test time has been accumulated (greater than several years), and

4. The failure to provide adequate control logic to protect the system and minimize operator intervention.

There are five fault diagnostic levels: avoidance, prediction, detection, isolation, correction and tolerance. The typical CMI is capable of providing fault detection of critical performance or components. As the degree of CMI technology maturity in the design expands, the detection of a broader range of faults is incorporated followed by isolation to the specific line replaceable unit or, in a limited number of cases, line replaceable components including isolation of CMI faults.

After the fault detection/isolation level, a designer has two directions to proceed. One, he may assume a fault has been detected and isolated and then take the diagnostics technology. The next step would be to provide fault correction instructions to the operator, either manually or automatically. Even further in this direction would be the tolerance to faults through such advanced techniques as self-healing and adaptive control.

If one utilizes advanced CMI that would proceed the detection of a fault, one employs fault prediction techniques based upon performance trend analysis. A level more sophisticated and advanced than fault prediction is the avoidance of faults by a self analysis of the operating conditions and corrective adjustment to avoid a fault. The latter technology will be evolving over the next 10 to 20 years and is beyond the scope of the projected ship board waste handling system.

The types of failures that must be considered are:

1. Failures in mechanical components including actuators,

2. Failures of electronic components including sensors and the CMI itself,

3. Failures due to out-of-tolerance conditions at the system's interfaces, and

4. Failures due to shortage or loss of power.

An assessment of experience with CMI and ongoing developments in the field reveals that:

1. All required system instrumentation for shipboard environments is within the state of the art.

2. Major problems to be resolved are associated with the specific unit processes selected to handle the wastes, the degree of advancement in technology to be incorporated, and the selection of an end level of capability based upon a cost vs. benefit analysis.

3. Virtually no scaling problems are anticipated since the CMI is almost independent of system capacity.

H. Incinerator Material Problems

Studies of material performance in refuse incinerators and other related experiences pertinent to shipboard incinerators were reviewed in depth in a previous NMAB report (1977). This section is intended to update the information presented in that report.

1. Materials Performance

The Coast Guard in cooperation with the Navy has conducted both field and laboratory studies of materials of construction for several different types of incinerator. The two incinerator designs that have received the most attention are: a vortex type and a multipurpose type. The latter is designed to burn all shipboard-generated wastes (i.e. sanitary, galley, trash, refuse, and oil). The vortex type is primarily designed to burn sanitary wastes only or a mixture of sanitary and pulped galley wastes.

a. Metallic Materials of Construction

The initial liner material evaluated in the vortex incinerator was Inconel 601. Liners of this material failed after operating times ranging from 250 to 450 hr. Figure 11 shows the extensive corrosion that occurred on the Inconel 601.

FIGURE 11 Deterioration of first Inconel 601 liner after 408 burn hours. Note that exhaust nipple in cone section has completely corroded away.

In light of this experience, the Navy initiated a screening program designed to identify those alloy systems most resistant to hot corrosion in the environment of sewage incinerators (Ketcham, 1977). The results of this program, which involved laboratory burner rig studies, are summarized in Table 6. Inconels 690 and 671; Haynes Alloys Nos. 150, 188, and 25; and the austenitic stainless steel Types 310 and 309 were all more resistant than Inconel 601. Based on these data, the Navy fabricated vortex incinerator liners of the nickel-base alloys Inconel 690 and 671. A liner also

TABLE 6 Hot-Corrosion Rates of Candidate Incinerator Liner Materials Based on Weight Losses.

No.	Alloy Class	Alloy Designation	Density		Average(1) Exposed Area	Average(1) Weight Loss	Average(1) Corrosion Rate		Remarks
			lb/in^3	g/cm^3	$in.^2$	mg	mdd(2)	ipy(3)	
1	Nickel-base	Inconel 690	0.294	8.14	1.439	30.9	16	0.0028	Very light scaling
2	Nickel-base	Inconel 671	0.284	7.86	1.350	34.95	19	0.0035	Very light scaling
3	Cobalt-base	Haynes 150	0.291	8.05	0.954	54.1	42	0.0075	Very light scaling
4	Iron-base	310	0.287	7.94	1.286	123.8	72	0.0130	Light scaling
5	Iron-base	446	0.270	7.47	1.299	220.4	126	0.0243	Moderate scaling
6	Iron-base	309	0.287	7.94	1.299	243.5	139	0.0253	Light scaling
7	Nickel-base	RA-333	0.298	8.25	1.380	444.2	239	0.0418	Moderate scaling
8	Cobalt-base	Haynes 188	0.330	9.13	1.469	584.7	296	0.0466	Moderate scaling
9	Cobalt-base	Haynes 25	0.330	9.13	1.473	683.4	345	0.0544	Moderate scaling
10	Nickel-base	Inconel 617	0.302	8.36	1.264	2,312.2	1359	0.2342	Heavy scaling
11	Nickel-base	Hastelloy "X"	0.297	8.22	1.294	2,472.9	1421	0.2488	Heavy scaling
12	Nickel-base	Inconel 601	0.291	8.05	1.364	3,773.5	2134	0.3815	Heavy scaling (fell apart)
13	Titanium-base	RMI-0.2Pd	0.163	4.51	1.187	2,460.6	1541	0.4918	Heavy scaling (fell apart)
14	Titanium-base	RMI-5Al-5Sn-2Zr-2Mo-0.25Si	0.163	4.51	1.316	3,626.8	2049	0.6541	Heavy scaling (fell apart)
15	Iron-base	RA-330	0.289	7.99	1.282	6,556.8	3800	0.6841	Completely corroded (no metal left)
16	Nickel-base	Hastelloy "S"	0.316	8.75	1.460	12,460.6	6347	1.0449	Completely corroded (no metal left)

(1) Average value for two specimens in the same test.

(2) mdd - milligrams per sq dm per day = $372W/AT$ where W = wt loss (mg), A = exposed area (in^2) T = length of test (hours).

(3) ipy - inches of penetration per year = mdd x 0.00144/density of material.

TEST CONDITIONS:
Length of test = 500 hours
Temperature = 1400° F
No. of thermal cycles = 11
Fuel = diesel (with 1.0% sulfur)
Air/fuel ratio = 30/1 (by wt)
Corrodent = undiluted urine (natural)

was made from the cobalt-base Haynes Alloy No. 188. No problems were encountered in the fabrication of these liners. After from 700 to 800 operating hr, all the above liners exhibited satisfactory performance. These materials, particularly the high-chromium nickel-base Inconel 690 and 671, appear to be the best alloys from the standpoint of resisting the hot corrosion experienced in sewage incinerator environments.

b. Ceramic Materials of Construction

The combustion gases in multifunctional incinerators are highly corrosive to metals; therefore, ceramic materials are the most likely candidates for liner materials. Land-based municipal incinerators and shipboard boilers use a variety of silicon carbide refractories where resistance to a particular corrosive environment is anticipated. For instance, a high-vanadium fuel will react with alumina-bearing refractories to form a spinel that, in turn, undergoes a growth in forming causing destructive results. Vanadium does not react with silicon carbide; therefore, the choice is clear. Likewise, certain glasses and metallic inclusions can react with silicate or clay bonded silicon carbide causing degradation of the bonding phase that leads to destructive results. Silicon nitride or silicon oxynitride bonded silicon carbide resists the action of these corrosive elements to provide a more stable system.

Silicon carbide is prone to low-temperature destructive oxidation that is accelerated by the presence of water vapor (steam). The temperature zone where this occurs is between 900 to 1200 °C. Above 1200 °C, a protective silica film forms and prevents further oxidation. In normal refractory practice, if it is anticipated that a silicon carbide refractory will remain in this critical temperature zone, materials such as barium carbonate are added during manufacture to produce a lower melting complex silicate that affords protection in the lower temperature regime. It becomes apparent that refractory selection is critical based on the exposure in terms of both temperature and corrosive elements encountered. These corrosive elements include oxygen, water vapor, carbon monoxide, vanadium, slags (acid/basic), chlorides, and fluorides. Mapping of the internal environment of the incineration vessel is important so that proper refractories for each zone can be selected. This mapping should consider temperature isotherms, flame impingement, glass interface zones, etc. The refractories available for this type of application are described in Table 7.

TABLE 7 Silicon Carbide Refractories.

Type Bonding Phase	Density g/cc	$/lb	Use Temp °C	Resistant to*	T.S.** Index
Clay	2.3 -2.5	.50- .70	1000-1300	CG, O, HO	80
Self (silica)	2.4 -2.6	.50- .70	1000-1300	CG, O, HO	70
Calcium Silicate/ Iron Oxide	2.4 -2.6	.60- .80	1000-1400	CG, O, HO	70
Silicon Oxynitride	2.45-2.65	.80-1.00	1000-1500	CG, O, HO, Slags	70
Silicon Nitride	2.5 -2.7	1.25-2.00	1000-1500	CG, O, HO, Slags	60
Recrystallized	2.5 -2.7	5.00-7.00	950-1600	CG, O, HO, Slags	50
Barium/Silica	2.35-2.55	.50- .70	850-1100	CG, O, HO	60

* CG - Products of combustion
O - Oxygen bearing gases
HO - Water vapor bearing gases
Slags - Generally, siliceous slags w/vanadium, iron, calcium

** Thermal shock index on a scale of 0 to 180
Thermal cycling of 6" diameter x 1/2" thick plates, cycled 10 times in and out of a furnace at 1200°C. Rating based on 3 point, no cracks, 2 points slight crack, 1 point open crack, 0, broken.

In addition to silicon carbide refractories, a host of fireclay, super-duty, and high-alumina bricks are used in industrial incinerators, but these materials are unsatisfactory for use in corrosive environments where thermal shock is common. Also, castable-type refractories that use calcium aluminate as a hydraulic setting bonding phase with an alumina bearing aggregate can be and are being used in some less corrosive environments. Two super refractories can be used depending on the environment. High alumina, either of a fused or calcined type, can be used when temperatures are high or when hydrogen-bearing gases are present. Silica will be attacked significantly above 1250°C by dry hydrogen, and rapid degradation of the refractory will occur if it constitutes the bonding phase. The sintered alumina bond resists chlorides, fluorides, and certain carbonates as well as hydrogen attack, at least to the melting point of alumina at about 2000°C. It cannot withstand the attack of certain metal phases which react with alumina to form spinels (e.g., vanadium). Sodium also will attack alumina significantly at temperatures above 1100°C resulting in the formation of beta alumina, a low density form that is destructive because of the volume change that occurs during its formation. Alumina also lacks resistance to thermal shock. Mullite is superior to alumina in thermal shock resistance and also is resistant to certain slags and salts. It also offers less thermal expansion and thermal conductivity than alumina, which reduces heat loss or the need for additional insulation. A brief summary of pertinent properties of these oxide-type refractories is presented in Table 8.

TABLE 8 Oxide-Type Refractories.

Refractory Type	Density, g/cc	Cost, $/lb	Use Temp., °C	T.S. Index
Fireclay	2.2-2.4	0.1-0.2	800-1400	< 10
Super-duty 65% Al_2O_3	2.4-2.6	0.3-0.4	800-1600	< 10
Hi Alumina 90% Al_2O_3	2.8-3.0	0.4-0.5	800-1700	< 15
Alumina				
Calcined	3.0-3.2	0.7-0.8	800-1800	< 20
Fused	3.0-3.4	0.8-1.1	800-2000	25
Mullite	2.5-2.8	0.6-1.0	800-1750	45
Calcium Alum				
Calcined	2.4-2.6	0.4-0.8	800-1700	< 50
Fused	2.6-2.8	0.6-1.0	800-1800	< 60

Both silicon carbide and aluminum oxide ramming mixes are available. Those with aluminum generally start with low-grade clays and run through the bauxite, kyanite types to the mullite group and then to the purer forms containing alumina grog and high-grade plastic clays. These materials probably would be unsatisfactory for shipboard incinerator applications due to the early failure of the bonding phase.

2. Recent Navy Experience

The Navy has been conducting experiments with a completely refractory-lined multipurpose incinerator (Figures 12 and 13) at its Dahlgren, Virginia, facility.

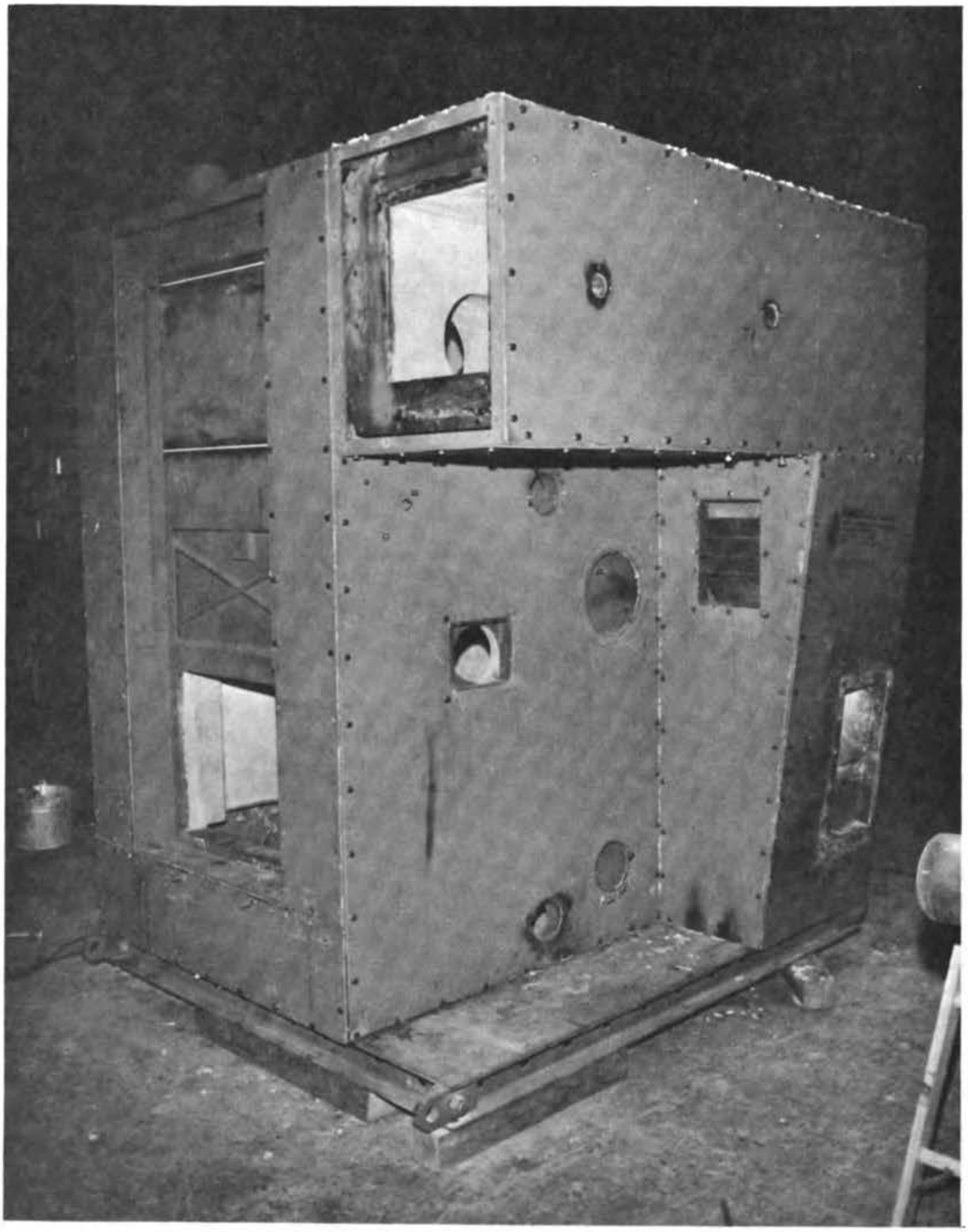


FIGURE 12 Multipurpose incinerator during assembly at Dahlgren test facility.

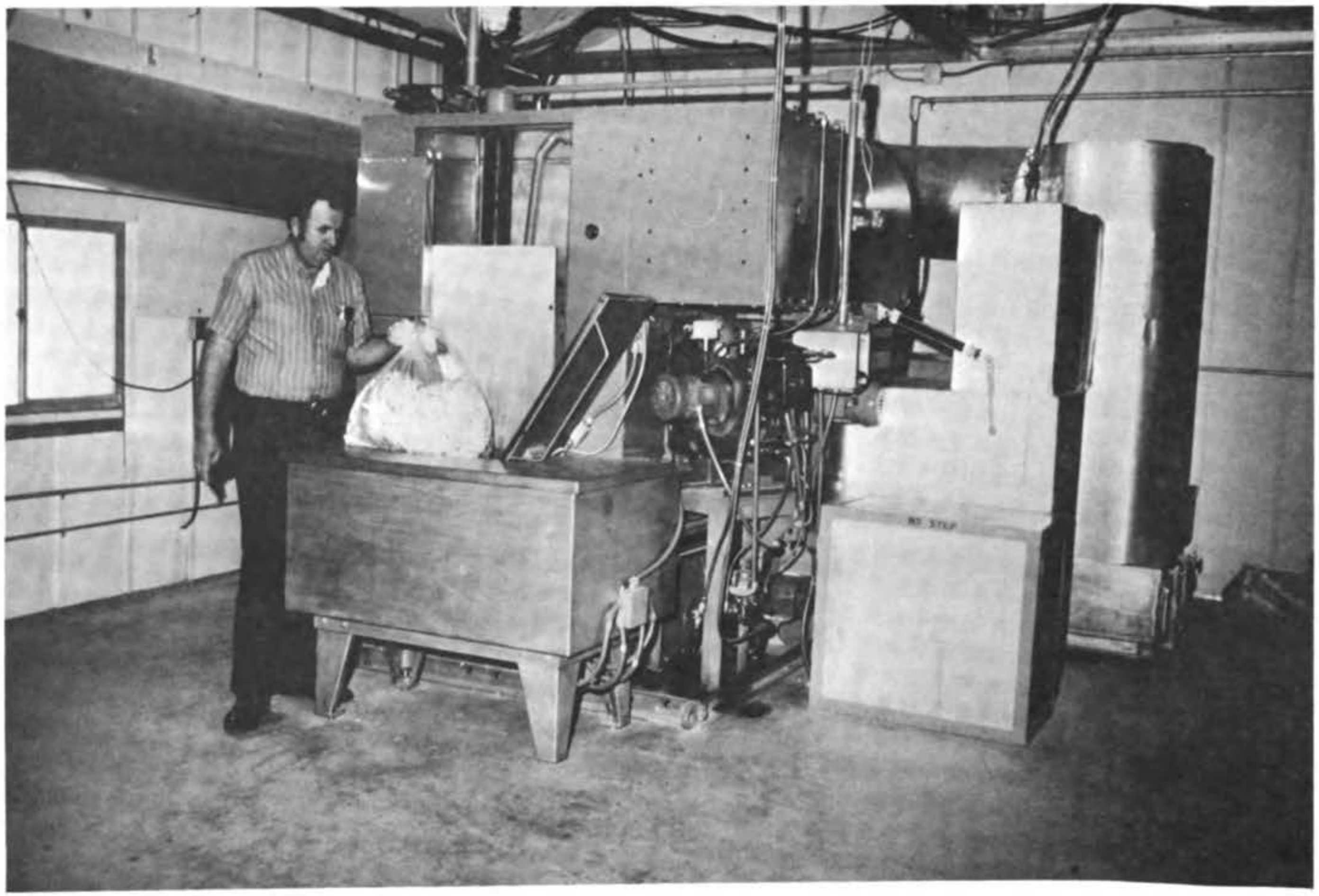


FIGURE 13 Multipurpose incinerator during studies at Dahlgren.

The main combustion chamber is lined with a cast ceramic composed of 97.5 percent Al_2O_3, 23 percent CaO, and 0.1 percent SiO_2. The liner of the combustion chamber door is composed of 59.5 percent Al_2O_3, 33.5 percent SiO_2, and 4.5 percent CaO. A test panel of 87 percent Al_2O_3, 10 percent Ca_2O_3, 2.5 percent SiO_2, and 0.06 percent CaO has been installed in one of the hottest zones (Figure 14).

The incinerator has been operated for about 1200 hr. The main problems involve cracking and spalling of the ceramic (Figure 15). In addition, some wasting of the ceramic liner has been observed in hot areas where salts build up. Because of this salt build-up, it will not be practical to burn sewage collected using a sea water flush system. The combustion chamber appears to be in satisfactory condition; however, no vibratory tests have been run as yet.

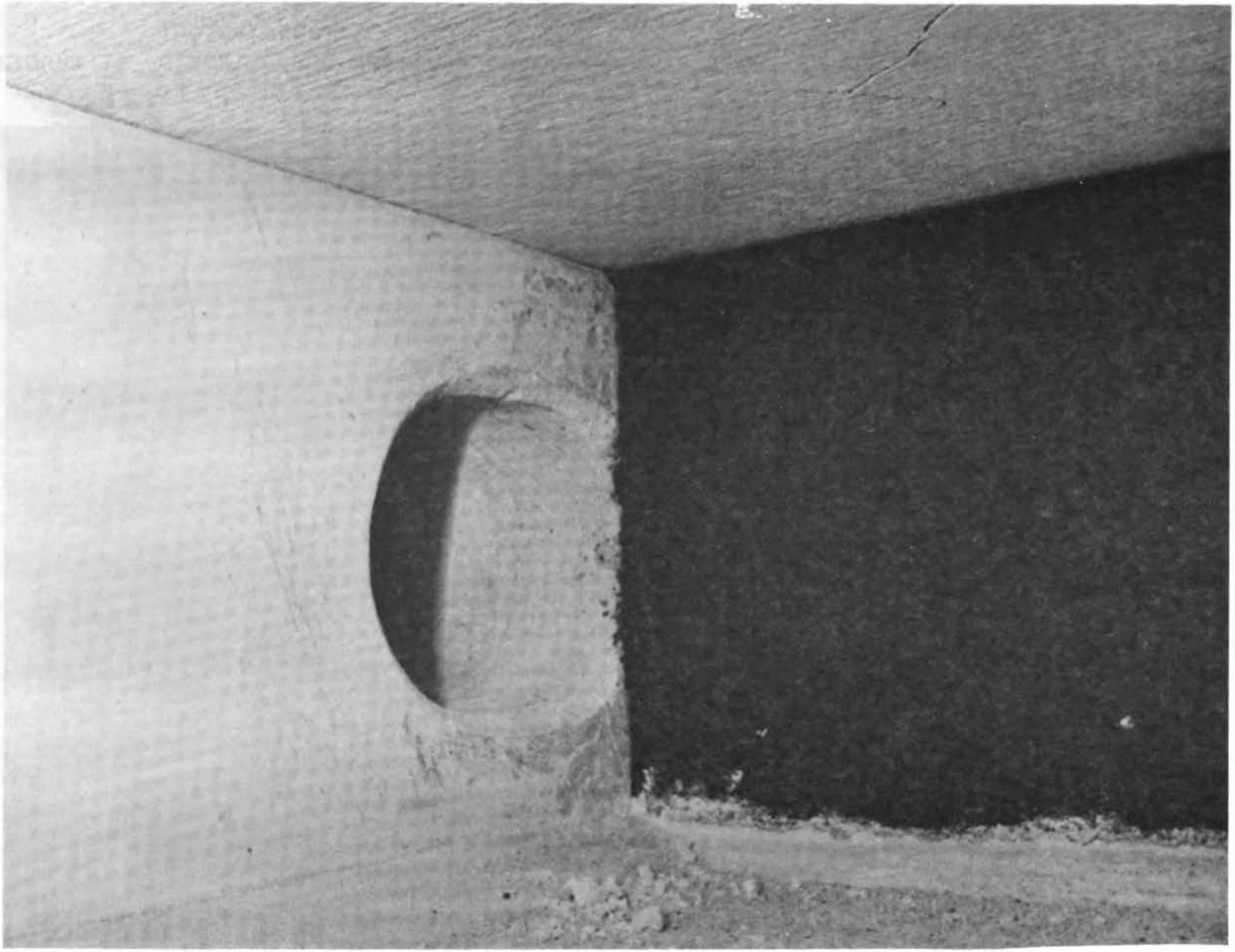


FIGURE 14 The 87 percent Al_2O_3, 10 percent Ca_2O_3, 2.5 percent SiO_2, and 0.06 percent CaO patch in hot zone of the multipurpose incinerator.

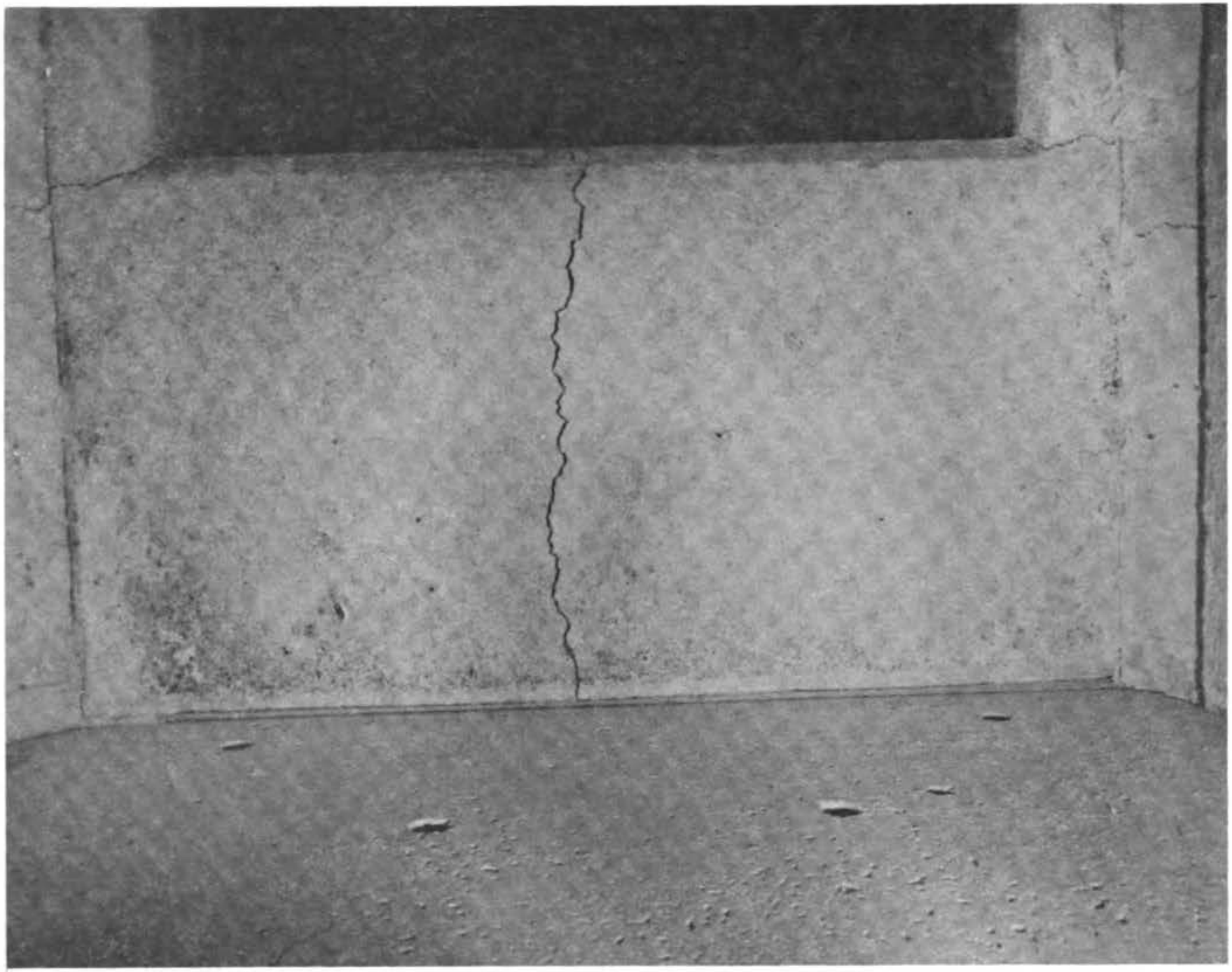


FIGURE 15 Cracking and spalling of the ceramic liner in the multipurpose incinerator.

REFERENCES

American Society of Mechanical Engineers. 1974. Combustion Fundamentals for Waste Incineration.

Brame, J.S.S., and King, J.G. 1955. Fuel. Edward Arnold.

Cheremisinoff, P.N., and Young, R.A. 1975. Pollution Engineering Practice Handbook. Ann Arbor Science Publishers.

Corey, R.C., Ed. 1969. Principles and Practices of Incineration. Wiley.

Essenhigh, R.H. 1974. "An Introduction to Stirred Reactor Theory Applied to Design of Combustion Chambers." In Combustion Technology, edited by Palmer and Beer. Academic Press.

Essenhigh, R.H. 1968. "Burning Rates in Incinerators." In Proceedings (Third) National Incinerator Conference, pp. 87-100. American Society of Mechanical Engineers.

European Protection Agency. 1973. Air Pollution Engineer Manual. 2nd ed., Pub. No. AP40.

Fristrom, R.M., and Westenberg, A.A. 1965. Flame Structure. McGraw-Hill.

Gard Inc. (GATX). 1978. Sewage Spray Drying System Technical Report.

Gaydon, A.G., and Wolfhard, H.G. 1960. Flames. Chapman and Hall.

Griswold, J. 1946. Fuels, Combustion and Furnaces. McGraw-Hill.

Hesketh, H.E. 1972. Understanding and Controlling Air Pollution. Ann Arbor Science Publishers.

Incinerator Institute of America. 1968. IIA Standards.

Incinerator Institute of America. 1966. Incinerator Standards Handbook.

Ketcham, S.J., Ed. 1977. *Proceedings of the Tri-Service Conference on Corrosion*. Metals and Ceramics Information Center Report MCIC-77-33. Battelle-Columbus Laboratories.

Kwon, H.S. 1978. "Waste Disposal by Fluid Bed Incineration and Energy Recovery Modes." Paper presented at Eighth Biennial National Waste Conference, Chicago, Illinois.

Lewis, B., and von Elbe, G. 1961. *Flames and Explosions of Gases*. Academic Press.

Lund, N.F., Ed. 1971. *Industrial Pollution Control Handbook*. McGraw-Hill.

Mansur, Raymond T. 1972 and 1975. *U.S. Navy Packaging Reduction Program*. Reports MRNO 90, 99, 106, 114. U.S. Army Natick Laboratories.

Marks, C.H. 1976. "Commercial and Government R&M Requirements for Shipboard Incinerators." In proceedings of the Annual Reliability and Maintainability Symposium, pp. 196-199.

National Academy of Sciences. 1977. "Technical Experience Obtained with GE Sewage Incinerator and the Jered Sewage Incinerator." Paper presented at NAS Solid Waste Incinerator Seminar, Washington, DC.

National Center for Resource Recovery, Inc. 1974. *Incineration*. Lexington Books.

National Materials Advisory Board. 1977. *Materials of Construction for Shipboard Waste Incinerators*, NMAB Report 331. National Academy of Sciences, Washington, D.C.

Niessen, W.R. 1970. *Systems Study of Air Pollution from Municipal Incinerators*. A.D. Little.

Perkins, H.C. 1975. *Air Pollution*. McGraw-Hill.

Raupuk, M.W. n.d. *Performance Analysis of Two Liquid Waste Incinerators*, Report MAT-75-45 to D.W. Taylor Naval Ship Research and Development Center, Bethesda, Maryland.

Rolke, R.W.; Hawthorne, R.D.; Garbett, C.R.; Slater, E.R.; Phillips, T.T.; and Towell, G.D. 1971. *Afterburner Systems Study*, Report No. S-14121. Shell Development Company.

Smith, M.L., and Stinson, K.W. 1952. *Fuels and Combustion*. McGraw-Hill.

Strehlow, R.A. 1968. Fundamentals of Combustion. International Textbook Company.

Trinks, W., and Mawhinney, M. 1955. Industrial Furnaces. Vol. I. Wiley.

Trinks, W., and Mawhinney, M. 1961. Industrial Furnaces. Vol. II. Wiley.

Velzy, C.R., and Velzy, C.O. 1978. "Incineration." In Marks Standard Handbook of Mechanical Engineers, 8th. McGraw-Hill.

Vent-O-Matic Incinerator Corporation. n.d. Development of Multi-Use Shipboard Incinerator - Final Report, Phase II," for the Sea Systems Command, Washington, D.C.

White, J.A. 1976. "Operational Experience with a Vacuum Collection and Waste Incineration System Aboard a U.S. Coast Guard Cutter." Paper presented at the Intersociety Conference on Environmental Systems.

Williams, F.A. 1965. Combustion Theory. Addison-Wesley Publishing Company.

Wyath, S.V., and Hagedorn, G.D. 1975. "Shipboard Multifunctional Waste Incinerator." Paper presented at Intersociety Conference on Environmental Systems,