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Construction Engineering
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Hydrothermal Processing of Base Camp Solid Wastes To Allow Onsite Recycling

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Final report

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Abstract: Bouldin Corp., McMinnville, TN, has developed a technology to process domestic solid waste using a unique hydrothermal system. The process was successfully demonstrated at Forts Benning and Campbell, where it was determined that, while the process was energy intensive, it had potential as a means to recycle Army solid wastes, both within and outside the Continental United States. The purpose of this study was to determine if the hydrothermal system could be made more energy efficient, thus making it suitable to deploy at Army contingency operations bases. Bench-scale experiments have shown that the desired characteristics of processed solid waste can be achieved at temperatures lower than temperatures currently used in the Bouldin process, thus decreasing projected energy requirements for a deployed system. A simple economic analysis shows that using waste wood as a fuel for steam generation would have even greater affect on reducing the power requirements for the system. It is recommended that the Army proceed with the development of a deployable WasteAway system. It is recommended that alternative operating scenarios and system configurations that address the treatment of other problem base camp wastes also be investigated.

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Preface

This study was conducted for the Office of the Directorate of Environmental Programs, Assistant Chief of Staff for Installation Management (ACSIM) under 622720D048 project “Industrial Operations Pollution Control Technology”; Work Unit 2GJJL1, “Physical, Chemical and Thermal Reduction of Expeditionary Waste.”

The work was performed by the Environmental Processes Branch (CN-E) of the Installations Division (CN), Construction Engineering Research Laboratory (CERL). The CERL Project Manager was Debbie Curtin, Chief, CN-E. Dr. John T. Bandy is Chief, CN. Technical Director for Installations is Martin J. Savoie. The Deputy Director of CERL is Dr. Kirankumar V. Topudurti and the Director is Dr. Ilker R. Adiguzel.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL Richard B. Jenkins, and the Director of ERDC is Dr. James R. Houston.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
miles per hour	0.44704	meters per second
pounds (force) per square inch	6.894757	kilopascals
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

Background

Base camp solid waste management

The Army Environmental Requirements and Technology Assessments (AERTA) process determined that disposal of nonhazardous solid waste at both permanent and deployed installations was a significant environmental problem for the Army, and that new technologies were needed to address that problem. This project addressed the problems associated with solid waste disposal at Forward Operating Bases during contingency operations (CONOPS).

When base camps are established in combat conditions, combat units consider solid waste management a very low priority. Field-expedient measures of open dumping, burying, and limited burning of solid waste are the standard procedures of Army units engaged in combat. These procedures continue when base camps are first established until the local threat level is low enough to allow units to address solid waste management as a general health and sanitation requirement.

Other factors besides threat level impact solid waste management at immature base camps. The environmental awareness and expectations of host nationals and combatants in times of war are very low compared with that in times of peace. In some nations, solid waste management has a very low priority among host nationals as a cultural phenomenon, even in times of peace. U.S. forces may deploy at compounds formerly occupied by other warring forces that left them in a highly unsanitary condition. Finally, in many wartime situations, a military unit has no idea whether they will occupy a given base camp for a week, a month, or several months. This sense of nonpermanence impacts priorities and actions relating to solid waste management.

After a base camp is relatively secure, the Army traditionally procures a service contractor to remove all solid waste. The Army may not prescribe a specific disposal point, especially in cases where an obvious disposal point is not readily apparent. If the disposal point is not delineated in the U.S. Army service contract, the service contractor historically seeks a disposal site that is authorized in some fashion by a host-nation or local-government entity. As a result the service contractor will often make disposal arrangements at a host-nation garbage dump, leaving the United States vulnerable to post-CONOPS liabilities. More sustainable options such as waste reduction and recycling are not required by the Government. The cost-plus method of compensating contractors eliminates incentives for contractors to minimize the cost to the Government for disposing solid wastes.

Other problems are associated with transporting wastes to landfills or dumps. The movement of contractor trucks in and out of the camp perimeter presents potential security risks. Landfills may also be long distances away as is the case in Kuwait and Iraq. According to a 3rd Army source, the roundtrip distance to a landfill is often 120 miles or more, driving up the cost of disposal considerably (personal communication between Gary Gerdes, ERDC-CERL, and Curt Williams, 3rd Army Contractor).

Air curtain destructors are also used to dispose of base camp wastes. Unfortunately, this technology cannot incinerate general solid waste to an inert form. These burners reduce the volume of garbage by only 65 to 75%, leaving a large amount of incinerator residue to be disposed by another method (see Figure 1). The wet material, paper, and plastics being burned require significant quantities of accelerant (usually JP8 fuel) and wood to provide the amount of heat needed to maintain a hot fire. The relatively low burn temperatures of the air curtain technology create smoke plumes that have caused complaints from residents and Soldiers alike in the vicinity of burning yards (Tucker et al. 2004) (see Figure 2). For the purposes of this study, air curtain destructors are not considered an acceptable alternative to sanitary landfills due to obvious health risks to Soldiers and host-nation citizens.

Clearly, current management of base camp solid wastes must be improved. Land disposal and air curtain incineration create security, cost, and health issues that need to be addressed by alternative technologies. One very promising alternative developed by Bouldin Corporation (McMinnville, TN) is a hydrothermal treatment technology currently being marketed in the private sector as a means of meeting recycling goals. This technology was demonstrated by the National Defense Center for Environmental Excellence (NDCEE), with oversight provided by U.S. Army Engineer Research and Development Center (ERDC) Construction Engineering Research Laboratory (CERL). The Bouldin systems were demonstrated at two sites: Fort Campbell, KY, and Fort Benning, GA. In its current state the technology was determined to be too energy intensive for deployment. This report discusses laboratory-scale experiments, an alternative energy source study, and an economic analysis to determine whether the hydrothermal process can be made deployable.

Figure 1. Smoking air curtain incinerator at a U.S. camp in the Balkans. The pile of material behind the incinerator is accumulated residue from the incinerator.

Figure 2. Pile of incombustible material removed from air curtain incinerator. This material accumulated near the base camp due to lack of final disposal site.

Previous demonstration of Bouldin Corporation technology

Process description

Bouldin & Lawson Corporation (now Bouldin Corp.) developed a processing system that significantly reduces municipal solid waste (MSW) volume by converting it into usable end products. The system includes: two shredders, a grinder, a hydrothermal process (hydrolyzer), dryer, and particle screens, as shown in the schematic in Figure 3. The input material is MSW, which includes glass, plastics, paper, cardboard, food scraps, metal cans, etc. The waste is first shredded and ground to reduce it to a consistent particle size, between 0.5 and 1 inch. The shredded waste is then augured through the hydrolyser where it is exposed to high-pressure steam. The process causes cellulose fibers in the paper, cardboard, food, etc. to expand, creating a soft, gray, end product appropriately named "fluff" by Bouldin personnel. Within the fluff are small kernels of plastics, metals, and glass. Metals, glass, and some plastics are not affected by the hydrothermal process, and are removed by screening.

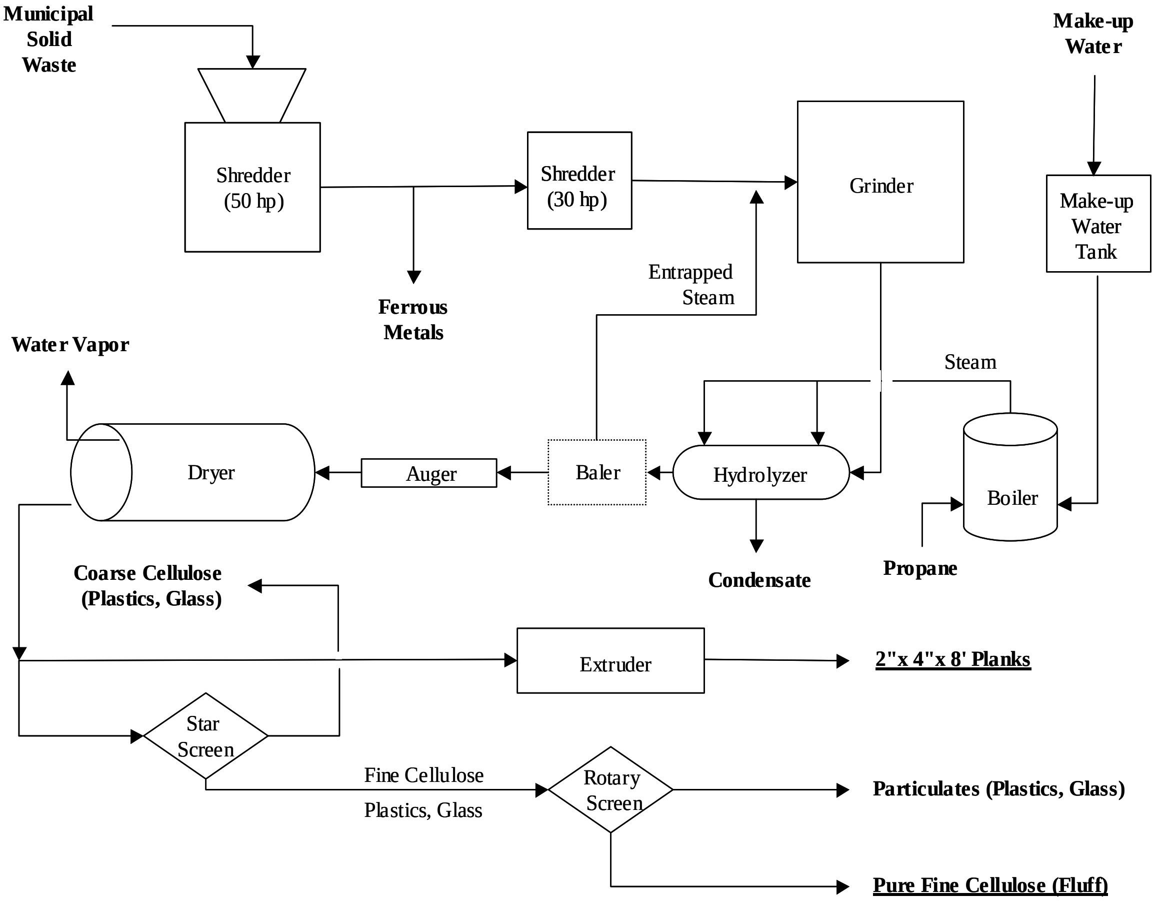

Figure 3. Schematic of the Bouldin Corp. solid waste processing system.

The output from the process can be reused in two ways. After the plastics, glass, and metal fines are removed, the cellulose material can be used as a soil amendment for improving soil quality or soil stabilization applications. Bouldin Corp. currently sells this material to the landscaping industry. Unscreened output from the hydrolyzer can be extruded to make a material similar in appearance (but not strength) to plastic lumber.

ERDC/CERL demonstration

In Fiscal Year 2001 an ERDC-CERL project to validate use of the Bouldin system on Army installations was funded by Congress. ERDC-CERL then contracted the National Defense Center for Environmental Excellence (NDCEE) to conduct a pilot-scale demonstration of the Bouldin system at Fort Campbell for 1 week in June 2001. This effort was followed by a second NDCEE pilot-scale demonstration conducted at Fort Benning over a 3-week period in June/July 2002. Figures 4 and 5 show much of the equipment used during the Fort Benning evaluation. Refuse from family housing areas was used as the input test material.

Figure 4. Bouldin processing system used during Fort Benning demonstration. A Bobcat is loading initial shredder with domestic waste from pile on right. Shredder is followed by metal removal, a second shredder, grinder, and hydrolyzer (on left).

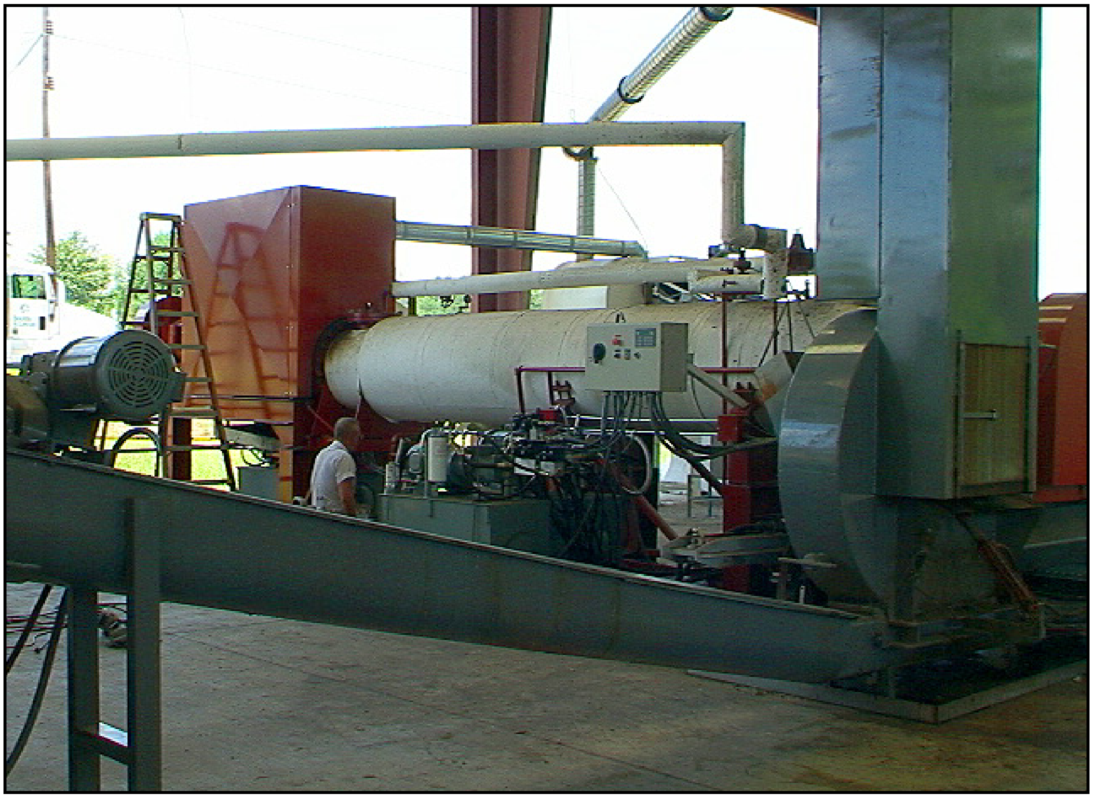

Figure 5. Hydrolyzer component of Bouldin Corp. processing system. Waste flows left to right through white cylindrical pressure vessel, then exits hydrolyzer into the auger chute (bottom right).

Three overall objectives were associated with these demonstrations:

1. To evaluate the hydrothermal process that reduced the volume and changed the physical/chemical characteristics of municipal solid waste;
2. To determine the viability of fluff as a soil amendment; and
3. To measure strength parameters of extruded fluff to determine its application as a building material.

Figure 6 shows waste after processing at Fort Benning.

Figure 6. Processed waste from Fort Benning demonstration.

Chemical analysis of the fluff confirmed the processed waste was not a characterized hazardous waste, and analysis of air samples for particulate matter and volatile organic compounds showed that the Bouldin system generated no air pollutants of concern. The system evaluation showed that it was fairly expensive to operate and maintain, and was not competitive with disposal by conventional sanitary landfill at most continental United States (CONUS) installations. The power requirements for the shredders, grinder, and especially the steam generator made the system energy intensive. Improvements Bouldin has made to the system since these demonstrations have made the system more efficient, however.

The screened fluff was land applied at test plots on Fort Campbell and Fort Benning and at USDA Agricultural Research Stations in Auburn, AL and Temple, TX. Revegetation was monitored to measure the efficacy of the fluff as a soil amendment for improving soil quality and plant growth. Results showed the screened fluff had excellent soil amendment properties. Further, because the fluff seemed to cause some crusting when incorporated into native soil, it was hypothesized that the fluff could also be used as a dust suppressant.

The heavier, unscreened fluff containing metal and plastic fines was extruded into composite plastic-like planks and tested for structural properties. While it did not have sufficient tensile strength to be used as structural members, it did have sufficient strength in compression to be used for block walls, walkways, etc. It was concluded that extruded fluff had good potential for use as a construction material, though it would be limited to specific types of use.

The overwhelmingly positive results from both the land application and extrusion tests indicated that use of the Bouldin system has potential to allow recycling of over 90% of the nonhazardous solid wastes generated at Army CONUS installations. It was also concluded that the potential was significant for the system to be used to process nonhazardous solid waste at Army base camps where the processed waste could be reused onsite. That potential would be greatly enhanced if the system were made more energy efficient.[1]

Objectives

The primary objective of this project was to determine if the hydrothermal process developed by Bouldin Corp. could be made more energy efficient. More specifically the objectives were to: show on a laboratory scale that base camp character waste could be processed at lower temperatures; project the economics of using a more efficient Bouldin system; and to suggest scenarios where the Bouldin system could address other waste disposal issues at base camps.

Approach

To achieve the above objectives it was necessary to:

1. Create a simulated waste stream—Using the results of a previous base camp solid waste characterization study (Gerdes and Jantzer 2006) as a guide, appropriate amounts of the various components were shredded and mixed.
2. Perform bench-scale tests on simulated base camp wastes—Parr reactor vessels were used to simulate the environment inside the Bouldin process hydrolyzer. Samples of the simulated waste stream were then subjected to numerous operating scenarios using the variables of temperature/pres-

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[1] It should be noted that, since the completion of the Fort Benning demonstration, Bouldin Corp. has made many changes to their system to improve materials handling and decrease labor for operation and maintenance.

sure, moisture content, and time. The goal of the tests was to determine the minimum values of each of the variables that produce processed wastes with desirable characteristics.

3. Prepare an economic analysis of a deployable Bouldin system—The estimated cost to process base camp solid waste with a deployed Bouldin system was compared with the estimated cost to landfill the waste off site.

NOTE: A second study has been conducted by Dr. Richard Gebhart and Ryan Busby (ERDC-CERL) to investigate the viability of fluff generated from base camp waste as a dust suppressant. A third ERDC-CERL study has been conducted by Jonathan Trovillion to investigate the use of extruded base camp fluff as a construction material. Results of those studies have been (or will be) published separately in scientific journals and in ERDC technical reports.

2 Base Camp Waste Characteristics

Characterization study

Buchart-Horn, Inc. performed a study under the direction of ERDC-CERL to determine the characteristics of nonhazardous solid wastes generated at Army base camps. A detailed description of that study is included in Gerdes and Jantzer 2006. Table 1, Base camp solid waste production by Soldier, is taken from that technical report.

Table 1. Base camp solid waste production by Soldier.

	lb/yr/soldier	kg/yr/soldier	% of total
Plastic Bottles [1]	295	134	5.1%
Polystyrene	9.3	4.2	0.2%
Other Plastics	143	65	2.5%
Aluminum	10	4.7	0.2%
Other Metals	11	4.8	0.2%
Corrugated Paper	349	158	6.0%
Other Paper	179	81	3.1%
Scrap Wood	4,151	1,883	72%
Kitchen Food Waste	328	149	5.7%
Post-consumer Food Waste	51	23	0.9%
WWTP Sludge (dry weight) [2]	70	32	1.2%
Sawdust	47	21	0.8%
Grass Clippings	39	18	0.7%
Glass	40	18	0.7%
Textiles	25	11	0.4%
Medical Waste	13	6.1	0.2%
Rubber	3.9	1.8	0.1%
Miscellaneous	5.3	2.4	0.1%
Total	5,769	2,617	100%

Table Footnotes:

[1] Reflects 100% drinking water distribution via disposable bottled water

[2] WWTP sludge weight expressed as 100% solids – multiply by 5 for a cake and multiply by 50 for a liquid

[3] Survey includes all discarded solid waste except hazardous waste, recycled scrap metal, and salvaged construction material and equipment

[4] Above values do not reflect additional loadings due to TOA rotations (estimated to increase annual waste production by approximately 1 month for bi-annual TOAs)

[5] Above values are based on relatively short-term studies and reflect a population “snapshot.” It is not known whether this table accurately includes the fraction of solid wastes generated by host-nation contract employees and transient combatants.

According to the U.S. Environmental Protection Agency (EPA 2003), domestic solid waste has been characterized as having component fractions considerably different than those found in base camp waste. Table 2 shows a comparison of the two types.

Table 2. Base camp constituents compared to municipal solid waste.

Constituent	Base Camp (%)	MSW (%)
Plastics	7.8	11.3
Metals	0.4	8
Paper	9.1	35.2
Wood	72.8	5.8
Food waste	6.6	11.7
Yard waste	0.7	12.1
Glass	0.7	5.3
Rubber and textiles	0.5	7.4
WWTP Sludge	1.2	n/a
Medical Waste	0.2	n/a
Other	0.1	2.4

Source: Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2003, USEPA530-F-05-003.

The most obvious difference is the much larger percentage of wood in base camp waste. Virtually everything that is shipped to a base camp arrives on wooden pallets or in wooden crates and boxes, creating the high fraction of wood in the waste stream. If the wood fraction was significantly decreased, the fractions of the other components would become somewhat closer to the component fractions in MSW.

The per capita generation rates are also significantly different between base camps and municipalities. The generation rate for base camps is 15.8 lb/day/Soldier, while the average generation rate in the United States is about 4.5 lb/day/person.

Simulated base camp waste

In order to conduct laboratory bench-scale experiments, a test material having characteristics the same or very similar to base camp solid waste was needed. That material was fabricated by collecting the various components, mixing together the appropriate fractions, and using the Bouldin system to shred and grind the wastes. The intent was to duplicate the particle size of the waste that normally is fed into the Bouldin hydrolyzer.

For experimental purposes, it was necessary to prepare a fairly homogeneous mixture. Components of the waste were primarily clean recycled materials. Used wooden pallets were the source of the wood component, as would be the case at a base camp. For the same reason, plastic drink bottles were the primary source of plastic in the fabricated waste, as well as high-density polyethylene (HDPE) bottles and a small amount of polyvinyl chloride pipe.

All of the dry materials were shredded and mixed during a one time effort, and stored for later use in the laboratory. When the laboratory experiments were conducted, appropriate amounts of dewatered sewage sludge and shredded food scraps were mixed with the dry components before each test.

3 Reducing Energy Required for the Bouldin Process

Creation of inoffensive fluff

The two most apparent physical changes that occur within the Bouldin process hydrolyzer are: the color of most waste components is neutralized to a light gray; and the processed waste is almost homogeneous, having a texture resembling course cotton—thus the name “fluff.” The physical and chemical mechanisms involved in converting domestic solid waste to fluff have not been previously studied. Funding limitations precluded such studies during this project also. However, hypotheses regarding those mechanisms were made and to some extent evaluated during bench-scale experiments.

Hypothesis 1

Cellulose matrix is expanded by sudden pressure release. Steam enters the influent end of the Bouldin hydrolyzer at about 100 psi and 350° F. This high pressure steam must partially condense on the cooler waste after it is fed into the processor. The porous components of the waste (i.e., most of the organics) would become saturated with high temperature hot water during the 30 minutes the waste travels through the hydrolyzer. The waste exits the hydrolyzer in small batches. As a gate opens to allow a ram to expel the waste, pressure in the exit chamber suddenly falls from 100 psi to atmospheric, and the super-heated water that had been absorbed by the wastes vaporizes almost instantly. This is evident by the explosion of steam and processed material exiting the hydrolyzer when the outlet gate opens. It is believed that, when the high temperature water absorbed by the organic material immediately and somewhat violently vaporizes, that event causes the cellulose fibers in paper, cardboard, food wastes, etc. to dramatically expand. (This process is similar to that used to make “puffed” breakfast cereal.) The expanded cellulose fibers give the processed waste a soft, light, almost cottony texture. The event when super-heated water violently vaporizes is sometimes referred to in the literature as “steam explosion” and is used as the initial step in many processes involving the conversion of cellulose fibers into commercial products (Ramos 2003).

It was presumed that, when shredded wood passed through the hydrolyzer, the cellulose fiber bundles would also expand in the same fashion as did the paper and cardboard in domestic wastes. Because of the large fraction of cellulosic material, it followed that processed base camp waste could be even more suitable for extrusion and for land application than processed MSW.

Hypothesis 2

Color change is caused by heating and/or hydrolysis. Homogeneous color and fluffy texture are two primary physical characteristics that allow processed solid waste to be used as an aesthetically acceptable raw material for land application and extrusion. It is not certain what causes the benign gray color of the fluff, but it is apparent that the dyes and pigments in the various wastes (primarily paper products) are altered by the hydrothermal process. It is also possible the oxidation of lignin in the wood and cardboard contribute to the gray color of the fluff, just as oxidized lignin causes graying of weathered wood.

The mechanisms involved in the removal of color from the solid waste were not investigated during the bench-scale experiments. However, the absence of color was the second primary indicator used when determining the success of individual bench-scale tests.

Hypothesis 3

Migration and coalescing of liquid lignin could enhance cellulose expansion in wood and improve the reuse value of fluff. Lignin is the substance in the wood that binds the cellulose fiber bundles together, giving wood its rigidity and strength. Lignin is a polymer and has many variants, so there is not a single chemical formula for it. For this reason, the physical-chemical characteristics of lignin are reported in ranges. The melting point can be as low as 75° C (see discussion in *Temperature* paragraph below). Most lignin compounds have a melting point below the normal operating temperature of the Bouldin hydrolyzer; therefore, the compounds should easily melt in that process. It was believed that melting the lignin in shredded wood would decrease the strength of the cellulose fiber bundles and allow the wood fibers to expand when exiting the hydrolyzer. It was also thought that the liquid lignin would tend to coalesce into discrete droplets on the surface of the processed wood particles. Because lignin is naturally adhesive, it was thought that the lignin droplets would significantly enhance the dust suppressant characteristic of the processed waste and would decrease the amount of polymer required when it is extruded.

Hypothesis 4

The three hypotheses described above led to the fourth and primary hypothesis regarding decreasing the energy requirements of the Bouldin system. Specifically, it was thought that the temperature and pressure of the steam used in the hydrolyzer could be decreased.

The rapid expansion of cellulose fibers can occur at temperatures lower than currently used by Bouldin. Super-heated water (water as a liquid above 100 °C or 212 °F) can exist only in an enclosed environment having a pressure above atmosphere (above 15 psi absolute). When the pressure of super-heated water is suddenly dropped to atmospheric pressure, water rapidly vaporizes until the system achieves thermodynamic equilibrium (i.e., the phase change of water to steam consumes the latent heat of the super-heated water to the point where the water temperature is lowered to 100 °C or less). This event can occur whenever the pressure is released on water above 100 °C. It can be assumed that the more the liquid water temperature is above 100 °C, the more violent the phase change to steam will be when pressure is suddenly released. It is also reasonable to assume that the more violent the phase change to steam, the greater the expansion of cellulose fibers in the materials that have absorbed water.

The temperature at which the Bouldin system operated during the Fort Benning demonstration was obviously adequate to create the violent steam explosion needed to convert hot soggy waste into fluff. However, no controlled studies have been done to optimize the operating environment within the Bouldin hydrolyzer. Factors such as process time, temperature, and moisture content all would affect the expansion of cellulosic waste material, but the relationship of those factors is not known. It was reasonable to assume that optimizing those operating parameters could significantly decrease the operating temperature and pressure (i.e., energy requirements) of the hydrolyzer. The primary focus of the bench-scale experiments was to optimize the operating conditions inside the hydrolyzer.

Bench-scale experiments

Description

Optimize thermal treatment process

The purpose of bench-scale experiments was to show that wastes having the same characteristics as base camp wastes could be processed to create an end product with the same benign physical appearance as the fluff created from MSW by the Bouldin system. The experiments had to show that processing base camp waste could require less energy than the current Bouldin process.

Experiments conducted to optimize the environmental conditions within the thermal treatment process had the test variables: temperature, pressure, %H2O, and time. The experimental goal was to minimize each of these operating parameters. The upper limits of these variables were the operating parameters of the existing Bouldin process. The system currently operates at 177 °C (350 °F); 100 psi; and has a 30-minute processing time. Moisture content within the Bouldin process is not known.

Pressure. In the Bouldin hydrolyzer, high pressure is necessary for steam to penetrate the shredded solid waste as it is augured through the hydrolyzer. As the steam condenses and is absorbed by the cooler waste particles, the pressure within the hydrolyzer lowers. As stated in the above hypotheses, super-heated water is necessary for fiber expansion, and super-heated water cannot exist unless the pressure within the hydrolyzer remains elevated. Therefore, the minimum acceptable pressure (and temperature) is that of the thermodynamic state at which there is enough latent heat held by the absorbed water to create a forceful transition to steam when pressure is released. Because temperature and steam pressure are directly related, pressure was not used as a variable in the bench-scale testing. Further, it was decided that an additional requirement to monitor and adjust system pressure would unnecessarily complicate the operation of a hydrolyzer in a CONOPS environment.

Temperature. At least four factors affect the theoretical minimum operating temperature. First, in order to expand the cellulose fiber bundles of wood, it is assumed that the operating temperature must be above the melting temperature of lignin. The melting temperature varies significantly, however, depending on the type of wood. It can be as low as 75 °C (167 °F) or higher than 165 °C (330 °F).

A second factor is the degradation of hemicellulose, which also contributes to the stability of the wood matrix. The hydrolysis of hemicellulose can begin at 140 °C (284 °F).

The third factor is not related to the conversion or expansion of organic material, but rather to disinfection. Because base camp waste will include food waste and wastewater treatment sludge, it is important to kill the pathogenic bacteria that may be in the waste stream. No standard methods are established for killing pathogens in solid waste. However, guidance exists for the thermal treatment of sewage sludge in order for it to be classified "Class A" (i.e., safe for incidental contact and for land application as a soil amendment). That guidance includes a formula to determine the duration at which a particular temperature must be maintained. For the purposes of this study, the guidance requires that the temperature must be raised to at least 72.2 °C (161 °F) for 15 minutes, to 70 °C (158 °F) for 30 minutes, or to 68 °C (154 °F) for 60 minutes (AEC 1996).

The fourth factor is the melting point of plastics. The plastics most commonly found in base camp wastes are polyethylene (PE), HDPE, and polyethylene terephthalate (PET). PE and HDPE melt at a fairly low temperature – 130 °C (266 °F), but PET melts at 245 °C (473 °F), which is much higher than the current operating temperature of the Bouldin hydrothermal processor.

Percent moisture. The absorption of super-heated water by waste is important to the conversion process—primarily for the creation of a "steam explosion" and possibly to aid the migration of liquid lignin. It is reasonable to assume that, as the amount of super-heated water absorbed by the waste increases, the magnitude of the steam explosion also increases. Thus, the potential for fiber expansion is directly proportional to the amount of super-heated water absorbed by the waste.

It was also thought that increasing moisture content would increase the efficiency of lignin-cellulose separation. When lignin melts and becomes fluid, the presence of liquid water may aid the migration of the lignin away from the cellulose fibers, even though lignin is largely insoluble. If this is the case, then the operating conditions within the hydrolyzer must maintain enough super-heated water above the melting temperature of lignin to allow migration.

The amount of water in the waste, however, is directly proportional to the amount of energy required to operate the hydrothermal process (see the "Discussion of reduced energy requirement" section in Chapter 4). When waste first enters the hydrolyzer, the water fraction of the waste will act as a heat "sink" (i.e., the greater the amount of water in the shredded waste, the more energy required to raise the temperature of the shredded waste to the optimum level). Lower percent moisture will decrease the power requirements for the process operation.

Since fiber expansion is one of the primary metrics for successful waste processing, a goal of the bench-scale experiments was to determine the minimum moisture content of the waste that can occur and still have an adequate degree of expansion.

Time. The duration of the thermal conversion process will affect the power requirements. It is assumed that three factors impact the ideal process time:

1. the length of time required for the entire shredded waste mass to achieve the optimum thermodynamic equilibrium temperature,
2. the length of time required for the lignin to migrate away from the cellulose and/or coalesce, and
3. most importantly, the length of time required for super-heated water to become absorbed by the cellulosic material.

Minimizing the first time factor will be most easily addressed by optimizing the process configuration.

Experiments

A mixture of shredded material having the same component fractions (wood, paper, plastic, etc.) as solid wastes generated at Army forward facilities was used as the test material for these experiments. The fractions (per cent by weight) of each component were in accordance with the results of the base camp solid waste characterization study (Table 1). Between 300 and 600 grams of test material were used for each individual test. The volume of material for each test remained at about 1 liter, but the weight varied depending on the initial moisture content. Each test subjected the test material to one of many possible environmental scenarios within the reactor vessel. The testing included combinations of the following test variable values:

Temperature: 70 °C; 120 °C; 150 °C; 170 °C
(158 °F; 248 °F; 302 °F; 338 °F)

%H2O: Initial; 40%; 60%; 85%

Time: 15 min; 30 min; 60 min.

A total of 45 tests were completed, including a few duplicate tests. After each test, the characteristics of the processed test material were evaluated. Color and texture were evaluated subjectively.

The conversion of waste into fluff is readily apparent to the naked eye and to the touch. The successful conversion of waste to fluff was used as the primary indicator of a successful bench-scale test, though determining the extent of each conversion was subjective. Conversion to fluff was considered to be successful when paper, cardboard, and food particles were no longer easily recognizable.

Apparatus

Laboratory-scale experiments were conducted using a high pressure, stainless steel reactor vessel (Figure 7) made by Parr Instrument Co. (Moline, IL). The Parr apparatus consisted of a 1 gallon vessel, motorized stirrer, heating jacket, and a controller. The access ports on the vessel were used to insert a thermocouple to monitor temperature, a pressure gauge, and to discharge steam. The controller was used to set the speed of the motor turning the stirring paddle, and to maintain a set temperature within the reactor vessel by controlling current to the heating jacket.

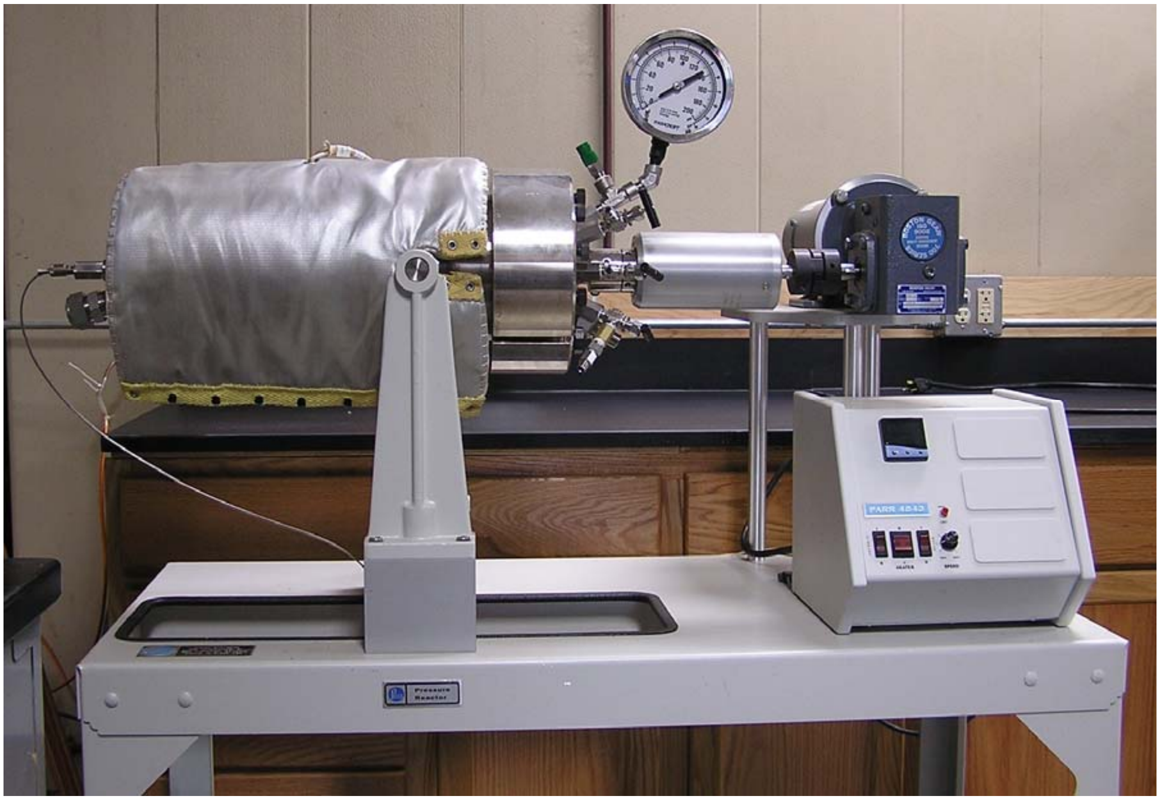

Figure 7. Parr reactor vessel used to mimic conditions inside hydrolyzer. Test material was kept at a set temperature within the heat-jacketed vessel on the left, while being constantly stirred by the motor on the right.

4 Results

General observations

1. The most prevalent component in original test material that created the "refuse" appearance was paper, as seen in the picture of unprocessed fabricated waste shown in Figure 8. Much of the paper disintegrated merely by coming in contact with hot water or steam.
2. The waste processed at 70° C had few physical changes (see Figure 9). As expected the process temperature must be above 100° C in order for the processed waste to have an inoffensive appearance. (See Hypothesis 1 in the previous chapter.)
3. Results of testing at higher temperatures were somewhat surprising in that the physical appearance of the processed test material was not remarkably different when comparing one test scenario to another. (See Figures 10, 11, and 12.) A marginal improvement in appearance occurred from 120° to 150° C, and virtually no difference between 150° and 170° C. The minimum processing temperature lies between 120° and 150° C.
4. The expansion of shredded wood into a fluff-like material was not successful. It is apparent from the appearance of the processed test samples that the cellulose structure of the shredded wood fragments remained intact for all scenarios. Apparently higher temperature and pressure is necessary to expand wood fibers. This is supported by observations made during a full-scale processing event at the Bouldin Corp. processing facility. During that event, fabricated base camp wastes were processed at the normal temperature of about 177° C. The expansion of wood fibers was observed to be only slightly greater during that event than during the bench-scale testing.
5. Correlation was not apparent between appearance and process time, or between appearance and percent moisture. This result was primarily because the wood fraction dominated the appearance of all processed samples. The appearance of the wood particles changed little except for a color change to gray.
6. The plastics PE and HDPE were no longer visible in the waste. Apparently those plastics melted and dispersed as small droplets that attached to other waste particles. As expected the process had no effect on PET plastic—those pieces were unchanged.
7. Processed waste containing a large fraction of shredded wood is not offensive in appearance and can be used as a soil amendment without concern regarding aesthetics. The wood particles turn gray in color after processing and will blend well with most soils.

Figure 8. Unprocessed test material. This waste was shredded again in the lab to further reduce particle size prior to being placed into the reactor vessel.

Figure 9. Test material processed at 70º C.

Figure 10. Test material processed at 120º C.

Figure 11. Test material processed at 150º C.

Figure 12. Test material processed at 170° C.

Discussion of reduced energy requirement

Current hydrolyzer energy requirement

As stated previously, the current Bouldin process uses 177 °C (350 °F) steam at 100 psi. During the Fort Benning demonstration, boiler water usage was monitored. The amount of water consumed for steam generation was 40 gal (334 lb) per ton of material processed. The enthalpy of steam at 350 °F is 1192 British thermal units per pound (BTU/lb) water (Badger 1967, p 501). Assuming the water fed into the boiler is 10 °C (50 °F; enthalpy = 18 BTU/lb), the amount of heat added to the water to create the steam generated is: (1192 BTU/lb - 18 BTU/lb) x 334 lb water/ton of waste processed = 392,116 BTU/ton of waste processed.

Basic thermodynamics of steam explosion

Two phase changes of water occur that allow the expansion of cellulose fibers by steam explosion. First, when steam enters the hydrolyzer it comes in contact with cooler waste material. Heat transfers from the steam to the wastes until a thermal equilibrium is reached. Because the steam loses heat, some of the steam condenses during this event, and the water created is absorbed by the waste. Pressure causes the water to absorb more readily into the waste particles. The second phase change occurs when the pressure is suddenly released, and the super-heated water absorbed by the cellulosic material explosively vaporizes.

To determine the amount of energy that may be saved by lowering the temperature of the steam, it is necessary to know the amount of heat required to raise the temperature of the waste material. Unfortunately, the bench-scale experiments did not accurately model the entire hydrolyzer process. So predicting the energy required for various operating scenarios used during the experiments must be estimated.

Since the waste material being processed is not homogeneous, it is difficult to accurately estimate the amount of energy required to raise the temperature of the waste material as it passes through the hydrolyzer. Because the material is primarily wood and paper, it is assumed that the specific heat of the waste material is close to that of wood, which is about 0.42 gram-calories/gram/°C or BTU/lb/°F (Hudson 1944, p 314). Because sewage sludge and food waste add moisture to the system, it is assumed that the approximate specific heat of the waste material to be about 0.45 (i.e., it takes about 0.45 BTUs to raise the temperature of 1 lb of waste material 1.0 °F, or about 900 BTUs to raise the temperature of 1 ton of material 1.0 °F). The amount of heat transferred from the steam to the waste is, of course, dependent on the initial and final temperature of the waste. The heat required to heat a ton of waste to a particular temperature is: (Final temperature – initial temperature) x 900 BTU. Assume the waste delivered to the system has a temperature range between a high of 32 °C (90 °F) to a low of 2 °C (35 °F). The heat required to raise the temperature of the waste to 350 °F (temperature rise between 260 and 315 °F) is between 234,000 BTU/ton and 283,500 BTU/ton. The amount of heat required to raise the temperature of the waste material to the experimental temperatures is shown in Table 3.

Table 3. BTUs required to raise temperature of 1 ton of waste during processing.

Initial Temperature	Final Temperature			
	120 °C (250 °F)	135 °C (275 °F)	150 °C (300 °F)	177 °C (350 °F)
2 °C (35 °F)	193,500	216,000	238,500	283,500
18 °C (65 °F)	166,500	189,000	211,500	256,500
32 °C (90 °F)	144,000	166,500	189,000	234,000

Steam requirement – example scenario

Assume that conditions at a base camp are such that the temperature of the waste (and boiler feed water) are 18 °C (65 °F). Also assume that the waste will be heated by steam to a temperature of 150 °C (300 °F). The steam must impart 211,500 BTU/ton of waste to achieve this. Assume that all of the heat transferred to the waste is derived from the condensation of 150 °C steam. The heat of evaporation (and condensation) of 150 °C steam is 910 BTU/lb. Therefore, the amount of steam required to heat 1 ton of waste to 150 °C is 232 lb (211,500 $\text{BTU/ton}_{\text{waste}} \div 910\ \text{BTU/lb}_{\text{steam}}$). The enthalpy of steam at 150 °C (1180 BTU/lb) less the enthalpy of water at 18 °C (33 BTU/lb) is 1147 BTU/lb. This is the amount of energy required to create 1 lb of 150 °C steam. Thus, it will require 266,000 BTU (1147 BTU/lb steam x 232 lb steam/ton of waste) to process 1 ton of waste. (This number will be used in the next chapter, Economic Analysis.)

According to the data presented in Table 3, the energy required for steam production can be significantly decreased. By decreasing the operating temperature from 177 °C to 150 °C (350 °F to 300 °F), the reduction of energy required decreases by 16 to 19%. An energy reduction of 24 to 29% occurs if the operating temperature is reduced to 135 °C (275 °F). The percent energy reduction increases as the ambient temperature increases.

5 Economic Analysis

Tables 4, 5, and 6 compare the estimated costs to dispose solid waste from a hypothetical base camp by:

1. landfilling off-site;
2. processing by the Bouldin process using an electric-powered steam generator; and
3. processing by the Bouldin system using scrap wood to fuel a steam generator.

The estimated cost per ton for each of the three alternatives are: Landfill — $217/ton; Bouldin process — $110/ton; and Bouldin process using wood for steam production — $82/ton.

Any economic analysis of deployment scenarios is dependent on information that is based on engineering judgment, and small, possibly unrepresentative studies. Information regarding deployments may be subject to political biases. Documented costs for the operation of base camps are difficult or impossible to obtain. The cost information used in the tables below is the best available at the time of preparation. Still, it appears that the use of a deployable WasteAway system at a base camp could significantly reduce the overall cost to dispose solid wastes. Because of this potential for significant savings, it is recommended that the Army develop and test a deployable waste processing system.

Assumptions and conditions

- Base camp population is 7300 (large Brigade Combat Team).
- Waste generation = 15.8 lb/person/day x 7300 persons x 1 ton/2000 lb = 58 ton/day.
- Waste disposed is only nonhazardous and does not include medical or bulky wastes.
- One hundred percent of the wastes processed by the Bouldin system will be reused at the base camp as a soil amendment for erosion or dust control, or will be extruded into a low-grade construction material.
- Fuel cost (including delivery) is $13/gallon.

Cost to landfill all wastes

Table 4. Landfill disposal.

Landfill Disposal Assumptions	
• 58 tons/day @ 5 tons/trip to landfill => 12 trips • Travel time to/from landfill = 120 mi. round-trip/30 mph = 4 hours (personal communication, 2006, Curt Williams, Third Army Contractor at Camp Arifjan, Kuwait) • One hour/day to load and unload transfer vehicle. • One driver and one guard on each trip • Total labor per trip to transfer 5 tons of waste = 2 x (4 + 1) = 10 hours • Total labor to transfer 58 tons per day = 10 hours/trip x 12 trips = 120 man-hours	Mileage for 5-ton vehicle = 4.1 mpg (Canes 2005) Fuel use for transporting waste = 120 mi/trip x 12 trips/day x 1 gal/4.1mi = 351 gal/day

	Quantity	Units	Unit Cost	Annual Cost
Landfill disposal	58.00	tons/day	$100.00/ton	$2,120,000.00
Transport to landfill 60 miles from camp				
Soldier labor (drivers and guards)	120.00	Man-hours/day	$18.40/hr	$806,000.00
Fuel for 5-ton transfer vehicle	351.00	gal/day	$13.00/gal	$1,670,000.00
Total				$4,600,000.00

Cost to process the entire waste stream by Bouldin process

Table 5. Costs for processing solid waste using Bouldin system.

Solid Waste Processing Assumptions

- Waste generated annually at a base camp is 15.9 lb/person/day x 7300 persons x 1 ton/2000 lb = 58 ton/day
- Cost to purchase and O&M requirements for a base camp hydrothermal processing system are same as for domestic WasteAway system. Capacity of hydrothermal processing system is 3 ton/day. Assume system operates 20 hr/day.
- Steam generator requires 3,335,000 BTU/hr. The electrical capacity required to power the steam generator is: 1000 KW.
- Water consumption = 31 gal/ton x 58 ton/day = 1800 gal/day. Cost ($0.41/gal) is for treated effluent from a wastewater treatment facility.
- Fuel consumption of loaders = 2 gal/hour x 20 hr/day x 2 vehicles = 80 gal/day
- A moveable 60'x120'x26' (14' sidewall) will be required to shelter the equipment and wastes, and will be constructed by contractor. Weight is approx. 10 tons. Cost includes erection.

Capital Costs:	Quantity	Units	Unit cost	Annual cost
Processing system (hydrolyser, two shredders, grinder, conveyers, drier, metal removal)	1.00	20-year life	$3,000,000.00	$150,000.00
Fabric shelter	1.00	10-year life	$120,000.00	$12,000.00
Front loader	2.00	10-year life	$150,000.00/ea	$30,000.00
Shipping of equipment	50.00	Tons	$500.00/ton	$25,000.00
Operating Costs:				
Labor - Supervision by ex-patriot contractor	1.00	Man-year	$250,000.00/man-yr	$250,000.00
Labor - Operation and maintenance by host-nation labor	16.00	Man-year	$12,000.00/man-yr	$192,000.00
Consumable and replacement parts				$210,000.00
Shipping of parts	5.00	Tons	$500.00/ton	$2,500.00
Water for boiler	1800.00	Gallons/day	$0.41/gal	$270,000.00
Electric power capacity required				
System (except boiler)	600.00	Kilowatts	$511.00/KW capacity	$306,600.00
Electric power capacity required for steam	1000.00	Kilowatts	$511.00/KW capacity	$511,000.00
Fuel for front loaders	80.00	Gallons/day	$13.00/gal	$380,000.00
Total				$2,339,000.00

Cost to process the waste stream by Bouldin process, using waste wood as a fuel

Table 6. Costs to process solid waste using Bouldin system and waste wood as energy source.

Solid Waste Processing Assumptions

- Cost to purchase and O&M requirements for a base camp hydrothermal processing system are same as for domestic Bouldin Corp. system. Capacity of hydrothermal processing system is 3 ton/day.
- Waste generated annually at a base camp is 15.9 lb/person/day x 7300 persons x 1 ton/2000 lb = 58 ton/day
- Steam generator requires 3,335,000 BTU/hr. That amount of heat can be produced by burning 930 lb scrap wood per hour at 60% efficiency.
- Because wood burned to produce steam will not be processed by the system, the amount of waste processed will be reduced to 50.25 ton/day. System will operate 17 hours/day
- Water consumption = 31 gal/ton x 50.25 ton/day = 1560 gal/day. Cost ($0.41/gal) is for treated effluent from a wastewater treatment facility.
- Fuel consumption of loaders = 2 gal/hour x 17 hours/day x 2 vehicles = 68 gal/day
- A moveable 60'x120'x26' (14' sidewall) will be required to shelter the equipment and wastes, and will be constructed by contractor. Weight is approx. 10 tons. Cost includes erection.

Capital Costs:	Quantity	Units	Unit cost	Annual cost
Processing system (hydrolyser, two shredders, grinder, conveyers, drier, metal removal)	1.00	20-year life	$3,000,000.00	$150,000.00
Fabric shelter	1.00	10-year life	$120,000.00	$12,000.00
Front loader	2.00	10-year life	$150,000.00	$30,000.00
Shipping of equipment	50.00	Tons	$500.00/ton	$25,000.00
Operating Costs:				
Labor - Supervision by expatriot contractor	1.00	Man-year	$250,000.00/man-yr	$250,000.00
Labor - Operation and maintenance by host-nation labor	16.00	Man-year	$12,000.00/man-yr	$192,000.00
Consumable and replacement parts				$210,000.00
Shipping of parts	5.00	Tons	$500.00/ton	$2,500.00
Water for boiler	1560.00	Gallons/day	$0.41/gal	$233,500.00
Electric power capacity required				
System	600.00	Kilowatts	$511.00/KW capacity	$306,600.00
Fuel for front loaders	68.00	Gallons/day	$13.00/gal	$322,700.00
Total				$1,734,000.00

6 Alternative Scenarios for Operating the Bouldin Process During CONOPS

This project addressed the potential for using the existing Bouldin WasteAway system to process typical nonhazardous solid wastes generated at base camps. Potential alternatives to the existing operation and system configuration could address further decreasing demand on the base power supply and address other base camp environmental issues. These alternative scenarios are as follows:

1. Process nonhazardous waste with the current system configuration, with the exception of using some of the waste wood as a fuel to fire the steam generator. The economics of this scenario are discussed in Chapter 5, Economic Analysis.
2. Use all of the waste wood as a fuel to fire the steam generator to produce steam for the process and additional steam for conversion to electricity. This scenario would significantly reduce the volume of solid wastes to be reused, as well as further reduce the system's electricity demand.
3. Process nonhazardous waste, altering the system configuration to heat the waste directly with exhaust from waste wood (or fluff) incineration. Water would be added to the waste to create the steam needed for the hydrothermal process.
4. Option 3, and add wastewater treatment sludge to the nonhazardous wastes. Moisture in the sludge will be heated by the wood incineration exhaust to become the steam needed for the process. The system becomes a means for processing wastewater sludge into an immediately usable product.
5. Option 3, and add black water or gray water to the nonhazardous wastes. The wastewater will become the source of steam needed for the process. The system becomes a means for processing wastewater.
6. Option 3, and mix other wastes, such as human waste, grease trap waste, medical waste, etc. with nonhazardous waste and process. Use of system to process human waste during the period when burn-out latrines are still in use would eliminate the need for burning human waste. The logistics for operation under this scenario will require further study.

Resources were not available to further investigate scenarios other than the existing configuration. Further research is needed to investigate these alternatives.

7 Conclusions and Recommendations

- The minimum processing temperature lies between 120° and 150° C.
- The expansion of shredded wood into a fluff-like material was not successful.
- The plastics PE and HDPE were no longer visible in the waste. Apparently those plastics melted and dispersed as small droplets which attached to other waste particles. As expected, the process had no effect on PET plastic as those pieces were unchanged.
- Processed waste containing a large fraction of shredded wood is not offensive in appearance and can be used as a soil amendment without concern regarding aesthetics.
- The cost to process solid wastes using a deployed Bouldin WasteAway system is very favorable compared with transporting the wastes to a remote landfill.
- Further development of a deployable prototype of the WasteAway system is warranted.
- Further research into innovative base camp applications for the system is also recommended.

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14. ABSTRACT

Bouldin Corp., McMinnville, TN, has developed a technology to process domestic solid waste using a unique hydrothermal system. The process was successfully demonstrated at Forts Benning and Campbell, where it was determined that, while the process was energy intensive, it had potential as a means to recycle Army solid wastes, both within and outside the Continental United States. The purpose of this study was to determine if the hydrothermal system could be made more energy efficient, thus making it suitable to deploy at Army contingency operations bases. Bench-scale experiments have shown that the desired characteristics of processed solid waste can be achieved at temperatures lower than temperatures currently used in the Bouldin process, thus decreasing projected energy requirements for a deployed system. A simple economic analysis shows that using waste wood as a fuel for steam generation would have even greater affect on reducing the power requirements for the system. It is recommended that the Army proceed with the development of a deployable WasteAway system. It is recommended that alternative operating scenarios and system configurations that address the treatment of other problem base camp wastes also be investigated.

15. SUBJECT TERMS
Base camp, solid wastes, waste disposal, waste management, recycling

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