

1. REPORT NUMBER CA14-2220	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
4. TITLE AND SUBTITLE Evaluation and Development of High Flow Vacuum Systems for Roadway and Roadside Litter Collection		5. REPORT DATE June 14, 2014
7. AUTHOR Allyson E. Clark, Wilderich A. White, Steven A. Velinsky		6. PERFORMING ORGANIZATION CODE AHMCT Research Center, UC Davis
9. PERFORMING ORGANIZATION NAME AND ADDRESS AHMCT Research Center UCD Dept. of Mechanical & Aerospace Engineering Davis, California 95616-5294		8. PERFORMING ORGANIZATION REPORT NO. UCD-ARR-14-06-14-04
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation P.O. Box 942873, MS #83 Sacramento, CA 94273-0001		10. WORK UNIT NUMBER
15. SUPPLEMENTARY NOTES		11. CONTRACT OR GRANT NUMBER 65A0416 Task 2220
16. ABSTRACT		13. TYPE OF REPORT AND PERIOD COVERED Final Report June 2012 to June 2014
17. KEY WORDS Litter, trash, telerobotic control, roadside maintenance, vacuum collection, articulated nozzle, ditch cleaning, drain cleaning		14. SPONSORING AGENCY CODE Caltrans
19. SECURITY CLASSIFICATION (of this report) Unclassified		20. NUMBER OF PAGES 55
18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.		21. COST OF REPORT CHARGED

Reproduction of completed page authorized

DISCLAIMER/DISCLOSURE STATEMENT

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aerospace Engineering at the University of California – Davis, and the Division of Research, Innovation and System Information at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, State and Federal governments and universities.

This document is disseminated in the interest of information exchange. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California, the Federal Highway Administration, or the University of California. This publication does not constitute a standard, specification or regulation. This report does not constitute an endorsement of any product described herein.

For individuals with sensory disabilities, this document is available in Braille, large print, audiocassette, or compact disk. To obtain a copy of this document in one of these alternate formats, please contact: the Division of Research, Innovation and System Information, MS-83, California Department of Transportation, P.O. Box 942873, Sacramento, CA 94273-0001.



Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Evaluation and Development of High Flow Vacuum Systems for Roadway and Roadside Litter Collection

Allyson E. Clark, Wilderich A. White, &
Professor Steven A. Velinsky: Principal Investigator

Report Number: CA14-2220

AHMCT Research Report: UCD-ARR-14-06-14-04

Final Report of Contract: 65A0416 Task 2220

June 14, 2014

California Department of Transportation

Division of Research, Innovation and System Information

ABSTRACT

The California Department of Transportation (Caltrans) has been actively searching for safer and more efficient methods of roadway and roadside maintenance. The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center has been developing successful Advanced Automation and Robotics (AAR) technologies and applying them to the maintenance and construction activities of Caltrans and other transportation agencies. AHMCT previously developed a telerobotic system that allows rapid movement of a vacuum nozzle under operator control from within the cab of a vacuum truck. The system could potentially improve worker safety and efficiency in many litter and debris collection operations. This report concerns the evaluation of such a commercial truck mounted telerobotic vacuum system used within Caltrans operations. Initial results suggest that the concept is viable and continues to be of value. The researchers provide suggested design improvements and recommend continued support and monitoring of operations.

EXECUTIVE SUMMARY

The California Department of Transportation (Caltrans) has been actively searching for safer and more efficient methods of litter and debris collection. This report concerns the evaluation of two commercial truck mounted telerobotic vacuum systems known as the Vacall ARDVAC (Automated Roadway Debris Vacuum) and the Madvac LT500. These telerobotic systems allow rapid movement of a vacuum nozzle under operator control from within the truck's cab. These systems will improve worker safety and may increase efficiency in many litter and debris collection operations. Results suggest that the concept is viable and continues to be of value. The researchers provide suggested design improvements and recommend continued support and monitoring of operations.

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center has been developing successful Advanced Automation and Robotics (AAR) technologies and applying them to the maintenance and construction activities of Caltrans and other transportation agencies. The research project concept of using a modified commercially available vacuum truck to collect litter originated within Caltrans and resulted in the ARDVAC nozzle development at AHMCT. The ARDVAC nozzle represents a telerobotic nozzle designed for integration with commercially available truck-based vacuum machines generally known as sewer trucks, drain cleaners, catch basin cleaners or Vactors (a generic trademark). The ARDVAC nozzle allows rapid movement of the nozzle tip under operator control from within the truck's cab. A commercially constructed Vacall brand vacuum truck utilizing the ARDVAC nozzle design is simply known as the ARDVAC. Caltrans purchased two of these commercially built units and began operating them in 2008 for research purposes.

Similar to the ARDVAC, but smaller and lighter duty, the Madvac LT500 became commercially available and was successfully demonstrated to Caltrans in 2008. The smaller LT500 chassis was expected to be more maneuverable and less expensive to operate. Caltrans planned to lease two of these machines for testing and evaluation as part of the research. The LT500 does not utilize the ARDVAC nozzle design.

These two differently designed systems are the only two available machines of their type. Caltrans needed to develop an understanding of the efficacy of these two litter and debris collection machines for use in its operations.

The discontinuation of the Madvac LT500 before Caltrans could execute a lease for the research hampered the evaluation of the two telerobotic designs. Caltrans' two ARDVAC machines are the first two production units. The units that Caltrans purchased required several in-service design changes from the manufacturer, which prevented the machines from operating successfully for several years. Caltrans provided the necessary support to keep the machines deployed, and the machines eventually saw increased usage when assigned to a stormwater maintenance crew. Unexpectedly, the crew used the machines for tasks other than litter collecting.

Based on the evaluation and testing of the ARDVACs, the telerobotic vacuum truck design concept remains a viable option for general litter and debris cleaning, although insufficient testing was done to determine the actual or potential efficiency of telerobotic litter collection.

A machine like the LT500 may be adequate for a majority of litter collection efforts. Unlike the ARDVAC, an operator with a Class C driver's license (the most common class of driver's license) can drive and maneuver the LT500 more easily. This smaller machine is potentially cost effective for Caltrans to use in litter collection. However, this Madvac LT500 unit is unsuitable for stormwater operations due to its lighter duty construction and its inability to collect heavy debris or water.

The ARDVAC's nozzle contains more articulation and dexterity than the LT500 nozzle, and the heavier duty components and articulation of the ARDVAC nozzle proved useful and beneficial for stormwater maintenance, in addition to litter and debris collection.

The Madvac LT500's unavailability for testing and marketing hampered the evaluation of the two telerobotic designs. Nevertheless, by deploying the ARDVAC machines, Caltrans gained insight into the potential value of these types of vacuum trucks, including for tasks other than litter collecting. The following list points out the recommendations considered most important.

a) *Document continuing ARDVAC usage to supplement the information in this report:* Caltrans' commitment towards the development of the telerobotic vacuum machine provides value to all Departments of Transportation (DOTs) and the equipment industry. Formally reviewing and documenting the experience with the ARDVAC units will prove to be important in future years. AHMCT recommends sharing this information with other DOTs and industry to support potential future development of this and similar telerobotic equipment.

b) *Using the most experienced ARDVAC operators, formally test the ARDVACs in litter collection operations along freeway medians to determine the maximum rates at which this operation can be performed:* Caltrans and others have calculated the costs of traditional litter collection operations. As such, testing the ARDVAC production rates will greatly benefit Caltrans and other DOTs by allowing a cost/benefit analysis to be performed to determine any increase in efficiency and associated cost savings. This information may encourage the industry to offer telerobotic litter collection equipment in the future. Additionally, if the LT500 or a similar machine under 26,000 lb gross vehicle weight (GVW) became available, such equipment should be tested within Caltrans' operations.

c) *Collect information necessary to determine the ARDVAC value in stormwater maintenance and other Caltrans' operations.* Determining and considering what major design changes should be implemented on any future version of this type of machine will be an important aspect of this review process. For example, the ARDVAC nozzle can be used as a robotic end effector to support tools such as vegetation cutters and other accessories. The stormwater maintenance crews have been using the machine regularly and stated the machines will be used to clear drain inlets before and during rain events. Cleaning inlets quickly before and during storms may be very valuable and could justify the cost of the machinery. To guide the future development of machines necessitates collecting detailed information regarding these tasks.

d) *Support ARDVAC operators by documenting and implementing design changes recommended by experienced operators.* Implementing design changes will be important to

improve the operator ergonomics and encourage the continued use of the machines. Redesigning the controls will provide the best ergonomic improvement.

TABLE OF CONTENTS

Abstract	ii
Executive Summary	iii
Table of Contents	vi
List of Figures	viii
List of Tables	ix
List of Acronyms and Abbreviations	x
CHAPTER 1 Introduction	1
1.1 Problem	1
1.2 Background	1
1.3 Research approach	2
CHAPTER 2 Vacuum Litter Removal Machines	4
2.1 Challenge of Litter Removal	4
2.2 The Telerobotic Truck Mounted Vacuum Concept	7
CHAPTER 3 Madvac LT500 History and Description	9
3.1 History of the Madvac LT500	9
3.2 Description of the LT500	9
CHAPTER 4 ARDVAC History and Description	13
4.1 History of the ARDVAC	13
4.2 Description of the ARDVAC	14
4.2.1 Boom	16
4.2.2 ARDVAC Nozzle	16
4.2.3 Description of Nozzle Design	17
4.3 ARDVAC Controls and Specifications	21
CHAPTER 5 Operational Experience	24
5.1 Operator Experience and Feedback	24
5.1.1 Challenges to Deployment	24
5.1.2 Results and Discussion of Litter Collection Field Testing	24
5.1.3 Results and Discussion of Sand Collection Field Testing	27
5.1.4 Results and Discussion of Drain Inlet Cleaning Field Testing	28
5.2 Operator Statements and Recommendations from Field Testing	30
5.3 Controller	30
5.4 Improvement to Nozzle	32
5.4.1 Working Envelope	32
5.4.2 Nozzle Stowage	35
5.4.3 Airflow	35

5.4.4 Dust Suppression	36
5.5 Comparison of ARDVAC and Madvac LT500	36
CHAPTER 6 Conclusions and Future Research	38
6.1 Conclusions Regarding ARDVAC Deployment.....	38
6.2 Research Task Results.....	39
6.3 Future Research Recommendations	41
References	43

LIST OF FIGURES

Figure 2.1 - The All Purpose Vacuum	5
Figure 2.2 - Example of vacuum integrated with a tractor chassis from US Patent 6263540	5
Figure 2.3 - AgriMetal Company Tuff Vac	6
Figure 2.4 - The Elephant-Vac EVC-4H	6
Figure 2.5 - The Madvac LX300	7
Figure 2.6 - ARDVAC (left) and Madvac LT500 (right) truck mounted telerobotic litter collector machines ..	8
Figure 3.1 - LT500 Front view.....	10
Figure 3.2 - LT500 demonstrating trash pickup and dumping.....	10
Figure 3.3 - LT 500 Extended to side.....	11
Figure 3.4 - LT500 Nozzle stowed on forward hangar.....	11
Figure 3.5 - LT500 View of cab	12
Figure 4.1 - Preproduction ARDVAC system by Clean Earth Company.....	14
Figure 4.2 - The ARDVAC's links and joints.	15
Figure 4.3 - Sections of the nozzle	15
Figure 4.4 - Skeletal diagram of the ARDVAC manipulator	16
Figure 4.5 - Upper section of the ARDVAC nozzle as originally designed	17
Figure 4.6 - Rotation about the vertical axis, Joint 3	18
Figure 4.7 - Articulation of ARDVAC nozzle Joints 4, 5 and 6.....	19
Figure 4.8 - Joint 5, showing original (left) and final design (right)	20
Figure 4.9 - Representation of the ARDVAC Workspace (inch)	21
Figure 4.10 - Layout of controls in cab.....	22
Figure 4.11 - Current control functions for the ARDVAC left and right joysticks	22
Figure 5.1 - ARDVAC positioned to collect litter on fence line.....	25
Figure 5.2 - Trash accumulating under guardrail.....	26
Figure 5.3 - Examples of litter hotspots.....	26
Figure 5.4 - Using the nozzle rotation to break up sand	27
Figure 5.5 - Comparing the ARDVAC to the standard vacuum truck	29
Figure 5.6 - Location of controls forces operator to rotate torso and head	31
Figure 5.7 - Corners on cradle that boom impacts when moving sideways.....	33
Figure 5.8 - Compliance of tip and extension.....	34
Figure 5.9 - Retracting the nozzle behind the cab	35

LIST OF TABLES

Table 3.1: Key Specifications of the Madvac LT500.....	12
Table 4.1: Key Specifications of the ARDVAC.....	23
Table 6.1: Summary of ARDVAC use.....	40

LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Definition
AAR	Advanced Automation and Robotics
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
APV	All Purpose Vacuum
ARDVAC	Automated Roadway Debris Vacuum
Caltrans	California Department of Transportation
DOTs	Departments of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
GPS	Global Positioning System
GVW	Gross Vehicle Weight

CHAPTER 1 INTRODUCTION

1.1 Problem

The California Department of Transportation (Caltrans) has been actively searching for safer and more efficient methods of litter and debris collection. As part of this effort, Caltrans committed to the testing of two recently developed truck mounted telerobotic vacuum machines in which an operator controls the vacuum operation from within the cab of the truck. Caltrans purchased two commercially available Vacall ARDVAC machines and committed to leasing two Madvac LT500 machines for use in actual litter and debris abatement operations. These two systems, significantly different in design, are the only two available machines of their type. Caltrans desired an understanding of the efficacy of these two litter and debris collection machines for use in its operations, and this report documents the research effort to compare and evaluate the two systems.

1.2 Background

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center has been developing successful Advanced Automation and Robotics (AAR) technologies and applying them to the maintenance and construction activities of Caltrans and other transportation agencies since the early 1990's. The AHMCT Research Center represents a partnership between Caltrans and the University of California at Davis. AHMCT researches and develops technology related to highway maintenance and construction tasks, with a focus on preventing injuries through automation and reducing employee exposure to traffic hazards.

Many present day roadway and roadside maintenance operations involve significant manual efforts, and Caltrans seeks to improve the working conditions of these operations. Litter collection is a costly operation that Caltrans would like to improve. Caltrans reported spending \$52 million on the collection of litter and debris in 2012 [1]. In addition to costly litter clean-up efforts, workers must spend many hours working close to high-speed traffic in order to limit the number of highway lane closures. The proximity to this traffic increases the risk of launched debris or an errant vehicle hitting Caltrans workers. These conditions may lead to work-related deaths and injuries, such as the three deaths that occurred within a short time frame near the outset of this research project.

On June 20, 2011, a vehicle struck and killed Richard Gonzalez while he picked up litter along the highway [2, 3]. His death marked the third Caltrans worker fatality within a 48-day span in San Diego. Previously, a vehicle struck Jaime Obeso while working on the highway, and a trolley struck Stephen Palmer, Sr. [2]. These incidents clearly indicate the need to implement options that remove personnel from direct exposure to traffic wherever possible.

Generally low in efficiency and moderately costly, litter collection and debris removal operations may involve high risk of injury. As such, AHMCT has been engaged to examine the types of methods and available machines to make improvements in this operational area. During previous research, AHMCT developed a system to rapidly remove small articles of trash and

litter that accumulated in areas not previously accessible by machine. This system, designated as the Automated Roadway Debris VACuum (ARDVAC) nozzle, represents a telerobotic nozzle designed to integrate with commercially available truck-based vacuum machines generally known as sewer trucks, drain cleaners and catch basin cleaners [4]. Caltrans often refers to these vacuum machines as Vactors, which actually corresponds to a generic trademark. The ARDVAC nozzle allows rapid movement of the nozzle tip under operator control from within the truck's cab.

Private companies, which owned the Vacall line of products, licensed and commercialized the ARDVAC nozzle design. The Vacall products contained the required 12-inch diameter vacuum lines and the boom structure needed to support the ARDVAC nozzle. The commercially integrated vacuum truck and nozzle is simply known as the ARDVAC. Caltrans purchased two ARDVAC units and began operating them in 2008. A similar but smaller telerobotic vacuum machine became commercially available through the Madvac, Allianz and Johnston consortium of companies. Madvac representatives successfully demonstrated this machine designated as the Madvac LT500 to Caltrans, who intended to lease two of these units and compare their utility with the ARDVAC. This report documents research and evaluation of the two machines.

1.3 Research approach

AHMCT researchers were tasked to formally compare the units in order to understand the efficacy of these two litter and debris collection machines for use in Caltrans' operations. The original scope involved the development of test methods and an engineering understanding of these machines' mechanisms of operation. This effort would include observation of the use of the machines within the Caltrans maintenance organization. Also, this included an effort aimed at the development of additional tools/accessories to improve operational efficiency. Such tools and accessories would be similar to the types of devices employed in home vacuum cleaners.

During the timeframe of the project initiation and execution, the Madvac LT500 was removed from the market, and the two ARDVAC machines required modifications by the manufacturer. The modifications, which improved the reliability of the nozzle, are discussed in more detail later in the report. Also, the ARDVACs transitioned to special crews, known as the stormwater crews, who do not generally collect litter except when the litter exists within or around drainage systems. Therefore, AHMCT engineering efforts focused on the development of improvements to the ARDVAC controls. A summary of Caltrans' experience with the machines was collected and included in this report.

The following tasks were defined to complete the research goals:

- Observe and track use of the machines through a combination of direct observation and user feedback.
- Track the machine using data loggers that record the location and status of the machine.
- Develop tests to compare the machines within the operations observed.

- Perform an engineering evaluation of the machines to understand their underlying operational principles.
- Develop tools and accessories to improve machine function and tailor the machines for optimal use in each function.
- Provide a performance evaluation to assess the value of the Vacall ARDVAC and the Madvac LT500 for Caltrans litter and debris abatement.

The following chapters provide an overview of the vacuum based litter collection machines, describe the Madvac LT500 and ARDVAC machines, describe the operational experience and summarize research conclusions and recommendations.

CHAPTER 2

VACUUM LITTER REMOVAL MACHINES

This chapter describes the state of the art in equipment used for general litter removal. These machines are selected to represent the various concepts that have been developed. The selection of machines is not comprehensive, and no recommendations are made as to the value of any particular vendor's machine.

2.1 Challenge of Litter Removal

Litter consists of many different sized objects. Common litter items include cigarette butts, paper and bottles, each of which possesses different geometric size and mass. The wide variety of litter represents a major challenge to the development of a general-purpose litter removal machine.

Randomly deposited by traffic along the roadways, litter typically migrates to the roadside due to the movement of traffic and winds. It tends to collect against structures such as curbs, barriers, and fences or collects in the grasses and weeds typically found on roadsides. The locations at which pockets of litter collect are sometimes referred to as 'litter hotspots'. Once the litter fully occupies the volume of a hotspot, additional litter tends to migrate elsewhere and becomes widely distributed.

To ensure the collection of all litter requires periodic general cleaning of the roadsides. This labor-intensive effort is challenging to accomplish through automation. Alternatively, frequent cleaning of litter hotspots will remove much litter before it possibly disperses to other areas. Potentially, this practice can be accomplished in an easier and more cost effective manner with a machine as opposed to traditional manual methods.

Implementing Adopt-a-Highway programs is one of the ways states have addressed their litter problems. Although these programs reduce litter abatement costs, they simply shift the labor effort from state employees to volunteers. Caltrans regularly partners with various correctional agencies and employs crews of probationers to clear areas that can be accessed relatively safely. The probation crews collect the litter into garbage bags and place the bags along the road as a reminder to the traveling public of the effort involved in gathering litter. Within a week or so, Caltrans crews collect these bags for disposal. In addition to the lightweight litter, both Caltrans and probation crews pick up large items, such as tires and pieces of wood that cannot fit in the bags.

The litter collection machines commercially available typically use vacuum action to lift the litter. Some machines use a rotating brush system in conjunction with a vacuum and a few use brushes without vacuum. The most versatile systems use a vacuum.

Figure 2.1 shows an example of the All Purpose Vacuum (APV) equipment that could remove litter in general cleaning mode. As shown in the figure, the operator could vacuum a wide roadside area in a pattern similar to carpet cleaning, but this method is not practical at a large scale for many reasons. First, this method requires prohibitively intensive manual labor. Second, this process removes a vast amount of organic material, thus increasing disposal costs.

Lastly, this practice requires personnel to manually operate this equipment and thus fails to achieve the goal of reduced worker exposure to traffic hazards. For these reasons, this type of equipment is not feasible for use in Caltrans' operations.



Figure 2.1 - The All Purpose Vacuum

Another vacuum system such as a tractor attachment designed primarily for turf grooming could be used for litter removal. US Patents 6029312 and 6263540 illustrate some examples of this equipment. Taken from US Patent 6263540, Figure 2.2 shows a descriptive example of equipment integrated into a larger tractor. Commercial versions of this type of design are limited to smaller garden tractors.

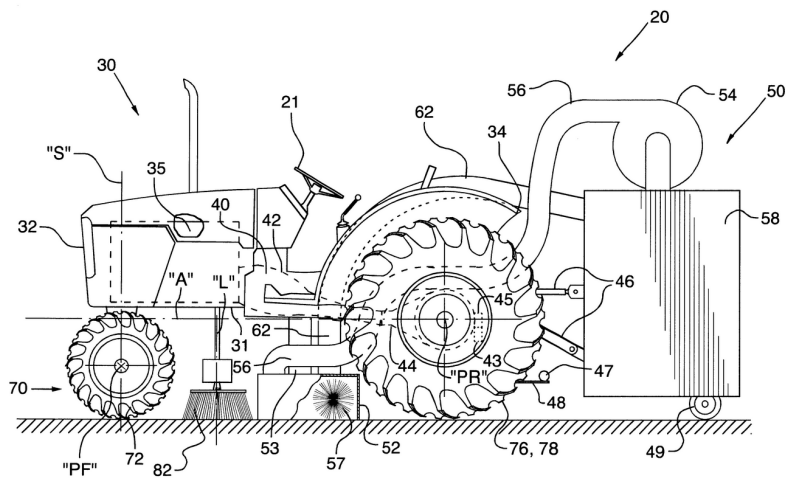


Figure 2.2 - Example of vacuum integrated with a tractor chassis from US Patent 6263540

The commercially available AgriMetal Tuff Vac shares similarities with the APV and tractor based systems. Figure 2.3 shows a trailer-mounted system driven by the tractor's power take-off. Geared toward general purpose cleaning of relatively even and smooth surfaces, these systems prove ineffective for spot cleaning processes. Furthermore, this type of machine is incompatible with typical roadside terrain.



Figure 2.3 - AgriMetal Company Tuff Vac

A type of litter cleaning machine, generally known as a riding litter vacuum, is designed to spot clean litter. It consists of a mobile vehicle with a self-contained vacuum and storage tank and a nozzle that an operator positions manually. Marketed by several companies and commonly used in city environments, this machine assists with cleaning sidewalks and parks. However, the small size of both the vehicle chassis and litter storage system prohibits effective use on roadways. Figure 2.4 shows the Elephant-Vac model EVC-4H, a hydraulic powered riding litter vacuum. The Elephant-Vac system looks very similar to the systems described by US patents 6389641, 5996174 and 5138742. Another similar system described in US patent 4535501 incorporates a battery-operated system.



Figure 2.4 - The Elephant-Vac EVC-4H

Encompassing a highly mobile end nozzle with a less mobile base station for the vacuum and tank serves as another design strategy for spot cleaning. This system includes a large-capacity trailer or truck mounted tank for litter storage that is filled by way of a long, manually controlled vacuum hose. The Madvac LX300 (www.madvac.com) unit displayed in Figure 2.5 represents an example of such a system. The highly mobile hose adds significant versatility to the operation, and the system contains a reasonably large storage tank that allows for less frequent emptying. The larger equipment can act as a barrier providing some protection to workers, but the manual effort required to manipulate the nozzle and hose remain significant. Necessary and frequent repositioning of the system requires repeated stowing of the hose.



Figure 2.5 - The Madvac LX300

Eleven of the systems described above rely on vacuum to provide a lifting force. This methodology is very practical for picking up litter and debris. In some designs, a brushing action supplements the vacuum action. Many companies sell sidewalk and street sweepers, which clean smooth and level pavement. These sweeper machines typically use some form of rotary brush, which scrubs the work area free of debris and collects litter. Some golf course grooming equipment also relies on a brush and preserves the desired turf.

Generally, the brush cleaning designs cannot be used to clean the area beyond the paved roadway. Most roadside surfaces, too uneven to use a brush, consist of dirt and vegetation. Litter also tends to land in places difficult to maneuver equipment using brushes. As an exception to this generalization, Caltrans experienced limited success using a machine known as the Barber Litter Picker, a trailer-based machine that rakes up litter and debris onto a conveyor that moves the material up into a bin. By careful adjustments of raking height, Caltrans used the Barber Litter Picker on roadsides with sparse low-lying vegetation.

Based on exploration of available equipment and capabilities, a practical, general-purpose roadside litter and debris collection system will rely on a vacuum system with a nozzle. The practical need to apply scaled up versions of the commonly available smaller vacuum machines drives the recent development of truck-mounted vacuums.

2.2 The Telerobotic Truck Mounted Vacuum Concept

Commercial vacuum trucks contain powerful vacuum systems, filtration systems and telescoping booms that position the vacuum line. The vacuum trucks are typically used to clean concentrations of debris that clog water drainage systems such as sewers and culverts. Often integrated with pressurized water systems for use in some cleaning operations, these vacuum systems by design usually operate while stationary. Two workers on the ground position the vacuum line through a combination of boom adjustments and manual placement of hoses and metal tubes.

The concept of using a modified commercially available vacuum truck to collect litter originated within Caltrans and resulted in the ARDVAC nozzle development at AHMCT. As

noted above, a machine with an integrated ARDVAC nozzle is simply referred to as an ARDVAC. Specific manufacturers designate such machines by the manufacturer's name followed by ARDVAC; e.g., Vacall ARDVAC designates the ARDVAC nozzle on a Vacall vacuum truck.



Figure 2.6 - ARDVAC (left) and Madvac LT500 (right) truck mounted telerobotic litter collector machines

Figure 2.6 shows the Vacall ARDVAC and the Madvac LT500 machines, and the following chapters of the report describe both types of machines in greater detail. These units represent the only known commercially available vacuum machines specifically designed to be operated from within the vehicle cab while moving. Uncommonly large for the industry and most practical for litter collection, each of these units is outfitted with a 12-inch vacuum hose. The typical vacuum truck comes equipped with an 8-inch diameter hose.

CHAPTER 3

MADVAC LT500 HISTORY AND DESCRIPTION

This chapter describes the Madvac LT500 system and its history in some detail. The information was collected from discussions with Madvac representatives and direct observation of a demonstration unit described below.

3.1 History of the Madvac LT500

The Madvac Company, which carries a line of small sweepers and riding vacuum machines, developed their truck-mounted vacuum in the early 2000s. In 2008, company representatives demonstrated this machine to Caltrans in Sacramento. At that time, this unit was marketed as the Johnston Allianz LT500. Highly interested in this equipment's design and capability, Caltrans planned to lease two of these machines for testing throughout California.

The LT500 was a relatively compact machine and could be driven with a basic Class C license, thus allowing for a large pool of potential operators in the Caltrans work force. This relatively compact machine was expected to be highly maneuverable and efficient to operate. As such, it could potentially be used for collecting litter in many locations that Caltrans maintains.

Unfortunately, California state budget restrictions triggered by the recession, which began in December 2007, forced Caltrans to delay its plan to lease the Madvac LT500 machines. During this time, the companies producing and marketing the LT500 reorganized and removed the machine from the market.

3.2 Description of the LT500

Figures 3.1 thru 3.5 show different views of the machine with enough detail to provide some useful design information. The photographs were taken at the 2008 demonstration to Caltrans.

Operated in the yard only, the machine demonstrated its litter and trash collecting ability with a single operator driving the truck and controlling the boom. A single joystick controls the following motions: boom up/down, boom left/right, boom extension/retraction and nozzle extension/retraction.

The nozzle itself hangs vertically and can extend and retract approximately 18 inches. This design feature allows the operator to reach easily into trash cans. The nozzle stows on a bracket in the front of the cab.



Figure 3.1 - LT500 Front view



Figure 3.2 - LT500 demonstrating trash pickup and dumping



Figure 3.3 - LT 500 Extended to side



Figure 3.4 - LT500 Nozzle stowed on forward hangar



Figure 3.5 - LT500 View of cab

Table 3.1 lists some of the key specifications related to size and power. These specifications for the LT500 represent approximations derived from various manufacturers' literature.

Table 3.1: Key Specifications of the Madvac LT500

Specification	LT500
Gross Vehicle Weight (GVW)	< 26,000 lb
Rated Airflow (cubic feet per minute)	6500 cfm
Fan Engine Power (horsepower)	87 hp
Hose Diameter	12 in
Hopper Size	5 yd ³
Lateral reach of nozzle from truck centerline (Estimated)	15 ft

CHAPTER 4

ARDVAC HISTORY AND DESCRIPTION

This chapter provides a description of the origins of the ARDVAC. Additionally, this chapter describes the ARDVAC's subsystems and capabilities.

4.1 History of the ARDVAC

Integrating a prototype telerobotic nozzle designed by AHMCT to a commercially available vacuum truck system created the ARDVAC. Originally associated with the nozzle design, the ARDVAC acronym now complements the designation of the complete truck based system. Operated from within the vacuum truck's cab, the telerobotic nozzle system allows for rapid and precise nozzle tip control. A Leach Company Vacall vacuum truck provided the requisite forward facing boom and 12-inch diameter vacuum line. The Leach Company's support for modifications needed to accommodate additional weight from the telerobotic nozzle and the higher airflow requirements of a litter collection system critically contributed to the development effort.

After AHMCT completed research development of the ARDVAC system consisting of the AHMCT designed vacuum nozzle integrated onto the Vacall vacuum truck, the Leach Company licensed the integrated vacuum nozzle technology for commercial development. Subsequently, the Clean Earth Environmental Group (Clean Earth Company) acquired the Leach Company's Vacall line of equipment and commercial development continued. The Clean Earth Company demonstrated their preproduction ARDVAC to Caltrans. Shown in Figure 4.1, the demonstration and testing of this machine led to an order for two commercialized Vacall ARDVAC trucks, simply referred to as ARDVACs hereafter. Prior to delivery of the two trucks, ownership of the Vacall line of equipment changed again, this time to the Alamo Group. The Alamo Group completed the construction of the first two ARDVACs at their GradAll facility in Ohio, and Caltrans started using them in 2008.

Since several transfers in ownership interrupted the commercial development, company engineers still considered the final design as a preproduction design. As such, these two machines that Caltrans owns represent the first and only two production units. The vendor had to make several in-service design changes to the units Caltrans purchased, which prevented the machines from operating successfully for several years. In the first year of use, Caltrans crews experienced repeated cases of jamming at the sliding joint of the nozzle due to debris being entrained in the sliding surfaces of the joint. After various unsuccessful attempts to seal the nozzle joint's sliding surfaces, the vendor eventually redesigned the nozzle to eliminate the failure. Section 4.2.3 of the report further describes the nozzle redesign. Additional failures included structural failures of some components. The equipment failures experienced are typical of new designs and have been resolved, but they slowed the implementation of the machines.



Figure 4.1 - Preproduction ARDVAC system by Clean Earth Company

The ARDVAC is designed to operate in median divider areas, roadway shoulders, around guardrails, and on some embankments adjacent to roadways. The ARDVAC's capability extends to removing light debris such as paper, cups, aluminum cans, fast food packaging and select denser trash such as glass bottles, sections of rubber tires, and surface soil or loose vegetation. An operator controls the articulating nozzle from within the vehicle's cab. The machine requires no on-site set-up and operates with controls of minimum complexity. The key element to the ARDVAC's effectiveness pertains to its vacuum hose positioning system, whose design defines the available litter removal work area and permits rapid and effective vacuum hose control.

4.2 Description of the ARDVAC

The ARDVAC consists of an articulated nozzle attached to the end of an overhead boom on the vacuum truck as shown in Figure 4.2, which depicts one of the Caltrans ARDVACs. The commercial version of the nozzle resembles a nearly identical replication of the original AHMCT nozzle design. The ARDVAC truck boom has three degrees of freedom and the nozzle has four degrees of freedom.

Figure 4.2 shows the locations of the links and joints of the telerobotic system (nozzle and boom) described herein. Links AA and AB connect the boom to the truck. Link B is the stationary section of the boom while link C represents the non-stationary or sliding section.

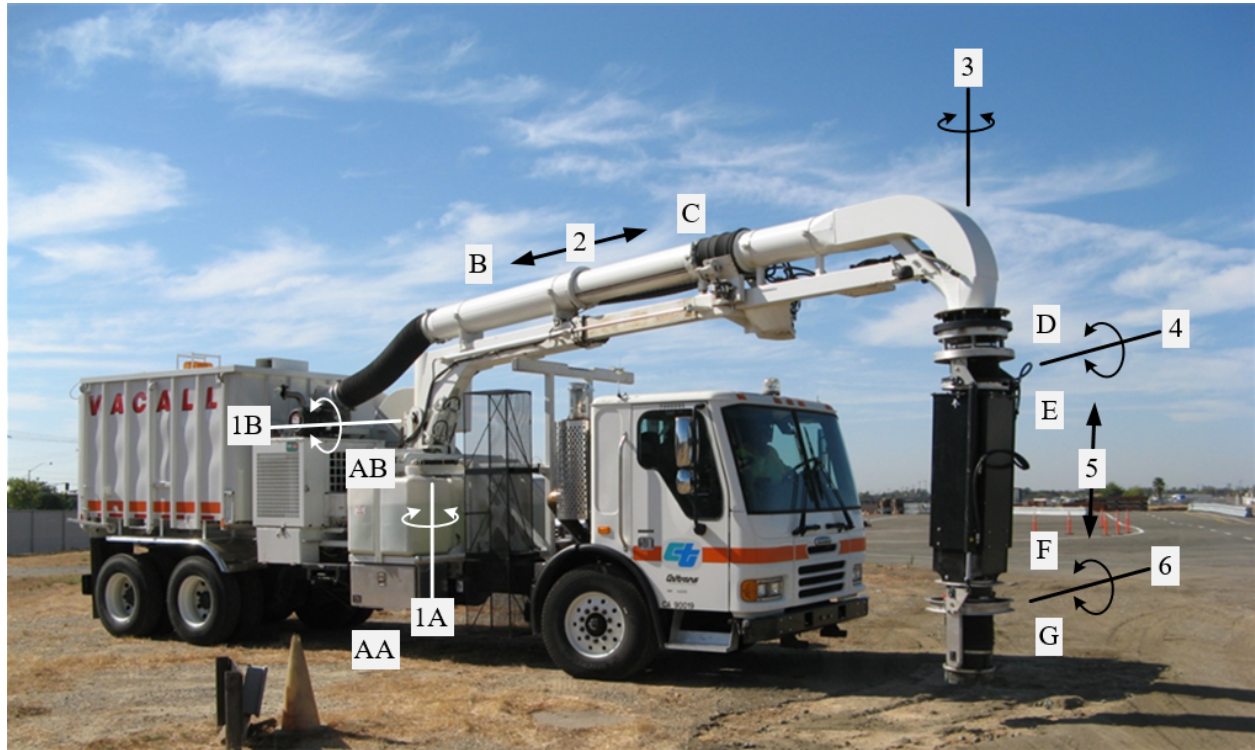


Figure 4.2 - The ARDVAC's links and joints.

The nozzle consists of three subsystems: the upper section, the middle section, and the lower section shown in Figure 4.3. Link D, a small cylindrical part, makes up the upper section while Link E, the base piece, and Link F, the fly or sliding piece, make up the middle section. Link G represents the nozzle end.

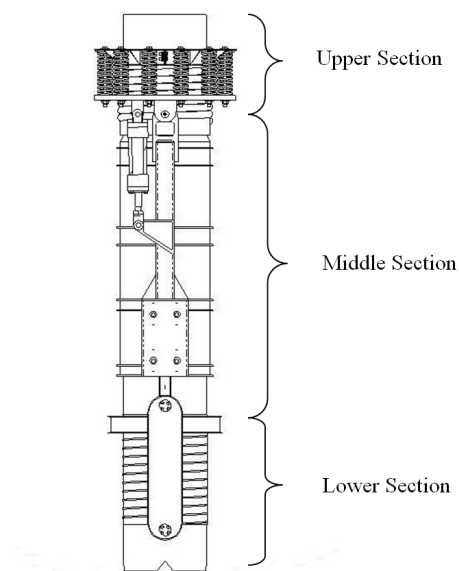


Figure 4.3 - Sections of the nozzle

Figure 4.4 shows a kinematic diagram of the ARDVAC mechanism. The joints consist of five rotational joints and two prismatic joints making the ARDVAC a 5R2P robotic manipulator. All the following joint motion descriptions occur about the axes displayed in Figure 4.2. Joint 1A rotates the boom left/right. Joint 1B rotates the boom up/down. Joint 2 extends the boom. Joint 3 rotates the end effector about its vertical axis. Joint 4 swings the nozzle and Joint 5 extends the end effector. Lastly, Joint 6 swings the nozzle tip.

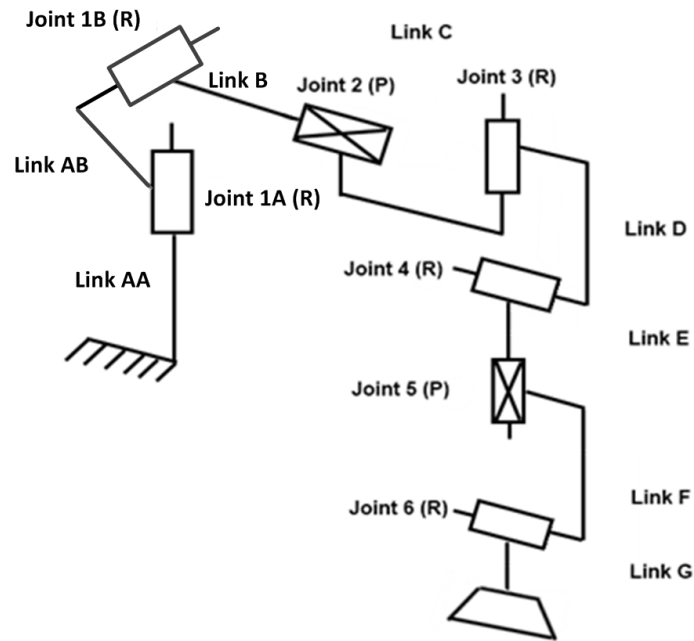


Figure 4.4 - Skeletal diagram of the ARDVAC manipulator

4.2.1 Boom

The boom is a telescopic arm attached to the Vacall vacuum truck behind the cab. It has three degrees of freedom provided by two rotational joints where the boom attaches to the truck, and one from a prismatic joint located in the middle of the boom. An original component of the Vacall machine, the boom supports vertical hanging rubber and metal tube sections that connect the nozzle to the debris storage tank.

4.2.2 ARDVAC Nozzle

The ARDVAC nozzle attaches to a lip at the end of the boom and comprises of three sections: upper section, middle section, and lower section as shown in Figure 4.3. The nozzle weighs about 500 lbs and has a total of four degrees of freedom. One degree of freedom comes from a rotational joint where the nozzle connects to the boom, one from the hinge or revolute

joint joining links C and D, one from the prismatic joint joining links D and E, and one from the second hinge joint that joins links E and F.

4.2.3 Description of Nozzle Design

The upper section connects the ARDVAC nozzle to the boom. Figure 4.5 displays a cross-sectional drawing of the original AHMCT design showing the key components found in the commercial nozzle. The upper section provides the rotation of Joint 3 and includes a spring assembly that provides a passive compliance between the upper and lower trays. This configuration allows the nozzle assembly to deflect when impacted to avoid overloading the boom. The lower tray connects to the base piece of the middle section by the sweep arm and cylinder supports shown in Figure 4.5. This connection allows the swinging action of the middle and lower sections about Joint 4. Flanges on the underside of the lower tray support the base of the middle section as well as the hydraulic cylinders.

The middle section is between Joint 4 and Joint 6 and includes the base and fly, which correspond to components of the prismatic Joint 5. Three actuation cylinders attach to the lower tray of the upper section to actuate Joints 4, 5 and 6. The short cylinder shown in Figure 4.3 permits the motion of Joint 4. Two long cylinders permit the extension of Joint 5 and rotation of the lower section about Joint 6.

The lower section, Link G, simply rotates about Joint 6 and includes a length of flexible tubing designed to allow compliance at the very tip of the nozzle.

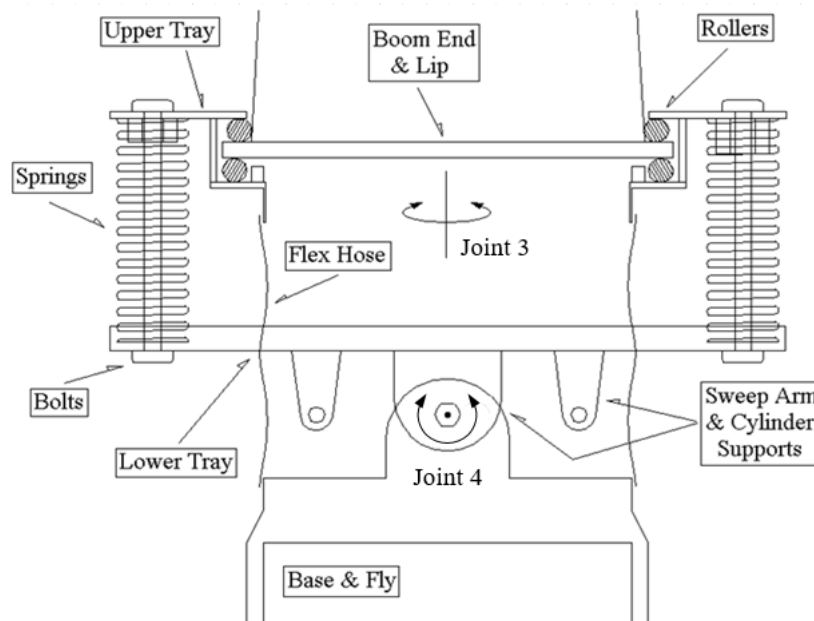


Figure 4.5 - Upper section of the ARDVAC nozzle as originally designed



Figure 4.6 - Rotation about the vertical axis, Joint 3

Figure 4.6 illustrates the rotation of the nozzle about the vertical axis whereas Figure 4.7 shows the articulation of the nozzle about the remaining axes. Located on opposite sides of the nozzle on the commercial ARDVAC, the long cylinders move in opposite directions and rotate the lower section (nozzle end) about Joint 6. By moving in tandem, the cylinders extend and retract the lower section (Joint 5).



Figure 4.7 - Articulation of ARDVAC nozzle Joints 4, 5 and 6

The sliding action between the upper and lower sections was originally designed as an inner and outer round tube with a sliding seal between the two. In the production units, debris accumulated in the seal that eventually locked the two sections thus preventing the sliding action. Vacall redesigned the nozzle by encasing a length of flexible rubber hose within the box section that contains the linear slide bearing. Figure 4.8 shows the design iterations.



Figure 4.8 - Joint 5, showing original (left) and final design (right)

Figure 4.9 shows the two-dimensional workspace of the ARDVAC, which is defined by the range of motion of Joint 1A and Joint 2 on the ARDVAC boom. The articulation of the nozzle adds another two feet of reach about the nozzle centerline.

The vertical motion results from the combined motion of the boom Joint 1B and Joint 5 of the nozzle. The original design of the nozzle permitted the nozzle tip to move from 1 foot below to 1 foot above grade with the boom static and in a neutral horizontal position. This 24-inch range of motion is reduced to 17 inches in the final design iteration.

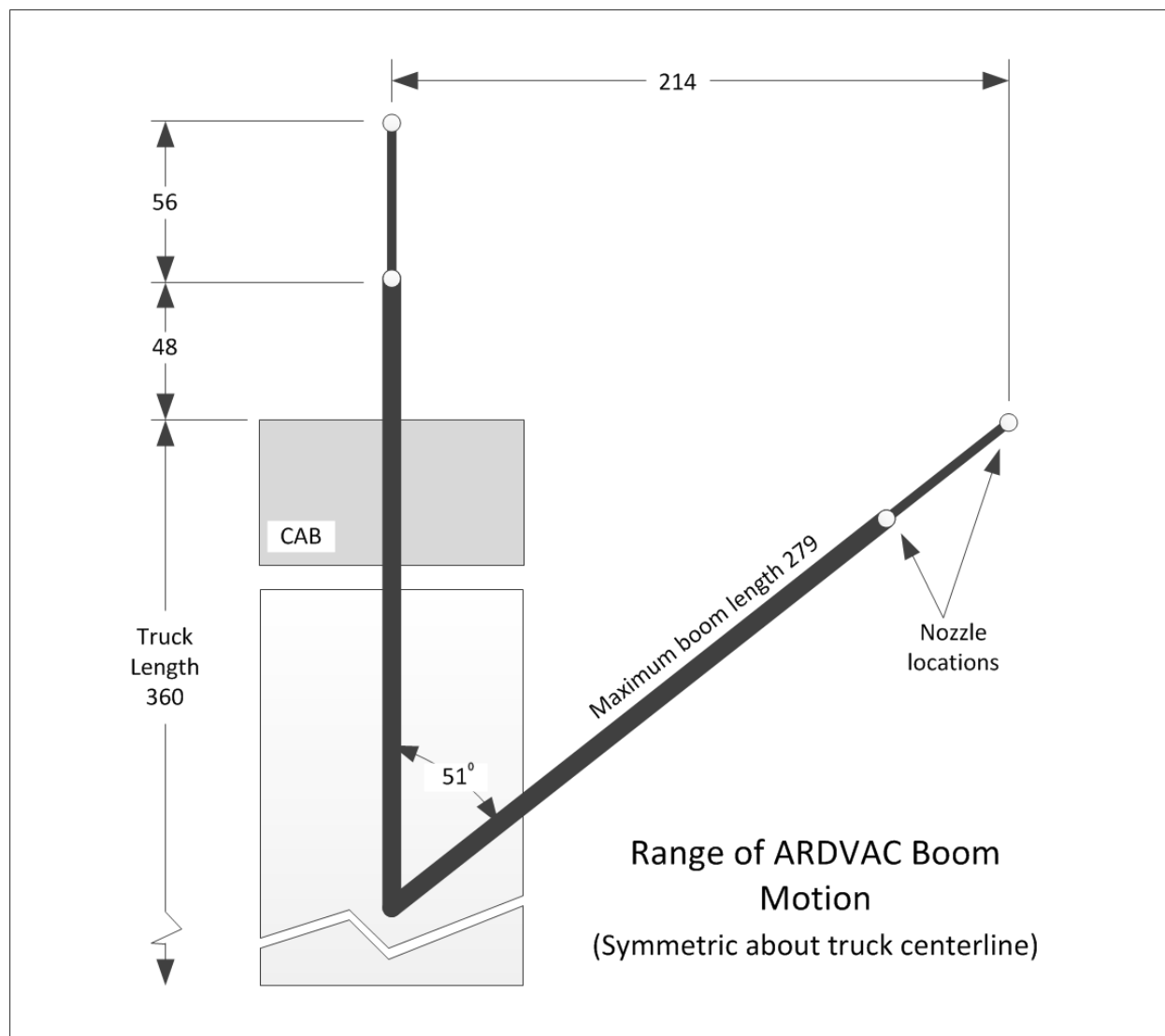


Figure 4.9 - Representation of the ARDVAC Workspace (inch)

4.3 ARDVAC Controls and Specifications

An electronically controlled hydraulic system actuates the ARDVAC nozzle. Figure 4.10 shows the control panel. The panel can be easily moved to either seat in the cab and can also be connected by cable to the outside of the truck at the front bumper. This allows the operator to control the system while standing next to the boom. Equipment operators control the functions of most commercial vacuum trucks while standing outside. Figure 4.11 shows the joystick control functions. The joystick-controlled functions provide speed control based on the proportional movement of the joystick. The functions actuated by buttons simply remain in an ON/OFF state.



Figure 4.10 - Layout of controls in cab

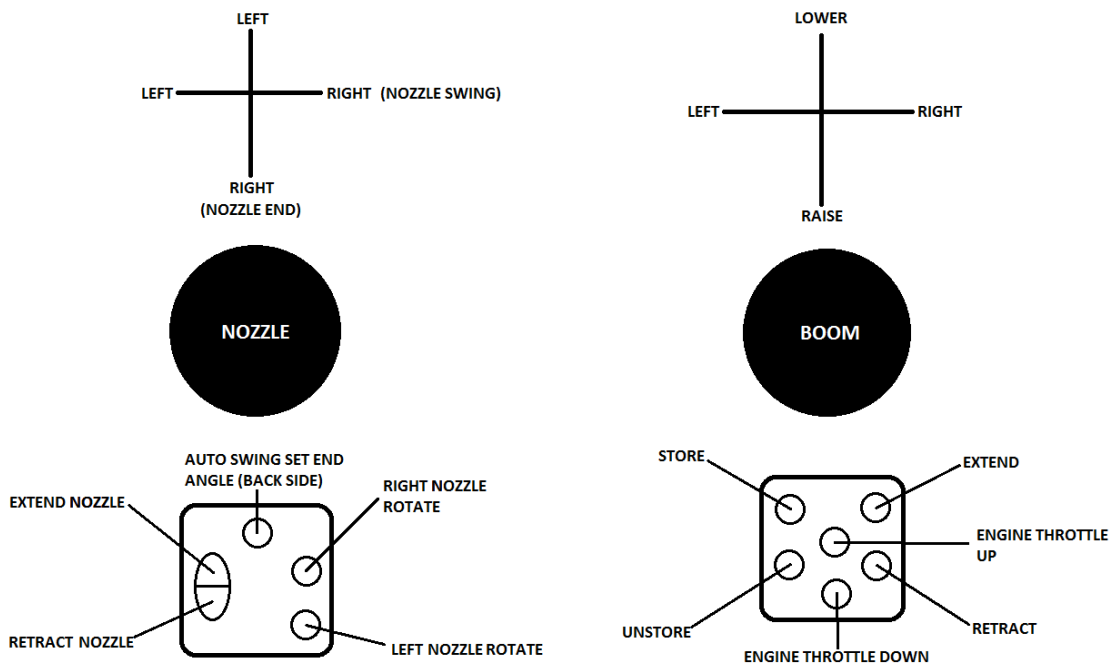


Figure 4.11 - Current control functions for the ARDVAC left and right joysticks

Table 4.1 lists some of the key specifications related to size and power of the ARDVAC.

Table 4.1: Key Specifications of the ARDVAC

Specification	ARDVAC
Gross Vehicle Weight (GVW)	60,000 lb
Rated Airflow (cubic ft per min)	16,000 cfm
Fan Engine Power (horsepower)	120 hp
Hose Diameter	12 in
Hopper Size	13 yd ³
Lateral reach of nozzle from truck centerline including 2 ft of nozzle articulation	19.8 ft

CHAPTER 5

OPERATIONAL EXPERIENCE

This chapter summarizes Caltrans' experience with the ARDVAC machines and includes recommendations for further improvements to the machines. The period of testing began in July 2010 and ended in June 2014.

5.1 Operator Experience and Feedback

Generally, Caltrans maintenance crews were very interested in the application of the ARDVAC concept during testing of the ARDVAC truck. They recognized that the ability to vacuum litter and debris with the articulated boom and nozzle could have applications in various maintenance operations. Crews noted the fact that equipment operators can run the ARDVAC's blower fan and hydraulic actuators while driving, which allows the ARDVAC machine to quickly move from one work location to the next without equipment setup or leaving the cab. The ability to perform mobile operations differentiates the ARDVAC from the typical vacuum truck that operates while stationary. The typical vacuum truck stays parked at the point of operation while two or more operators manipulate the nozzle by actuating the boom and manually maneuvering the nozzle tip into the material being collected. The consensus was that the ARDVAC would perform applications in maintenance operations throughout the year.

5.1.1 Challenges to Deployment

Using novel equipment like the ARDVAC involves a learning curve that applies to all levels of the organization from the operators on up. By nature, incorporating the equipment into operations remains an iterative process that requires a high level of effort and persistence. The operators require training and regular practice to become proficient on a novel piece of equipment. Deploying the ARDVAC into Caltrans' operations faced all of these challenges.

Frequent failures of various components hampered the positive experience with the ARDVAC. As the delays due to repairs and design changes became part of the cycle, some operators lost enthusiasm for the concept even though Caltrans provided the necessary support to keep the machines deployed. Given the resolution to major deficiencies, the ARDVAC machines should be more reliable than initially experienced during this evaluation.

5.1.2 Results and Discussion of Litter Collection Field Testing

Originally developed for litter collection, the ARDVAC experienced limited use in this operation. The task of litter collection is typically assigned to the general maintenance crews that operate smaller vehicles. Heavy equipment operators with special licenses and added training do not typically perform trash collection. Using the ARDVAC for litter collection required atypical work assignments since operating the machine requires a trained operator with a Class B or A license. Some larger maintenance yards rearranged assignments and tested the vehicle for short time periods. Figure 5.1 shows the system in action during one such use.



Figure 5.1 - ARDVAC positioned to collect litter on fence line

Figure 5.1 illustrates the challenge of working around roadside features such as power poles. In one case, a crew working in a similar scenario positioned one person on the ground to watch for potential impact with power poles and other infrastructure. During one of the first demonstrations, the ARDVAC collected trash from a ditch along the shoulder at a reported slow cleaning rate of 300 feet per hour. Additionally, people on foot supported the machine, which negates the potential to reduce traffic exposure.

Based on observations and discussion with Caltrans, the current ARDVAC design remains unlikely to be used to clean litter spread over wide and relatively safe areas for crews on foot. Currently, Caltrans has agreements to use low risk probation workers in these types of areas on a regular basis.

The ARDVACs still have the potential to be used in hazardous areas closer to traffic. Figure 5.2 shows one such example where trash accumulated under a guardrail in the median. Figure 5.3 shows an additional example of locations that could be best cleaned with the ARDVAC. The possibility exists of using the machine in a moving closure without requiring static lane closures. Nevertheless, Caltrans typically allows the trash to build up and then collects the trash within a lane closure. During such a situation, Caltrans maintenance workers typically repair guardrail, remove vegetation and perform multiple tasks to take advantage of the lane closure. In this scenario, litter collection becomes an incidental task.

Although the ARDVAC continues to have potential application for litter collection work, especially along busy congested corridors in metropolitan areas, the machine was not tested extensively.



Figure 5.2 - Trash accumulating under guardrail



Figure 5.3 - Examples of litter hotspots

5.1.3 Results and Discussion of Sand Collection Field Testing

The stormwater crew from the Northgate maintenance yard in Caltrans District 3 utilized one of the ARDVACs in their operations and provided much of the operational feedback presented in this report. One of the unique applications demonstrated was the removal of sand from the edge of the roadway along Highway 50. This sand remains a remnant of that used in the winter operations. Caltrans collects this material with sweepers at the end of each winter storm to limit its intrusion into the waterways. Some of the sand accumulates in the drainage at the edge of the road beyond the reach of sweeper brushes. In some of the locations, a sweeper can be driven off the road edge to engage the sand with the gutter brooms. As an alternative to this ineffective approach, the ARDVACs can be used to collect this otherwise unrecovered sand. Figure 5.4 shows the nozzle in action.

Another objective involves removing sand buildup around the entrance to the drain inlets. This practice reduces the amount of sand and debris entering the drainage system with the water during rain or snow events. The sand in this case hardened into a packed layer that is difficult to vacuum clean. The equipment operator rotates the nozzle around the vertical axis and drives the nozzle tip into the packed material in order to break it up. The articulation of the nozzle permits this digging action. Alternatively, a customized powered tool, similar to the gutter broom found on a sweeper, could be placed on the nozzle tip to break up the packed material.



Figure 5.4 - Using the nozzle rotation to break up sand

The machine can be used more effectively through its use for sand removal during the winter directly after a storm and before the sand hardens. The regimen of digging out the sand at the end of the season can be virtually eliminated by utilizing the capabilities of the ARDVAC to regularly maintain the drain inlets and collect sand that the street sweepers miss. Accordingly, the amount of material entering the drainage system will be greatly reduced.

5.1.4 Results and Discussion of Drain Inlet Cleaning Field Testing

The Northgate stormwater crew used the ARDVAC primarily for cleaning the area around drain inlets as shown in Figure 5.5. As noted, implementing this ARDVAC practice as a regular maintenance effort reduces the need to clear out the drain inlet itself. The lack of specialized tubing outfitted to the ARDVAC prohibited the stormwater crew from using the ARDVAC to reach into the drain inlet below the grate like a standard vacuum truck.

The crews often took the unit out before storms for last minute clearing around inlets to remove leaves and trash thus preventing potential flooding. In addition, the machine effectively unblocks drains during a rain event. The crew noted that the ARDVAC cleaned areas around drain inlets much more effectively than the usual practice of manual cleaning with rakes or even the typical vacuum truck nozzle. The ARDVAC's ability to deploy easily allows stormwater crew members to move quickly from drain to drain.

The stormwater team demonstrated the use of the ARDVAC during drain cleaning operations on the median of Interstate 5 south of Sacramento. The crew inspected the drain inlets and cleaned a few drain inlets with their standard vacuum truck. However, most of the work entailed removing the dirt that accumulated on the concrete apron around the inlet. Crew members softened the hard packed dirt with water and manually broke up the wet dirt with shovels.

Due to the higher airflow rate and larger opening, the ARDVAC removed the dirt more quickly and eliminated any manual effort from the operation once the dirt was broken up. The catch basin cleaner required the use of three people on the ground, one for the spray line (bean gun), a second to manipulate the snorkel, and a third person for general assistance. The crew suggested outfitting the ARDVAC nozzle with a spray line to break up material in some applications. By adding a spray line and specialized tubing, the ARDVAC could also be used for drain inlet cleaning, thereby eliminating the need for the standard vacuum truck.



Figure 5.5 - Comparing the ARDVAC to the standard vacuum truck

The operators reported that typically, two people operate the ARDVAC machine, one who drives the vehicle and monitors the dust suppression at the exhaust stack and one who controls the nozzle. In rare instances, a single operator drives the truck and maneuvers the joystick controls simultaneously. This practice depends on the complexity of the area being cleaned and the level of exposure to traffic. Figure 5.5 shows an example of a potential single crew member operation. In this particular case, the operation is stationary for several minutes at a time and located far from traffic. Crew members stated that in most cases, operating the ARDVAC safely and efficiently requires two operators.

To avoid expelling dust into the air, the standard vacuum truck requires a substantial amount of water sprayed at the dirt just before being drawn into the snorkel. The ARDVAC system sprays water in the airstream at the base of the elbow above the nozzle. In the experience of the crew, they normally can dispose of the ARDVAC collected debris at a dry dump site since the debris contains a minimum amount of water. However, other trucks must dump at special sites that allow for water retrieval.

Overall, the stormwater crew suggested that the ARDVAC efficiently complements the standard vacuum truck in typical drain cleaning operations.

5.2 Operator Statements and Recommendations from Field Testing

The following contains a list of recommendations collected from the operators. The remaining sections discuss some of the items in greater detail.

- Two operators are required for almost all operations.
- Operating the nozzle requires full concentration by one person.
- A second set of eyes is required to watch for obstacles such as telephone poles.
- Operators will exchange roles periodically during a shift to avoid fatigue.
- An operator requires several days on the machine to become proficient.
- Stowing the boom is very difficult.
- A better view of the boom and cradle will help in stowing. Suggest moon roof, mirrors or camera to help.
- Controls should be improved.
- The controls are very heavy when harnessed to a vest and working outside.
- Wireless controls would be useful when controlling on foot.
- Design the nozzle end to float on casters to avoid the need to continually adjust height.
- Nozzle should reach 2 ft. below grade.
- Nozzle attachments should be developed for different tasks.
- Operator should be able to turn off the airflow without spooling down the fan.
- Add a nozzle hanger on the front of the truck for stop and go work on the road.
- Plugging of the vacuum tube does not occur very often.
- Lids of 5-gallon buckets and small branches are items that cause plugging.

5.3 Controller

The large joystick control box sits at the center console and can be positioned to work from either seat. However, the ergonomics of the control box requires a twisted seating position, which after an extended period of time, can lead to discomfort for the operator (Figure 5.6).

Since the steering wheel constantly moves, the controls cannot rest against the steering wheel or be placed on the operator's lap. Caltrans considered the use of a removable steering wheel to mitigate this problem.



Figure 5.6 - Location of controls forces operator to rotate torso and head

The operators noted that the controls system lacks responsiveness and intuitiveness. Crew members suggested that the left-hand joystick control the gross movement of the boom, and the right-hand joystick control the fine movements of the nozzle tip. The suggested modifications oppose the present configuration of the joystick controls.

The original AHMCT design concept integrated the control functions into a single joystick controller with an additional rotational motion on the stick. Alternative controller design concepts have been investigated, but this single joystick concept remains the most practical. Crew members and researchers highly recommend implementing a design change to incorporate a single joystick configuration. Redesigning the controls to use one joystick for both the boom and nozzle functions allows the control box to be placed on an armrest or in other more ergonomic locations.

In addition, the operators stated that situations exist in which they need to control the ARDVAC remotely from outside the truck. The present system uses a cable connected to the front bumper, but the operators strongly prefer a wireless connection. Also, implementing a wireless controller potentially increases the flexibility and maneuverability of the controller inside the truck cab. Operator acceptance could be greatly improved by implementing the recommended design changes on the existing units and/or developing a new control interface mechanism.

5.4 Improvement to Nozzle

The following subsections contain several recommended changes to the nozzle design.

5.4.1 Working Envelope

The primary workspace limitation of the ARDVAC correlates to the vertical reach below grade (road level). By design, the nozzle was setup to reach 1 foot below grade with the boom in a horizontal position. The boom can be lowered below the horizontal if an operator rotates the boom to the side, permitting it to drop below the header beam shown in Figure 5.7. Figure 5.1 shows this configuration where the ARDVAC reaches to the side. The work area is often directly in front of the cab, and in this position, the latest nozzle design cannot drop more than six inches below grade. When working in this position, the boom will often drop into the cradle section of the header beam and then impact the corner when moving laterally. The operator is unable to see the gap between the header beam and boom. Adding a length to the nozzle tip yields the most reasonable solution given that other options require changes to major mechanical components. The extension would need to be removed before stowing. Crews recommended a reach of 2 ft. below grade.



Figure 5.7 - Corners on cradle that boom impacts when moving sideways

The flexible extension tested, as shown in Figure 5.8, works for some operations, but the lack of rigidity at the end makes accurate placement more difficult and any digging action impossible. Operators also suggest locking the compliant nozzle tip at the far end of the lower section to prevent any free rotation of the tip. The compliance of the short rubber tube as indicated in Figure 5.8 resists this point of tip rotation.

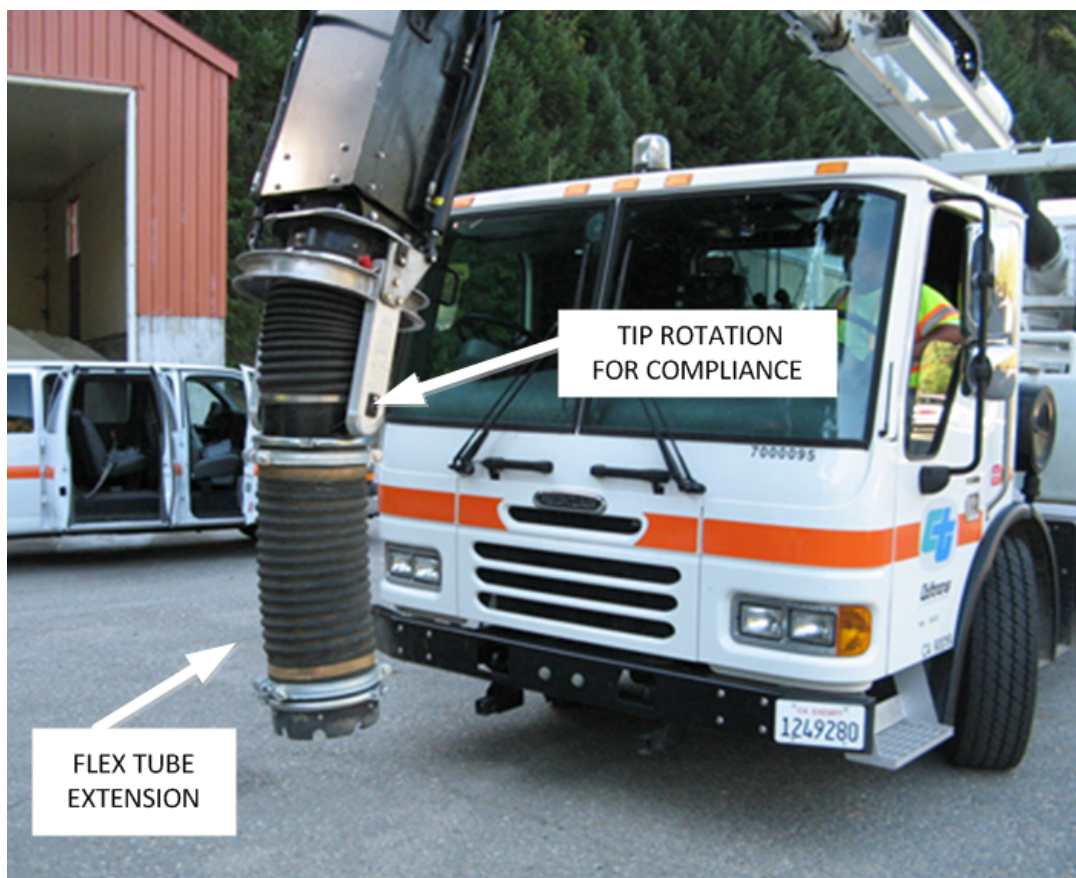


Figure 5.8 - Compliance of tip and extension

Different nozzle attachments could assist crew members in accomplishing a variety of work with the ARDVAC, but none were requested. The flexible extension tube is a standard accessory for this type of vacuum machine. Passive devices such as tines or bristles along with different extensions might serve as useful tools for different tasks in the future. During previous research, AHMCT developed some concepts for powered vegetation removal tooling for use with the ARDVAC [5].

The ability to push the nozzle tip against the road surface remains critical to expanding the usefulness of the machine. Accidental bumping or the actuator forcing the nozzle against the road or other structures occurs during regular use. The ARDVACs experienced some structural failures potentially due to overloading. The array of springs in the upper section mitigates some of the forces, but the operators need to avoid overloading the structure. Since some of the operations would potentially benefit by applying force at the tip, future designs need to consider structural changes.

The ability to apply a force at the tip without compromising the machine potentially adds value to a design. At a minimum, the systems need to be compliant enough to absorb some level of impact during normal operation.

5.4.2 Nozzle Stowage

The Clean Earth Company prototype described earlier stowed the nozzle at the front of the truck. The subsequent Caltrans purchase specification required stowing the nozzle behind the cab rather than on the front of the truck because it obstructed the driver's view to a much greater extent than the nozzle on the typical vacuum truck. The folding action seen in Figure 5.9 required major changes to the design and requires the use of a longer chassis. Initially, the operators experienced difficulty stowing the nozzle and felt the need to exit the truck cab to check on the progress of maneuvering the nozzle into the proper stowed position. However, the operators became proficient at stowing the nozzle after some practice.



Figure 5.9 - Retracting the nozzle behind the cab

5.4.3 Airflow

Generally, the ARDVAC distributes adequate airflow, but users of vacuums tend to prefer additional flow. Although rated at 16,500 cubic feet per minute (cfm), measuring the velocity at the entrance to the nozzle yielded a rate of about 9,500 cfm, which users generally accept as adequate. To reduce airflow restrictions requires routine cleaning of the filter screens in the bin. A system with less than 9,500 cfm of airflow in a 12-inch tube is likely to be inadequate for the collection of heavier material such as the debris collected with the ARDVAC.

The operators prefer the ability to shut the airflow off quickly to drop items sucked up against the nozzle opening. Airflow is controlled by changing the speed of the auxiliary engine driving the fan. Presently, they slow the fan speed down to idle to drop the item and then bring

the fan back up to operational speed. This process can take 30 seconds or more depending on the object's weight and shape.

5.4.4 Dust Suppression

As a standard configuration for the Vacall vacuum truck, injecting water into the airstream retains and confines dust within the bin. Crews experienced difficulty adjusting the flow rate with the ARDVACs' existing ball valve system and suggested replacing the ball valve system with a gate valve system. The 400-gallon tank provides an adequate water supply for up to four hours in most cases. Although the operators initially experienced frustration from running out of water too quickly, the experienced user learned how to optimize water usage. Typically, the driver turns the water on and off as needed depending on the surface type in the operation. The operators did not suggest an automated watering system.

5.5 Comparison of ARDVAC and Madvac LT500

The following comparison is made based on the experience with the ARDVAC and on the knowledge of the Madvac LT500. Both machines share the configurations of a 12-inch diameter hose and high flow fan required to pick up most litter. There are two key differences between the machines. First, the LT500 is a smaller, lighter duty system, and second, the ARDVAC nozzle is more articulated. The advantages of each machine are listed below.

ARDVAC Advantages

- **Articulated nozzle**
 - 3 additional degrees of freedom
 - Could reach under bushes or guardrails
 - The robotic end effector that could support tooling
 - Applies usable force at nozzle tip
- **Larger workspace**
 - Will reach 19.8 ft vs. 15 ft for the Madvac LT500
- **Heavy duty vacuum truck**
 - Can collect wet and abrasive material
 - Collects sand and cleans drains
- **Higher Power and Airflow**
 - 120 hp vs. 87 hp for the Madvac LT500

- Actual 9,500 cfm vs. claimed 6,500 cfm for the Madvac LT500
- **Larger Capacity**
 - 13 yd³ vs. 5 yd³ for the Madvac LT500

LT500 Advantages

- **Under 26,000 lb GVW**
 - Can be driven with a standard driver's license
 - More maneuverable
- **Lower cost (assumed since it is not commercially available)**
- **Single Joystick**
 - Simpler controls
- **Single Person Operation Likely**

Since the ARDVACs collected a minimal amount of litter during testing, determining the viability of the telerobotic litter collection requires additional testing. Expectations are that the Madvac LT500 and ARDVAC would have comparable performances in litter collection. Presently, crew members utilize the ARDVACs for stormwater maintenance operations. The LT500 is not suited for this operation.

CHAPTER 6 CONCLUSIONS AND FUTURE RESEARCH

Based on the evaluation and testing of the Vacall ARDVACs, telerobotic vacuum truck designs such as the Madvac LT500 and the ARDVAC remain viable options for general litter and debris cleaning. These telerobotic systems will allow rapid and precise control of a vacuum nozzle under operator control from within the truck's cab. Using the machines will enhance worker safety and may improve efficiency in many litter and debris collection operations. The machines provide particular value for spot cleaning along the medians and other difficult to reach areas. In addition, this equipment may offer value by functioning in conjunction with normal sweeping operations along freeways to reach material missed by the sweeper. Limited machine usage in litter collection resulted in an insufficient collection of test data to determine the actual or potential efficiency of telerobotic litter collection.

The 12-inch diameter hose system is considered a minimum size for general litter and debris collection on roadways. Although the ARDVAC's nozzle contains more articulation and dexterity than the LT500 nozzle, the LT500 may be adequate for a majority of litter collection. Unlike the ARDVAC, an operator with a regular driver's license can drive and maneuver the LT500 more easily. This smaller machine is potentially more cost effective and likely easier to integrate into Caltrans' litter control operations due to less restrictive operator requirements.

In addition, this research revealed these machines have value in stormwater maintenance by performing sand removal, catch basin cleaning, and drain inlet debris removal to alleviate clogging before and during storms. The heavier duty components and better articulation of the ARDVAC nozzle proved useful and beneficial for stormwater maintenance. The Madvac LT500 is not suited for this application due to its lighter duty construction and its inability to collect heavy debris or water. Sections 5.1.3 and 5.1.4 contain a full discussion of the stormwater maintenance value of the ARDVAC.

The Madvac LT500's unavailability for testing hampered the evaluation of the two telerobotic designs. Nevertheless, by deploying the ARDVAC machines, Caltrans obtained insight into the potential value of these types of vacuum trucks. The usage of the ARDVAC machines is expected to increase since most of the equipment design problems have been resolved. The last reported usage information suggests that Caltrans has been using the machines for stormwater related tasks more than litter collection tasks.

6.1 Conclusions Regarding ARDVAC Deployment

Caltrans committed significant resources in the effort to obtain and deploy the two ARDVAC machines. At this time, whether the ARDVAC will be marketed by Vacall in the future remains unknown. Caltrans' effort to deploy the machines created valuable information that may encourage continued commercialization, especially if they can be shown to be cost effective. Determining their value requires more regular usage.

Testing and developing new equipment like the ARDVAC involves a learning curve that applies to all levels of the organization from the operators on up. The operators require training and regular practice to become proficient at the machine's use. Until the operators gain

proficiency and comfort with the machine, its efficiency in any particular operation cannot be fully established. The Caltrans training process supported the ARDVACs, but the ARDVAC equipment failures impeded the process of developing operator proficiency. Ultimately, a conclusive evaluation of the ARDVAC equipment will require the additional commitment of time and resources.

One ARDVAC unit began to see much higher usage when assigned to the Northgate stormwater crew. These specialized crews use the large, standard vacuum trucks to clean sumps, drain inlets, culverts and similar features. They tend to have multiple operators familiar with the pumps, fans, and auxiliary engines found on vacuum trucks. The efforts of this crew critically contributed to the deployment effort. Based on the results of this research, we recommend assigning the ARDVAC to crews experienced with supporting specialized equipment.

Based on operational testing and operator feedback, redesign in a few key areas could create significant improvements and lead to more effective operation and better integration into maintenance activities. These areas include improvements to the telerobotic arm controls used by the operator, making the joystick control box wireless, and designing the nozzle to extend below grade.

6.2 Research Task Results

The research goals, as originally defined, intended to develop a detailed comparison of the Madvac LT500 and the Vacall ARDVAC. However, the LT500's unavailability and the ARDVAC's inoperability for extended periods of time prevented completing these goals as planned during the course of the project.

The following list states the tasks along with the associated conclusions and recommendations.

- a) *Observe and track use of the machines through a combination of direct observation and user feedback:* This evaluation relied primarily on the feedback from Caltrans personnel. Several field visits were arranged but limited to machine demonstrations in various applications within controlled environments. The information collected, both informative and mostly qualitative, formed the basis of this report and is contained in the previous chapters.
- b) *Track the machine using data loggers that record the location and status of the machine:* The data loggers record machine status to indicate the On/Off status of both the truck engine and the auxiliary engine. The auxiliary engine powers the vacuum fan and the ARDVAC system in general. The data logger units collected this data, along with global positioning system (GPS) coordinates, in two-minute increments during operation. Reviewing the data integrated into a map on the data logger vendor's web site helped define the general movement and status of the machine. The logged data is most useful to track machines performing well-defined operations. Table 6.1 summarizes the use of the ARDVACs during the period of the research project.

Table 6.1: Summary of ARDVAC use

SUMMARY OF ARDVAC USE: July 1, 2010 thru June 30, 2014								
Year (July1 start)	ARDVAC 7000095				ARDVAC 7000096			
	2010-11	2011-12	2012-13	2013-14	2010-11	2011-12	2012-13	2013-14
Number of Days Operated	22	7	26	14	5	11	3	20
Average Hours of Operation per Day	6.4				6.1			
Fraction of Time Vacuum Fan is Running	40%				45%			

The on-line map's insufficient resolution to see features such as drain inlets eliminated any possibility for the data logger to accurately determine the machine's exact usage. Additionally, irregular performances and unknown details of the operations prohibited the possibility of quantifying valid production rates solely using the data loggers.

For future evaluations, AHMCT recommends establishing a direct line of communication with maintenance crews using the evaluated machine in order to obtain more detailed information and arrange regular field visits. Logbooks may also have to be maintained by operators. Additionally, in this particular type of evaluation, the data logger's data should be supplemented with photographs and video for review.

- c) *Develop tests to compare the machines within the operations observed:* Due to the significantly different designs of the Madvac LT500 and the Vacall ARDVAC, AHMCT anticipated that the tests would provide value to the development of Caltrans specification of equipment and procedures. However, the unavailability of the LT500 machine prohibited the comparison between the Madvac LT500 and the Vacall ARDVAC, thus preventing the development of the tests.
- d) *Perform an engineering evaluation of the machines to understand the underlying operational principles of the machines.* The inaccessibility of the ARDVAC units committed to Caltrans operations and the unavailability of the LT500 unit limited this task to assessing general characteristics of the ARDVAC machine.
- e) *Develop tools and accessories to improve machine function and tailor the machines for optimal use in each function:* The anticipated need for accessories to improve operation did not materialize. The need to improve production rates will drive the future development of accessories, and the industry has developed various end attachments for vacuum machines. Once the machines see regular use in specific applications, the crews will define the needed accessories. AHMCT engineers developed control schemes that will improve the machine controls. Caltrans maintenance crew members and AHMCT engineers recommend that the ARDVAC nozzle and boom controller be redesigned to use a single joystick similar to the original AHMCT design concept.
- f) *Provide a performance evaluation to assess the value of the ARDVACs and Madvac for Caltrans litter and debris abatement:* The ARDVACs' lack of utilization in litter

abatement operations and the Madvac LT500's unavailability prohibited this task from being performed. The stormwater related tasks differed from litter collection and extended beyond the scope of the research project. Based on subjective feedback from the Northgate crew, the ARDVAC has value in their stormwater operations.

6.3 Future Research Recommendations

The following list points out the recommendations considered most important.

- a) *Document continuing ARDVAC usage to supplement the information in this report:* The commitment Caltrans made to the development of the telerobotic vacuum machine provides value to all DOTs and the equipment industry. Formally reviewing and documenting the experience with the ARDVAC units will prove to be important in future years. AHMCT recommends sharing this information with other DOTs and industry to support potential future development of this and similar telerobotic equipment.
- b) *Using the most experienced ARDVAC operators, test the ARDVACs in the litter collection operations along freeway medians and then roadsides in general:* AHMCT researchers recommend that Caltrans test the ARDVAC units specifically in litter collection applications. Given that the machines receive more frequent utilization, some operators will become more proficient in using this equipment. Although not necessarily their usual job function, another recommendation pertains to the most experienced operators participating in a series of tests and demonstrations of litter collection to determine the maximum rates at which this operation can be performed. At the time Caltrans purchased the ARDVACs, the machines' estimated travel speed of 2 miles per hour would potentially clean 10 miles per day along the median. Initial cost estimates result in significant savings if dedicated operators used the ARDVAC machines for this application. Whether these and other assumptions are correct remain unknown. Testing should then be expanded to demonstrate effective litter collection on the various surfaces found along roads. This would include sloped and uneven surfaces and areas covered with mulch and other treatments. Since Caltrans and others have calculated the costs of traditional litter collection operations, testing the ARDVAC production rate will greatly benefit Caltrans and other DOTs and may encourage the industry to offer valuable telerobotic litter collection equipment in the near future. Additionally, if the LT500 or a similar machine under 26,000 lb GVW became available, that equipment should be tested within Caltrans operations.
- c) *Collect information necessary to justify the ARDVAC value in stormwater maintenance and other Caltrans operations:* Determining and considering what major design changes should be implemented on any future version of this type of machine will be an important aspect of this review process. For example, the ARDVAC nozzle can be used as a robotic end effector to support tools such as vegetation cutters and other accessories. The stormwater maintenance crews have been using the machine regularly and have mentioned that the machines will be used to clear drain inlets before and during rain events. Cleaning inlets quickly before and during storms may be very valuable and may justify the cost of expensive machinery. To guide the future development of machines necessitates collecting detailed information regarding these tasks.

- d) *Support ARDVAC operators by documenting and implementing design changes recommended by experienced operators.* If the ARDVACs continue to be used and prove valuable to Caltrans' operations, implementing design changes will be important to improve the operator ergonomics. Recommendations from the operators who utilize the ARDVACs regularly should be carefully documented. Based on operator feedback, redesigning the controls will provide the best ergonomic improvement. Implementing improvements will encourage the continued use of the machines. This type of machine will likely be marketed again by industry in the near future, and ARDVAC deployment experience will allow Caltrans to define important design features in future specifications.

REFERENCES

1. California Department of Transportation, Headquarters Press Release dated April 25, 2013, <http://www.dot.ca.gov/hq/paffairs/news/pressrel/13pr033.htm>
2. Lopez, R.J., *Caltrans Worker Killed by Vehicle on San Diego Freeway*, Los Angeles Times June 20, 2011
3. Adami, C., *Another CALTRANS Worker Killed on the Job*, Imperial Valley Press, June 21, 2011
4. Porterfield, Andrew; White, Wilderich; Velinsky, Steven *Development of a Prototype Telerobotic System for Debris Vacuum Positioning (Final Report)* UCD-ARR-00-09-14-01, 2000
5. Harker, R.; McPhee, J.; Bieniek, R.; White, W.; Velinsky, S. *Development of Vegetation Cutting Tool Attachments for the Automated Roadway Debris Vacuum (Final Report)* UCD-ARR-05-12-31-02, 2005.