

Remote Operated Vehicle with CO₂ Blasting (ROVCO₂) Phase 1

Topical Report

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ABSTRACT

This report documents the first phase of the Remote Operated Vehicle with CO₂ Blasting (ROVCO₂) Program. The ROVCO₂ Program's goal is to develop and demonstrate a tool to improve the productivity of concrete floor decontamination. The first phase adapted and tested the critical subsystems: the CO₂ blasting, the workhead manipulation, the controls, and the base vehicle. The testing documented the performance of the subsystems and performed a concept demonstration of the integrated ROVCO₂ system. This testing and demonstration verified that the ROVCO₂ development exceeded its Phase 1 success criteria.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

1.0	INTRODUCTION	1
1.1	Purpose	1
1.2	Background	1
2.0	METHODOLOGY	2
2.1	System Engineering	2
2.1.1	System Requirements	2
2.1.2	System Trade Study	5
2.1.3	Functional Allocation	9
2.1.4	System Operation	10
2.2	Subsystem Development	12
2.2.1	CO ₂ Blasting Subsystem	12
2.2.2	COYOTEE	17
2.2.3	Vehicle Subsystem	23
2.2.4	Vacuum and Filtration Subsystem	28
2.2.5	Support Structure	30
2.2.6	Control Subsystem	34
3.0	SUBSYSTEM TESTING, RESULTS & CONCEPT DEMONSTRATION	37
3.1	Test Safety	37
3.2	Concept Demonstration	37
3.3	Blasting Tests	38
3.3.1	Nozzle Tests	38
3.3.2	Blasting Strip Rate Test	45
3.4	COYOTEE Tests	48
3.4.1	COYOTEE / Workhead Motion Test	49
3.4.2	Work Area Measurement	50
3.4.3	Sweep Rate Control	50
3.5	Vehicle Tests	52
3.5.1	Vehicle Positioning and Alignment Test	52
3.5.2	Vehicle Indexing Test	53
3.5.3	Vehicle Maneuvering Test	54
3.6	Operator Control Unit Tests	56
3.6.1	Programmable Interface Tests	56
3.6.2	Vehicle control Verification	61
3.6.3	OCU Display and Sensor Tests	62
3.7	Decontamination and Sealing	63
4.0	CONCLUSIONS AND DISCUSSION	65
4.1	Success Criteria Performance	66
4.2	Conclusions	68
5.0	BIBLIOGRAPHY	69

APPENDICES

Appendix A — PHASE 1 SUCCESS CRITERIA 70
Appendix B — SAFETY FOR THE ROVCO₂ SYSTEM 71
Appendix C — ROVCO₂ CONTROL SOFTWARE SPECIFICATION 73
Appendix D — LIST OF ACRONYMS AND INITIALISMS 77

LIST OF TABLES

ROVCO₂ System Requirements 4
Functional Allocations of System Requirements By Subsystem 9
Features and Benefits Table 17
Effectiveness Testing Tables 41
Concept Testing Results Summary Table 46
CO₂ Blasting Test Data Tables 47
COYOTEE Motion Test 49
COYOTEE Work Area Test 50
COYOTEE Sweep Rate Test 51
ROVCO₂ Positioning and Alignment Testing 53
Vehicle Indexing Test Results 54
ROVCO₂ Programmable Interface Results 56
ROVCO₂ Programmable Interface Integration 59
Vehicle Control Test Results 61
Display and Sensor Tests 62
Success Criteria Performance Table 66

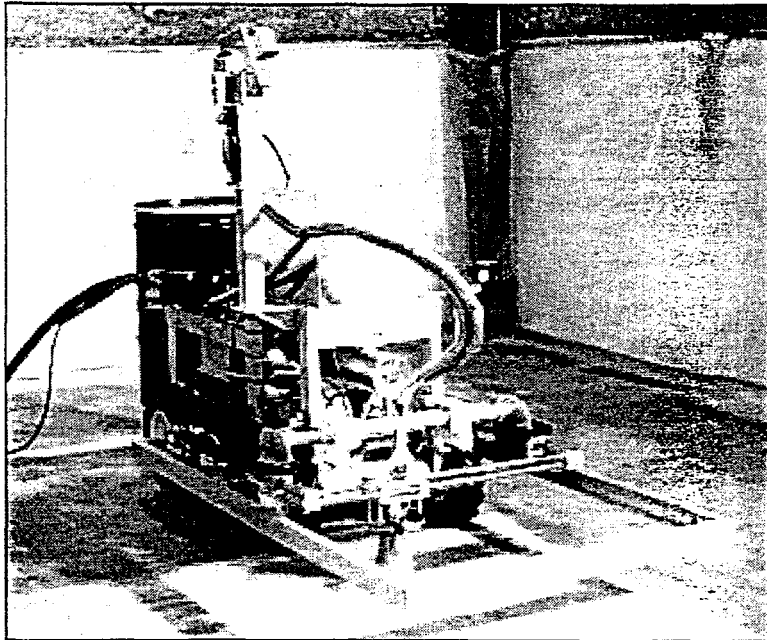
LIST OF FIGURES

Figure 1	The System Engineering Baseline Design	8
Figure 2	ROVCO ₂ Blasting Patterns as a Function of Operating Approach	11
Figure 3	Cryogenesis Supply Unit and Central Valves on the ROVCO ₂ System	12
Figure 4	Drice (Dry Ice) Pellets in a stored condition	14
Figure 5	Cryogenesis Subsystem Block Diagram	16
Figure 6	COYOTEE Assembly on ROVCO ₂	17
Figure 7	COYOTEE Assembly Drawing	18
Figure 8	Workhead with Nozzle in the COYOTEE Cursor	19
Figure 9	COYOTEE Subsystem Diagram	20
Figure 10	ROVCO ₂ Vehicle Modifications Block Diagram	22
Figure 11	Vehicle Subsystem	23
Figure 12	ANDROS 6x6 Vehicle	25
Figure 13	Subsystem Diagram	27
Figure 14	Vacuum Subsystem Diagram	28
Figure 15	The Material Recovery Drum	29
Figure 16	ROVCO ₂ Support Structure Elevation	30
Figure 17	ROVCO ₂ Support Structure Plan View	31
Figure 18	Operator Console	36
Figure 19	Operator Panel	36
Figure 20	COYOTEE Testing Setup	48
Figure 21	Vehicle Maneuvering Test	55

Executive Summary

Phase 1 of the Remote Operated Vehicle with CO₂ Blasting (ROVCO₂) Program to develop a tool for efficient decontamination of concrete floor has achieved its Success Criteria goals. Oceaneering Technologies (OTECH) has led its team in the design, production, integration, and concept demonstration of the critical subsystems of the ROVCO₂ system. The ROVCO₂ subsystems include:

- The "Cryogenesis" CO₂ blasting subsystem,
- The vehicle subsystem,
- The CO₂ xY Orthogonal Translation End Effector (COYOTEE) manipulation subsystem,
- The control subsystem,
- The vacuum and filtration subsystem, and
- The support structure.

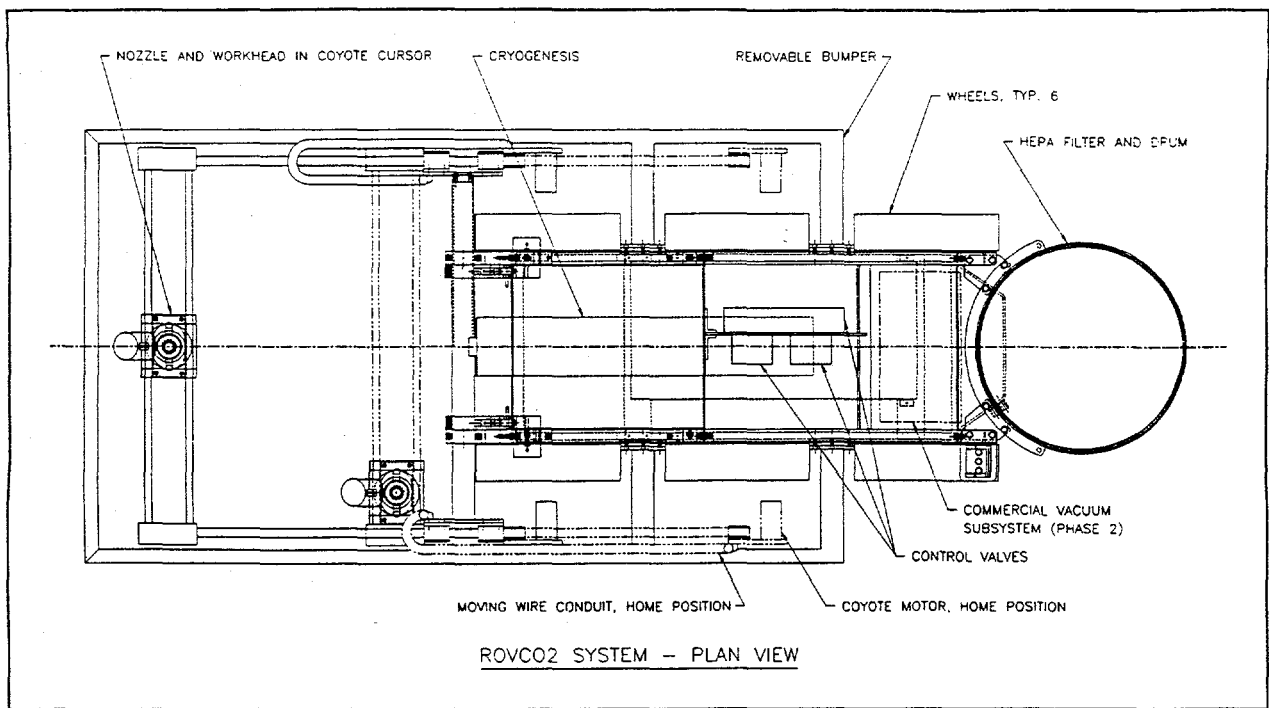


The ROVCO₂ System in Concept Demonstration

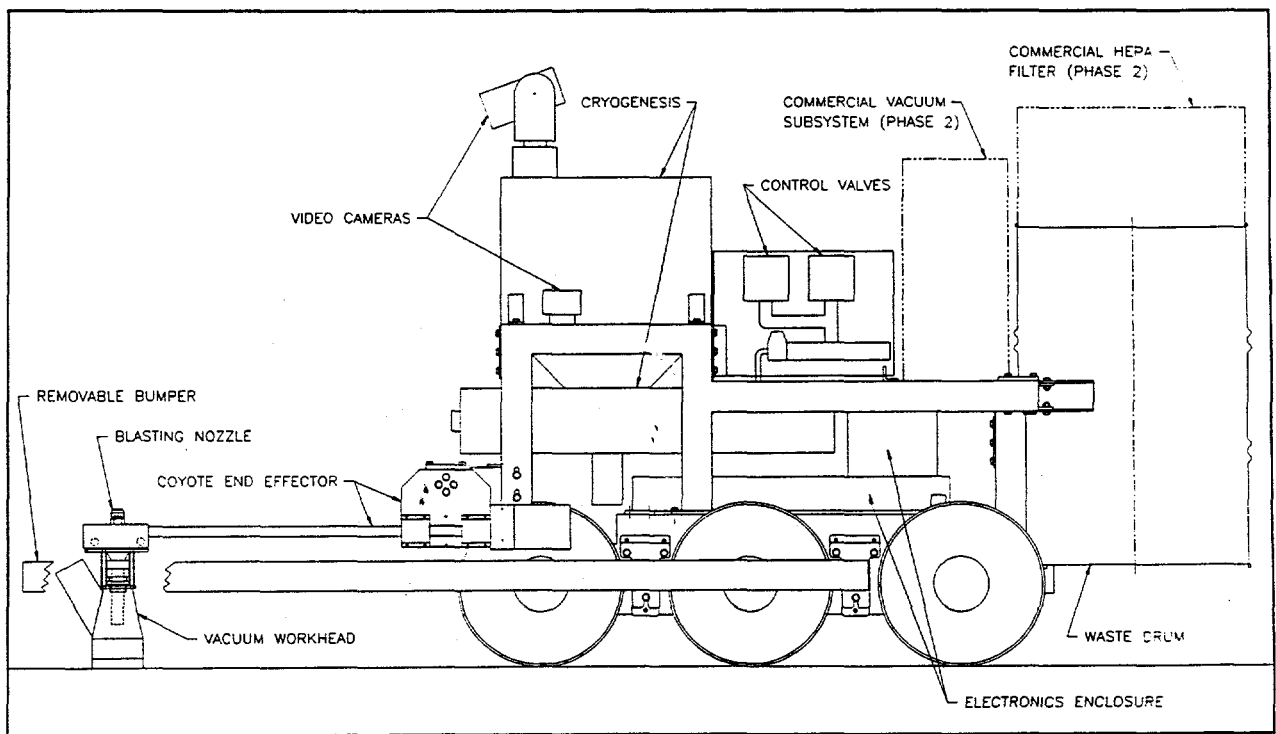
These subsystems have been adapted from other applications and integrated into a single system. The ROVCO₂ system now lacks only the commercial-off-the-shelf (COTS) components, to be added in Phase 2, to be ready for Integrated Demonstration.

The initial work of the ROVCO₂ program was to develop the system and subsystem requirements. The requirements were developed from the Success Criteria, input from personnel at the Oak Ridge K-25 site, and the team's experience. From these requirements, a baseline design integrating all the subsystems for effective operation was developed.

Much of the engineering work focused on the adaption of the ROVCO₂ subsystems to integrate smoothly into ROVCO₂ operation (see elevation below). The Cryogenesis CO₂ blasting system, for example, was adapted from a manually operated, pneumatically controlled system into a computer controlled remote system. The advantage of having computer control of the blasting operation is that dry ice pellets are conserved by automatically stopping the pellet flow when the workhead is stopped. By control coordination, efficiency in both the workhead movement and pellet consumption is achieved. The vehicle design resulting from the engineering effort is depicted in the plan and elevation views shown on the next page. The design accommodates the blasting and containment systems on the vehicle for greater operating range.

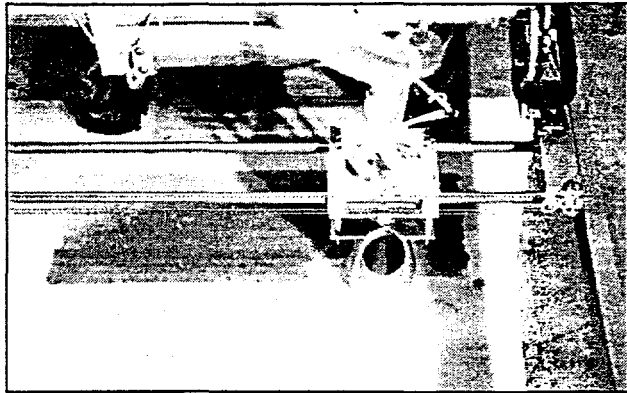


The ROVCO₂ System Design, Plan View



The ROVCO₂ System Design, Elevation View

The subsystem testing verified that each subsystem met the design requirements and exceeded the success criteria. The test included COYOTEE speeds of up to 7.5 inches per second (ips) and blasting rates of up to 115 square feet per hour. The testing culminated with the Concept Demonstration of the ROVCO₂ System removing coatings from concrete floors (see Figures). The integrated operation of the system validated the success of the Phase 1 development work.



ROVCO₂ Blasting during Concept Demonstration

1.0 INTRODUCTION

This is the Topical Report on Phase 1 of the Remotely Operated Vehicle with CO₂ Blasting (ROVCO₂) System development program. The report describes the accomplishments of Phase 1 and is organized per DOE's specification in the contract.

1.1 Purpose

The ROVCO₂ program was proposed in response to the Department of Energy's (DOE) requirement for concrete floor decontamination at the Oak Ridge K-25 site and other sites. The proposed ROVCO₂ system minimizes waste generation and maximizes worker productivity and safety by functional automation of tedious, precise tasks.

Goals of the ROVCO₂ program for concrete floor decontamination are:

- Reduced decontamination costs,
- Reduction in waste volume,
- Reduction in worker exposure to contaminants,
- Improved decontamination effectiveness, and
- Faster decontamination of floors.

The development has been contracted in three phases.

- PHASE 1) Development and Integration of Critical Subsystems including: CO₂ Blasting, Vehicle, Manipulation, and Controls.
- PHASE 2) Integration of Off-The-Shelf Subsystems (Vacuum and Filtration) and System Testing of Productivity, Reliability, and Effectiveness.
- PHASE 3) Integrated Demonstration at a DOE Hot Site (Building K-29 at the Oak Ridge K-25 site).

The culmination of the Phase 1 effort was a successful concept demonstration of the ROVCO₂ system.

1.2 Background

- C The ROVCO₂ proposal was submitted in response to a solicitation from DOE's Morgantown Energy Technology Center (METC). The final customers for the ROVCO₂ System are the Decontamination and Decommissioning (D&D) site personnel.

The development of ROVCO₂ required expertise and experience in remote operations and CO₂ blasting. OTECH has over 20 years of experience developing and operating remotely operated systems. To provide the CO₂ blasting portion of ROVCO₂, OTECH selected Waste Minimization & Containment (WMC) as our teammate. WMC invented and manufactures the patented Cryogenesis CO₂ Blasting System.

2.0 METHODOLOGY

Phase 1 of the ROVCO₂ program followed a conventional development path including:

1. System Engineering:
 - Development of system requirements,
 - Functional allocation of requirements to subsystems, and
 - Interface definitions.
2. Development:
 - Engineering analysis,
 - Fabrication drawings, and
 - Procurement specifications.
3. Testing and Concept Demonstration.
4. Data Analysis.

This section covers steps 1 and 2. Steps 3 and 4 are covered in Section 3. The description of the development is organized by subsystem.

2.1 System Engineering

System engineering is the input filtering process that ensures the requirements used for the engineering and design are serviceable and constructive. On ROVCO₂, system engineering work defined the System Requirements, distributed the requirements to the subsystems by Functional Allocation, and ensured smooth system integration by interface definition. The results of each of these areas of work are described below.

2.1.1 System Requirements

The development of System Requirements for the ROVCO₂ system was based on three sources:

- The Success Criteria included in the contract;
- Observations at the Oak Ridge K-25 site and recommendations from DOE personnel at METC, Oak Ridge, and other DOE sites; and
- The development team's experience on remote operations and manual CO₂ blasting.

2.1.1.1 Success Criteria

The Success Criteria from the contract are attached in Appendix A. These criteria are the guidelines for evaluation of the work, indicating the agreed upon direction of the research and development.

The Success Criteria were initially developed during the proposal effort by the ROVCO₂ development team. They are based on OTECH's 20+ years of experience in remote operations and WMC's experience with manual CO₂ blasting decontamination operations. During contract negotiations, these criteria were refined to meet DOE's requirements.

Two Success Criteria were modified during Phase 1 to accommodate equipment limitations. Both were driven by the limitation that a wide rectangular nozzle would have lower velocities than a round nozzle. To meet the primary goal of higher productivity, Success Criteria 1.5.1, CO₂ Blasting, was changed to modify the width criteria, and 1.2.3, Manipulation, was adjusted to require higher speeds.

The Success Criteria are divided by phase, but, since the Phase 1 hardware will be used in all three phases, all the Success Criteria were used in developing the System Requirements. The Success Criteria, which are mostly performance based, were reduced to hardware requirements in the system engineering process.

System Requirements drawn from Success Criteria are primarily based on productivity. The criteria to decontaminate 30-75 sqft/hr (in Phase 2) drive requirements on nearly all systems including work-head speed, waste weight, and blasting rates.

2.1.1.2 DOE Input

The input from DOE included:

- The requirements on maneuverability and obstacles, clearances, and excess floor debris were drawn from OTECH's inspection of the buildings to be decontaminated at Oak Ridge.
- OTECH met with D&D personnel at Oak Ridge who provided recommendations on operation of the system. These recommendations led to requirements for waste handling and the concept of operation.
- Comments from reviewers at METC, Oak Ridge, and INEL on the Design Review presentation provided requirements for applications for ROVCO₂ at sites with higher radiation levels than K-25 and standardization and compatibility with other DOE development work.

The DOE input continued to be received after the system engineering work had been completed. Whenever possible, this additional input was included in the Phase 1 design, otherwise, it was noted for consideration as part of Phase 2 modifications.

2.1.1.3 Development Team Experience

System Engineering also drew on the experience of the team members. OTECH's experience in remote operations was drawn upon in defining the requirements for remote functionality and the operator interface. WMC's experience in CO₂ blasting was used in defining the blasting and COYOTEE requirements.

2.1.1.4 System Requirements

The table of System Requirements is organized by functions.

ROVCO ₂ SYSTEM REQUIREMENTS	
<ul style="list-style-type: none"> ● Productivity (from Phase 2 Success Criteria): <ul style="list-style-type: none"> ● Strip coatings at > 30 sqft/hr, Goal ≥ 75 sqft/hr 	
<ul style="list-style-type: none"> ● Mobility: <ul style="list-style-type: none"> ● Speed: ≥ 1.25 fpm (0.02 fps) average ● Directional Precision: ≤ 1° ● Longitudinal Precision / Stopping Distance ≤ 1" ● Obstacle crossing: <ul style="list-style-type: none"> Holes ≤ 6" trench Bumps ≤ 2"x 4" Climb ≤ 4" curbs 	
<ul style="list-style-type: none"> ● Dimensions: <ul style="list-style-type: none"> ● Pass through w/ COYOTEE: 6'-8" x 6' (double doorway) ● Pass through w/o COYOTEE: 6'-8" x 3' 	
<ul style="list-style-type: none"> ● Manipulation: <ul style="list-style-type: none"> ● Work-head speeds: 0.6 - 3.45 ips ● Work-head Precision: << 1" ● Work Area: ≥ 30" x 24" ● Automated sweep: ~ 0.25" smaller better ● Overlap: > 0" smaller better 	
<ul style="list-style-type: none"> ● Operator Control Unit: <ul style="list-style-type: none"> ● Single operator, integrated controls ● Automated repetitive functions ● Video Display ● Equipment status feedback ● Hand Portable 	
<ul style="list-style-type: none"> ● Sensing: <ul style="list-style-type: none"> ● Obstacle sensing: Cameras ● Linear vehicle motion measurement (to adjacent work areas) ● Blasting function monitor(s) ● Vehicle vital signs 	

ROVCO₂ SYSTEM REQUIREMENTS

- CO₂ Blasting [WMC]:
Adaptation for ROV
 - Interface with the ROV without inhibiting mobility.
 - Controllable from Operator's Control Unit (OCU): i.e., gun trigger; adjustments stay on supply unit.Nozzle Enhancement
 - Improved speed of cleaning, stripping paint at over 1.8 sqin/sec; improve Decontamination Factor over existing nozzle.Vacuum Work-head Enhancement
 - Effective containment of blasted material: $\geq 99\%$ of material contained.
 - Minimize recontamination from work-head surface contact.Cryogenesis Enhancements
 - Accommodate higher pressures and flows of 200 to 275 scfm of gas over 2.5 lb/min CO₂.
- Decontaminability and Sealing:
 - System to be mostly cleanable by CO₂ blasting.
 - System to be sealed against contaminants penetrating to internal compartments.
- Umbilical Management System:
 - Assist vehicle motions by paying out or pulling in the umbilical.
 - Able to recover vehicle in contingency situations.
- Reliability:
 - Mean Time Between Failure (MTBF) > 100 hr
 - Mean Time to Repair (MTTR) < 20 hr, Goal < 10 hr

2.1.2 System Trade Study

The system level trade studies established and refined the baseline design to meet all the System Requirements within the capabilities of each subsystem. Some iteration was required in the form of re-defining the baseline design when requirements allocated to a subsystem proved too difficult or costly to meet. The trade studies performed were:

- Location of Vacuum & Filtration Subsystem
 - Alternatives:
 - Near the operator console, or
 - On the vehicle.

-
- Criteria:
 - Umbilical diameter: Placing the vacuum and filtration subsystem on the vehicle reduces the umbilical diameter from nearly 5" to less than 2.5". The larger diameter umbilical is stiffer and heavier, thus decreasing system mobility.
 - Operation: Oak Ridge D&D personnel indicated that the ROVCO₂ system would be operated with the vacuum and HEPA filter in the Radiological Control Area (RCA) regardless of subsystem placement.
 - Weight on vehicle: Vacuum, filter, receptacle, and waste = 480 lbs. This limits the number of vehicles that can be used.
 - Vacuum hose clogging: The long, bending, horizontal hose which runs back to a vacuum system near the operator console would clog with debris.

 - Selection:
 - Carry the Vacuum and Filtration Subsystem on the Vehicle.

 - Rationale:
 - When suitable vehicles were found that could carry the subsystem, the advantages of a smaller umbilical and short vacuum hose drove the on-vehicle choice.

 - Location of Cryogenesis Pellet Supply Unit
 - Alternatives:
 - Near the operator console, or
 - On the vehicle.

 - Criteria:
 - Weight on vehicle: 300 lbs. This limits the number of commercial vehicles that can be used.
 - Dry ice (Drice) pellet hose clogging: If supply unit is near the operator console, clogging is a problem. Testing proved that even with smooth silicon, hose length must be < 120', limiting system mobility. A system to de-clog the hose, involving backing the air pressure into the drice hose, would be required, adding complexity and cost.
 - Umbilical Management System: With multiple hoses in the umbilical, a linear type umbilical management system would be required, increasing cost and prohibiting carrying the umbilical with the vehicle.
 - Drice re-supply: If Cryogenesis unit is mounted on the vehicle, the system must be brought to a Drice supply cooler periodically for refilling. If the unit is near the operator's console, it can be re-supplied without interrupting blasting.
 - Cryogenesis control: The Cryogenesis at the operator's console can use the existing pneumatic control. On the vehicle, an electrical control system would have to be developed.
-

-
- Selection:
 - Carry the Cryogenesis drive supply unit on the vehicle if a commercial vehicle with sufficient payload for both Cryogenesis and the vacuum filter systems can be procured.

 - Rationale:
 - It is clear that if the vehicle can carry the additional payload, placing the Cryogenesis unit on the vehicle will alleviate umbilical size and hose clogging.

 - Along Vehicle Work-head Motion (This trade study was carried out as part of the COYOTEE Internal Research And Development (IRAD) work.)
 - Alternatives:
 - Increment vehicle forward to achieve Y motion,
 - Use a two-axis end effector, or
 - Use a manipulator to hold the end effector.

 - Criteria:
 - Design complexity: Using the vehicle motion would simplify end effector design. Applying the same end effector to walls (as is planned for COYOTEE), the motion could be achieved using a fully resolved manipulator.
 - Accuracy and Resolution: A survey of commercial vehicle platforms indicated difficulty effecting very short moves (~1") with any accuracy. The limitations are driven by static friction, drive motor resolution, and control signal timing.
 - Reliability: Argues for vehicle incrementing forward and against a resulting manipulator.

 - Selection:
 - A two-axis end effector was selected to reduce requirements on vehicles or manipulators.

 - Rationale:
 - The vehicle movement was not available in the desired payload. The Z-axis end effector eliminated the need of a manipulator for decontaminating floors.

The resulting baseline design is shown in Figure 1.

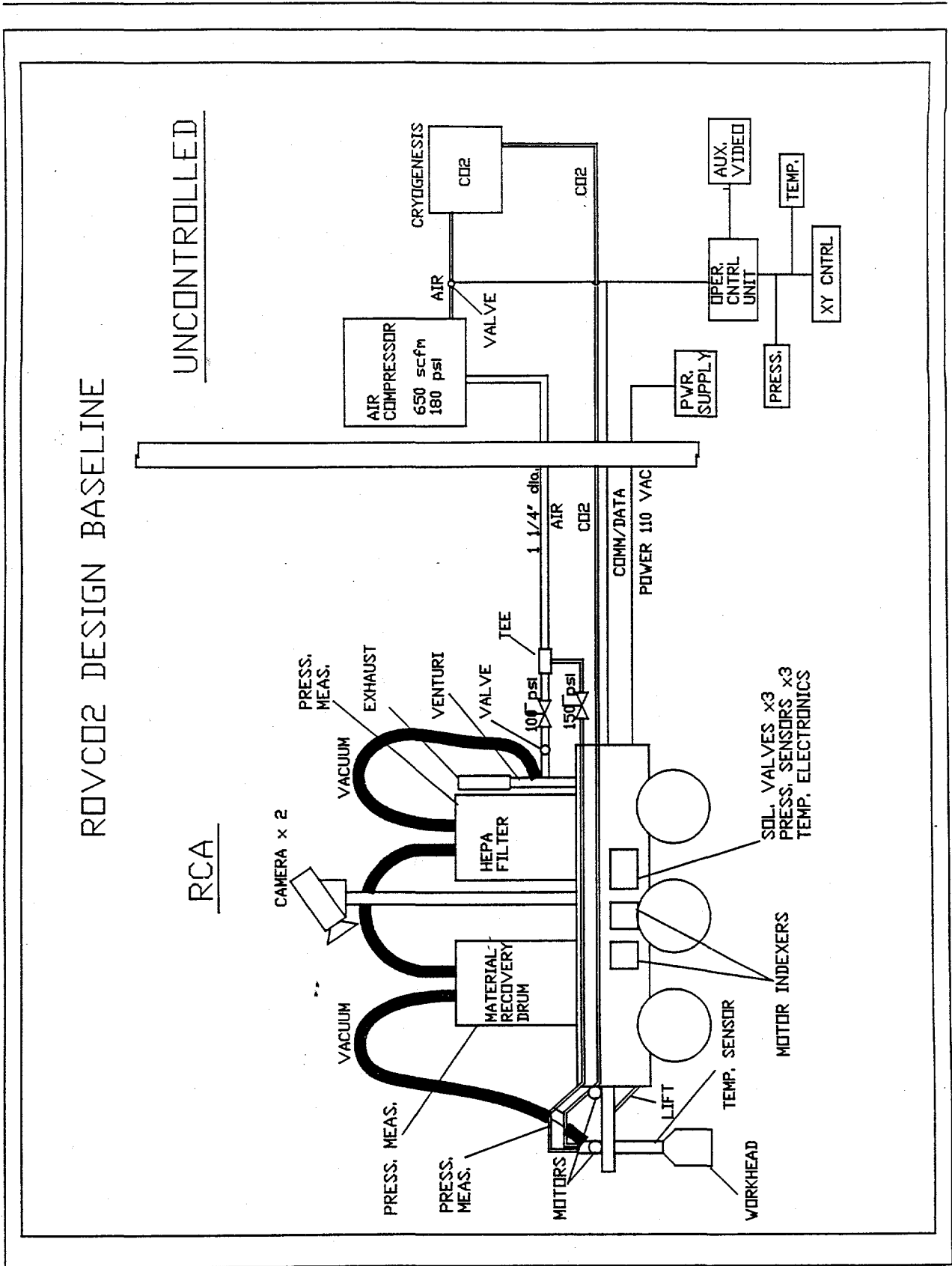


Figure 1 The System Engineering Baseline Design

2.1.3 Functional Allocation

In this task, the system requirements are allocated to the subsystems and components in the baseline design for application by the design engineers. In many cases, a system requirement must be distributed among subsystems and translated into relevant design parameters. For example:

- System Requirement:
 - Strip coatings at > 30 sqft/hr, Goal ≥ 75 sqft/hr.
- Allocated Functions:
 - COYOTEE: Work-head speed - 0.6 - 3.45 ips, and
 - Blasting: Stripping at - > 1.8 sqin/sec.

The allocated functional requirements were also used to specify procured equipment including the vehicle, vacuum, and filter.

The following table is the result of the Functional Allocation.

FUNCTIONAL ALLOCATIONS OF SYSTEM REQUIREMENTS BY SUBSYSTEM	
<u>Wheeled/Track Vehicle:</u>	
● Speed:	≥ 1.25 fpm (0.02 fps) average
● Directional Precision:	$\leq 1^\circ$ smaller better
● Longitudinal Precision:	≤ 3 " smaller better
● Obstacle crossing (perpendicular):	Holes ≤ 6 " trench Bumps ≤ 2 "x 4" Climb ≤ 4 " curbs
● Obstacle Sensing and Avoidance:	Video Cameras
● Dimensions:	Fit through openings 6'-8" x 3' w/o COYOTEE
<u>COYOTEE End Effector:</u>	
● Work-head speeds:	0.6 - ≥ 3.45 ips
● Work-head Precision:	$<< 1$ " smaller better
● Automated sweep:	~ 0.25 " smaller better
● Overlap:	> 0 " smaller better
● Area:	≥ 30 " x 24"
● Dimensions:	Fit through 6'- 8" x 6' openings

FUNCTIONAL ALLOCATIONS OF SYSTEM REQUIREMENTS BY SUBSYSTEM

Cryogenesis CO₂ Blasting System (WMC):

- Cryogenesis Drive Supply Unit:
 - Interface with the ROV without inhibiting mobility.
 - Controllable from Operator Control Unit (OCU): i.e., vacuum, blasting, air, and pellet feed.
- Nozzle:
 - Improved cleaning, stripping paint at > 1.8 sqin/sec.
 - Pressures and flows > 120 psi, 200 cfm, and 2.5 lb/min.
- Vacuum Work-head Enhancement:
 - Effective containment of blasted material: > 99% of material contained (vacuum flow of twice the blasting flow).
 - Minimize recontamination from work-head surface contact.

Controls Subsystem:

- Provide full standard operation with a single operator.
- Automate repetitive tasks.
- Support future development of the ROVCO₂ system with spare capacity.

2.1.4 System Operation

The objective of the ROVCO₂ system design was efficient operation in the vast open spaces of the Oak Ridge K-25 site processing buildings. From OTECH's experience with design and operation of remotely operated work systems, we have concluded that efficient, reliable equipment results from dedicated, limited designs. To that end, the ROVCO₂ system is designed to achieve productivity on continuous open floors at the expense of flexibility and operation in small confined rooms.

There is a basic division in the approaches to ROVCO₂ operation: keeping the vehicle on cleaned surfaces, or keeping the vehicle on contaminated surfaces. The approach will have a significant impact on blasting patterns as shown in Figure 2.

After reviewing the design, D&D personnel of Martin Marietta Energy Systems at the Oak Ridge K-25 site clearly indicated a preference for keeping the system on contaminated surfaces. The reasoning is that the system will be operating in contaminated areas and will therefore get contaminated. Rather than constantly decontaminating the system, the D&D personnel expect to operate it as a contaminated tool. Since several buildings at the K-25 site have several hundred thousand square feet of floor, the ROVCO₂ system can operate a long time within a single building's RCA.

The contaminated approach will essentially reverse the vehicle's forward and aft ends so the blasting area is behind the vehicle. The reversal is readily accomplished by repositioning the cameras on the frame and rotating the vehicle joystick.

The operation approach for a contaminated vehicle can also be a little more efficient. In the two possible blasting patterns shown in Figure 2, the clean approach requires backtracking down the blasted area. Due to the relative speeds of blasting and transit, the time lost backtracking is small compared to the blasting time. The contaminated approach has less transitting, and therefore higher productivity. Further evaluation of the operational approach will be conducted as part of the Phase 2 productivity testing.

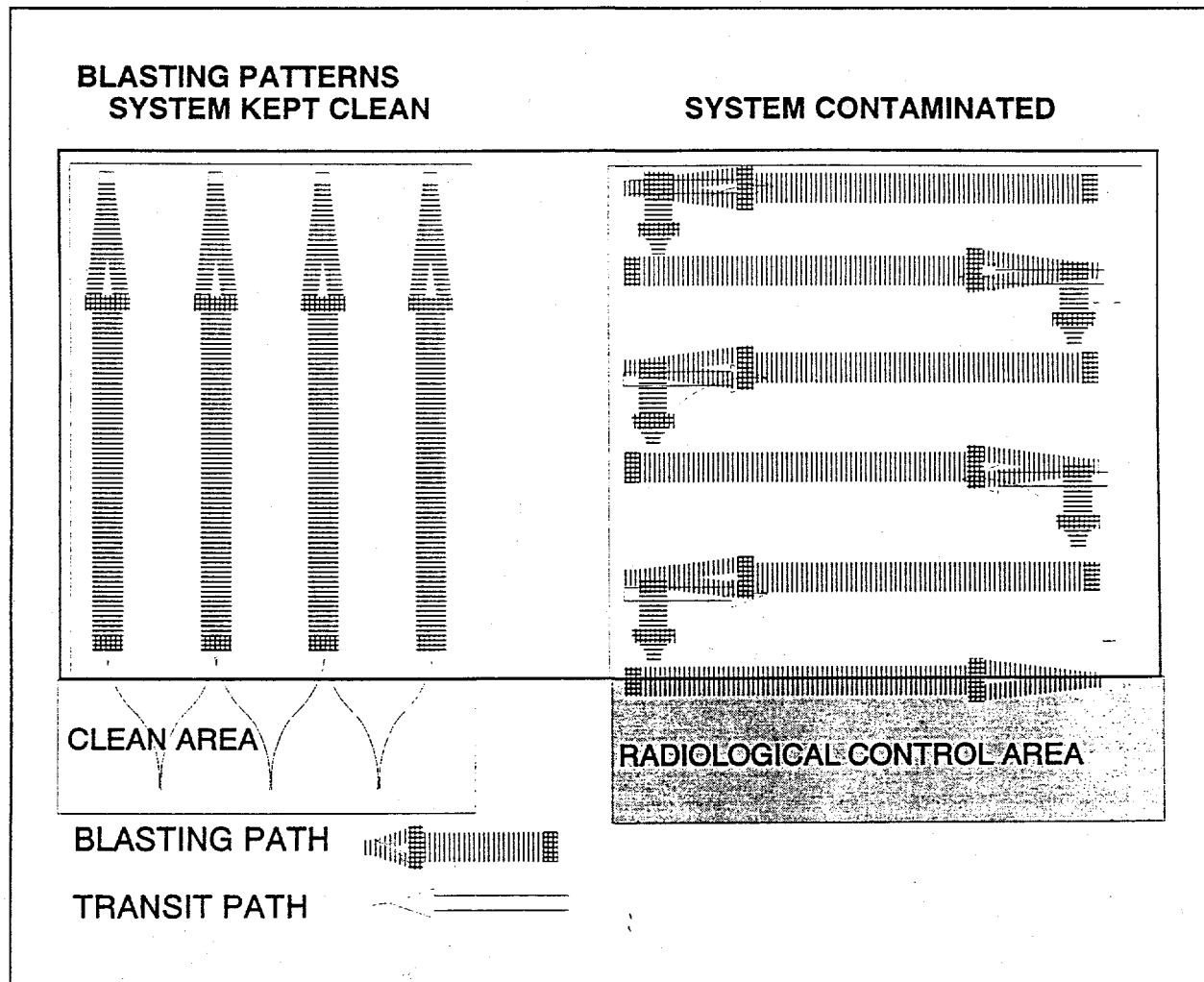


Figure 2 ROVCO₂ Blasting Patterns as a Function of Operating Approach

2.2 Subsystem Development

2.2.1 CO₂ Blasting Subsystem

The CO₂ Blasting Subsystem does the actual decontamination work. The function of the other ROVCO₂ subsystems is to increase the effectiveness and productivity of the blasting. Because the CO₂ Blasting Subsystem is critical to the success of the development, OTECH chose to team on the proposal with Waste Minimization & Containment (WMC), inventors and manufacturers of the Cryogenesis CO₂ blasting system.

For the ROVCO₂ system, WMC carried out three developments: 1) adapting a Cryogenesis system for remote operation, 2) designing and testing an improved nozzle, and 3) designing a vacuum work-head to work with the improved nozzle. The result is the Cryogenesis unit for ROVCO₂ (pictured below) integrated with the rest of the system.

The CO₂ Blasting Subsystem consists of:

- The Cryogenesis CO₂ drice (dry ice) supply unit,
- The Cryogenesis blasting nozzle,
- The remotely controlled electric and pneumatic valves, and
- The vacuum work-head.

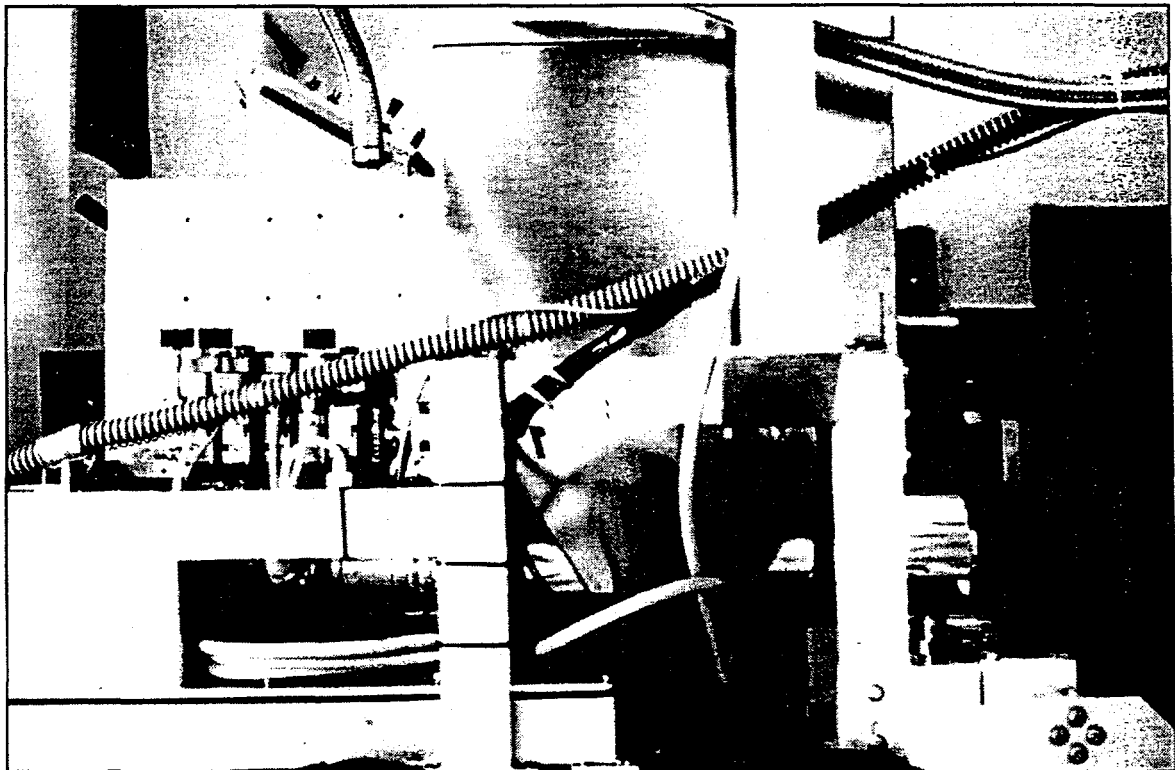


Figure 3 Cryogenesis Supply Unit and Central Valves on the ROVCO₂ System

2.2.1.1 Performance Specifications

- Cryogenesis 380 Nozzle:
 - Speed: Stripping paint 0.35 - 0.5 sqin/sec,
Stripping epoxy concrete sealant 3.4 - 4.6 sqin/sec
 - Pellet Velocities: > 1000 fps (calculated)
 - Pressure: 80 - 350 psi
 - Flow rate: < 200 - > 300 scfm
- Cryogenesis Drice Supply Unit:
 - Drice feed rate: 120 - 175 lbs/hr
 - Electrically activated via 24-VDC solenoid valves. Rate control manually set at vehicle, change only for different coatings.
- Vacuum Work-head:
 - Mounts to COYOTEE cursor
 - Supports Cryogenesis Nozzle
 - Circumference brush, 5" diameter, contacts floor

2.2.1.2 Trade Studies

There were trade analyses conducted for each of the design areas. These trade studies were performed by WMC, and reviewed by OTECH.

- Nozzles:

The goal of the trade study on nozzles was to maximize the coating stripping rate. Maximum stripping rates are theoretically achieved by maximizing the pellets kinetic energy (KE) at impact.

$KE = \frac{1}{2}mv^2$, where m is the pellet mass, v the pellet velocity, and KE the pellets' kinetic energy. The energy transferred to the surface is maximized most efficiently by maximizing the pellet velocity.

Several factors determine the pellet velocity including pellet mass and nozzle jet velocity. The total mass of the pellets impacting the surface is independent of pellet size assuming that the difference in pellet sublimation rates is negligible (true for very short durations such as the Cryogenesis nozzle). The acceleration of the pellets is driven by drag, a quadratic function of pellet diameter, and resisted by the pellets inertia or mass, a cubic function of diameter. The acceleration and velocity of the pellets can be maximized by minimizing the pellets' size (diameter) which maximizes the KE.

Cryogenesis also exploits an empirical abrasive blasting rule to maximize stripping rates. In abrasive blasting, a jagged, rough pellet will strip faster than a rounded, smooth pellet. Cryogenesis stores the drice in long pellets until a few seconds before they impact the surface. The final breaking occurs when the pellets enter the nozzle. The

broken, rough, thin points of the pellets do not have time to evaporate to smoother shapes.

WMC's nozzle analysis is as follows (quoting from WMC):

"The nozzle wall contour is numerically optimized by iterating between wall surface distribution and the flow solution. The optimization process is initiated using an assumed nozzle wall contour of a polynomial form. The assumed wall distribution is then used to find the corresponding inviscid flow solution using the Method of Characteristics (MOC) which is then checked for any flow discontinuities, such as shock-waves, and that it satisfies the required boundary conditions in pressure and Mach number. Then the flow solution is used to correct the wall profile so that the nozzle expansion regions, nozzle exit region, nozzle compression regions are matched. Approximately 40 to 140 iterations are required to generate a nozzle contour that is optimal and satisfies all of the nozzle boundary conditions."

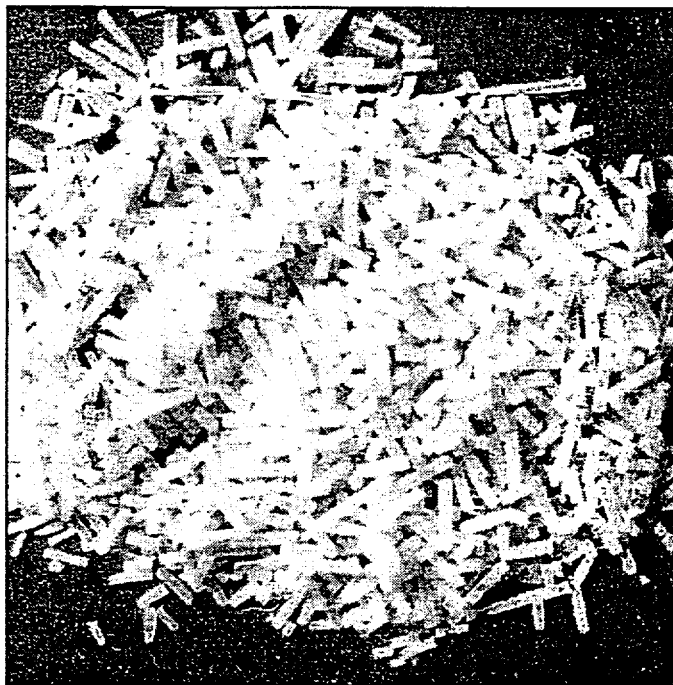


Figure 4 Dry Ice (Dry Ice) Pellets in a stored condition

"The nozzle design is then optimized to: correct and minimize viscous losses, eliminate flow separation losses, and meet the demands of the pellet delivery system."

WMC analyzed five different nozzle designs, four round and one rectangular. Three of these were produced and tested, two round and one rectangular. The description and results of WMC's nozzle testing is in Section 3.3, Blasting Tests.

From this testing, WMC selected the 380 nozzle (round) that was used in the testing and concept demonstration.

- Controls:

The standard Cryogenesis unit works without electrical power. The controls are all pneumatic including the start-up logic. After it was determined that the pellet supply unit would be mounted on the vehicle, a trade study was performed to determine if the pneumatic control should be retained or replaced with electrical controls.

The pneumatic control was existing and proven in operation, but for ROVCO₂ it required:

- Running four 1/4" pneumatic control lines in the umbilical from the control console to the vehicle,
- Mounting the large pneumatic control cabinet on the control console, and
- Manual operation of the blasting controls or added electro/pneumatic hardware at the control console.

Switching to electrical control had several advantages:

- The Programmable Interface in the control console could control the solenoid valves without additional hardware,
- Spare channels in the vehicle's control system could be used, avoiding adding to umbilical size,
- The blasting control logic could be linked with COYOTEE's for greater automation, and
- The solenoid valves were available commercial-off-the-shelf (COTS) with proven operation.

OTECH and WMC concluded that switching to electrical control was preferable.

- Vacuum Work-head:

WMC performed an evaluation of COTS vacuum work-heads to modify for ROVCO₂. This evaluation determined the minimum diameter of the containment brush which would provide acceptable containment. The evaluation was based on observations of blasting with various vacuum work-heads loaned from the manufacturers. Problems with containment, due to irregularities in the surface, presented containment problems with brush diameters less than 5". The 5" diameter was selected for modification.

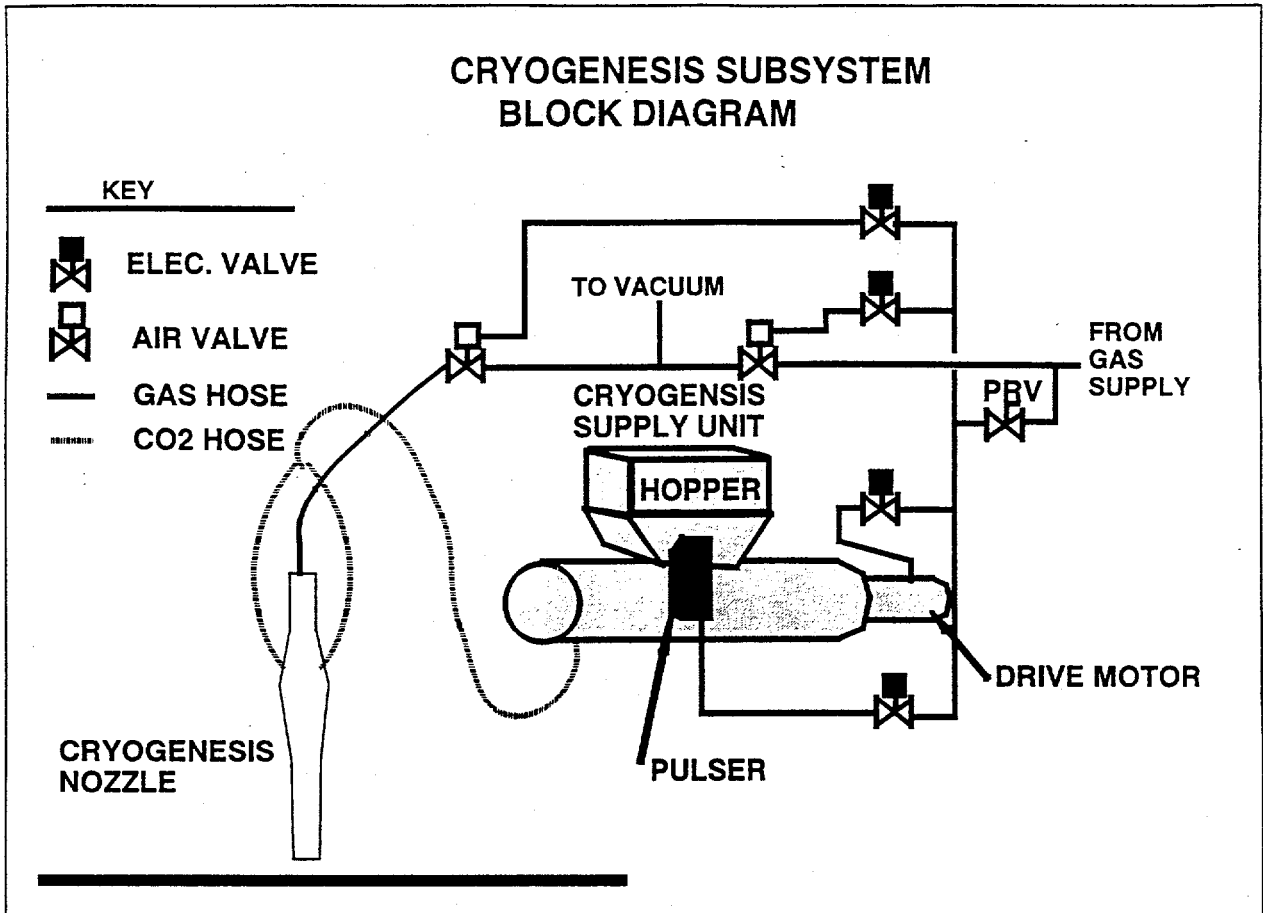


Figure 5 Cryogenesis Subsystem Block Diagram

The major components of the Cryogenesis Subsystem are:

- Cryogenesis Drive Supply Unit:
 - Drive Hopper,
 - Feed Auger,
 - Drive Motor (pneumatic), and
 - Pulser.
- Control Valves:
 - Solenoid manifold,
 - Air powered main valves, and
 - Pressure reducing valve (PRV).
- Nozzle.

2.2.2 COYOTEE

The CO₂ xY Orthogonal Translational End Effector (COYOTEE), pictured below, positions the blasting work-head within a rectangular work space. The COYOTEE design was performed as an OTECH Internal Research and Development (IRAD), and DOE bought one unit for the ROVCO₂ Program.

The initial requirements of the COYOTEE were to design a planar positioning system capable of maneuvering a decontamination work-head within a 24" x 30" area of flat floor or wall. The resulting design is light enough to allow a vehicle manipulator to support the device vertically, allowing decontamination of walls and ceilings as well as floors. To increase reliability and productivity and reduce the risk of the ROVCO₂ development, COYOTEE was fixed in a horizontal position on the ROVCO₂ vehicle. Future development of ROVCO₂ could add a manipulator to position COYOTEE on floors, walls, and ceilings.

The result of this design effort is a unique positioning device which has the following characteristics:

FEATURE	BENEFIT
2 Linear axes	Planar motion
Independent drive axis motors	Full raster motion
Light-weight	< 35 lbs.
Configurable work space	21" x 31.5" (present hardware)
Cable driven	Inexpensive, expendable
Programmable motion	Operator controls area and speed
Open loop stepper motors	Inexpensive, expendable
Decontamination swath wider than vehicle	Minimize recontamination

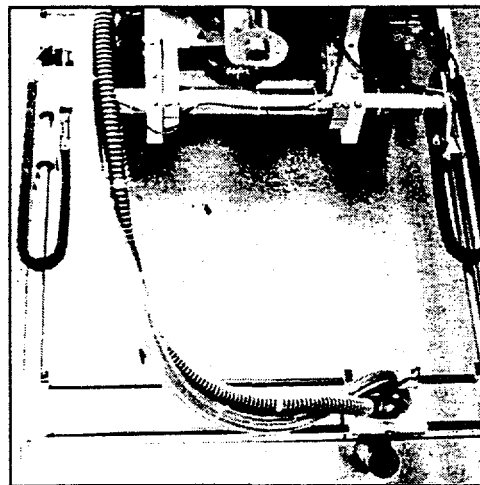


Figure 6 COYOTEE Assembly
on ROVCO₂

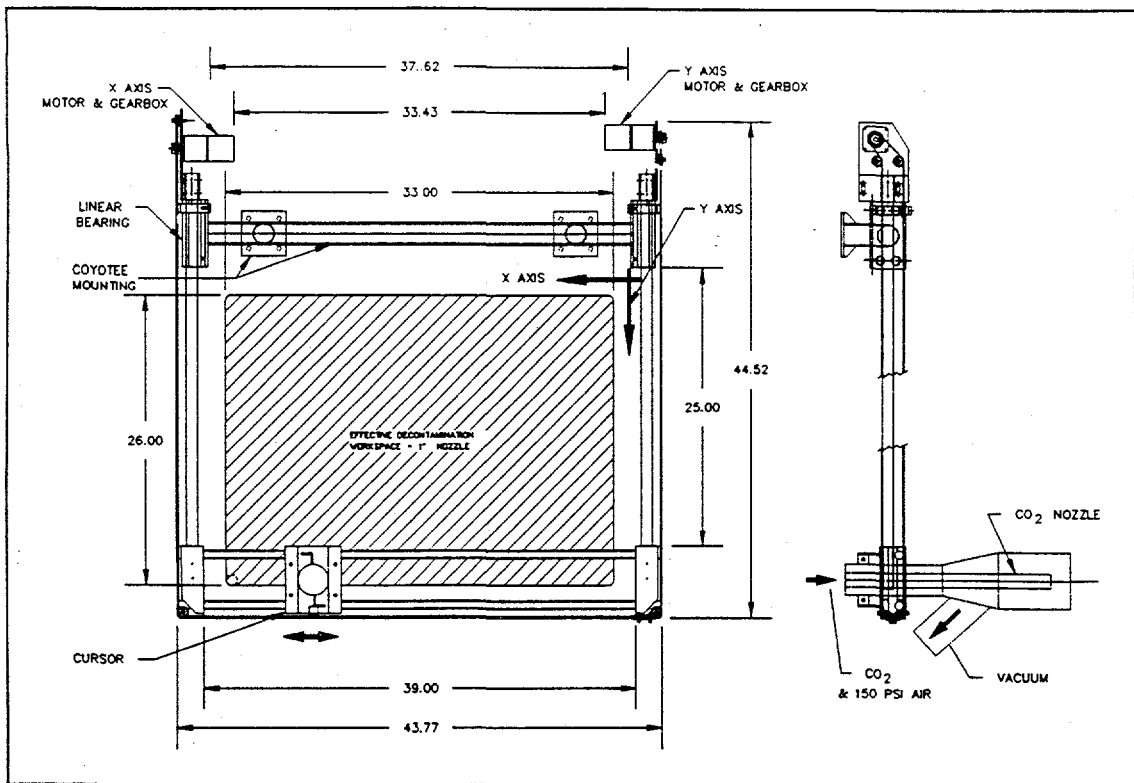


Figure 7 COYOTEE Assembly Drawing

COYOTEE utilizes a cantilevered, U-shaped, tubular frame. The entire frame moves on the linear bearing to effect the Y motion. The cursor slides on parallel tubes to effect the X motion. The Y motion, fore/aft on the vehicle, is provided by a single stepper motor. The motor drives a cable loop which winds around the entire frame using several idler pulleys. The cable is attached to two separate sets of fixed linear bearings which support the two "legs" of the U-shaped frame. These bearings are mounted directly to the COYOTEE mounting structure, which is in turn attached to the front verticals of the support frame. When the motor tensions the cables, the entire frame translates in the Y direction. Travel limits are provided by magnetic reed switches and hard stops.

The X motion, or cursor function, is provided by a second stepper motor. This motor drives a cable which is attached to the cursor supporting the blasting work-head. The cursor bearing is machined from Ultra-High Molecular Weight Polyethylene and rides on two 3/4" aluminum tubes which make up the front of the frame (bottom of U). The motor tensions the cables and pulls the cursor. Travel limits are provided by magnetic reed switches and hard stops.

COYOTEE is controlled by a programmable interface in the control console sending motor command sequences, via the umbilical, to two motor controllers (one X and one Y) located in the vehicle electronics box. The controllers provide step pulses to the motors as directed. The limit switch outputs are wired to the controllers causing the motors to stop when triggered. The operator interface (described in Section 2.2.6, Control Subsystem) allows several parameters to be varied, such as speed, distance traveled, acceleration, and other parameters. The speed variation is useful for different decontamination surfaces and contaminants.

COYOTEE is mounted to the front of the ROVCO₂ Support Frame and extends out in front of the vehicle. The COYOTEE'S mounting structure allows it to be manually rotated upwards to provide clearance during vehicle positioning prior to beginning blasting operations. The mounting allows vertical height and leveling adjustment to accommodate different work-head sizes. A convenient feature of the mounting structure allows quick removal of the positioning system to prevent damage during vehicle transport. When removed, the mounting structure still maintains the rigidity of the COYOTEE which simplifies handling and prevents damage when unmounted from the vehicle.

2.2.2.1 COYOTEE Trades

There were several trade-offs which were considered during the design of the COYOTEE. These involved decisions over whether to provide the Y motion using the vehicle or the COYOTEE, and a number of trades associated with using a standard manipulator to position the COYOTEE for decontamination of walls.

The potential to use the vehicle's motion versus the COYOTEE Y-axis was readily evident, however, there were some disadvantages. First, it was unlikely that vehicle motion could be controlled accurately enough. Second, vehicle motion control most likely would require proprietary software and/or hardware modifications of the vehicle. Providing the Y motion in the COYOTEE allowed the design team to control the positioning accuracy and also the level/programmability of control inherent in the subsystem. The latter option allows flexibility for future growth and enhancements such as using radioactive sensor feedback to control end effector rates and position.

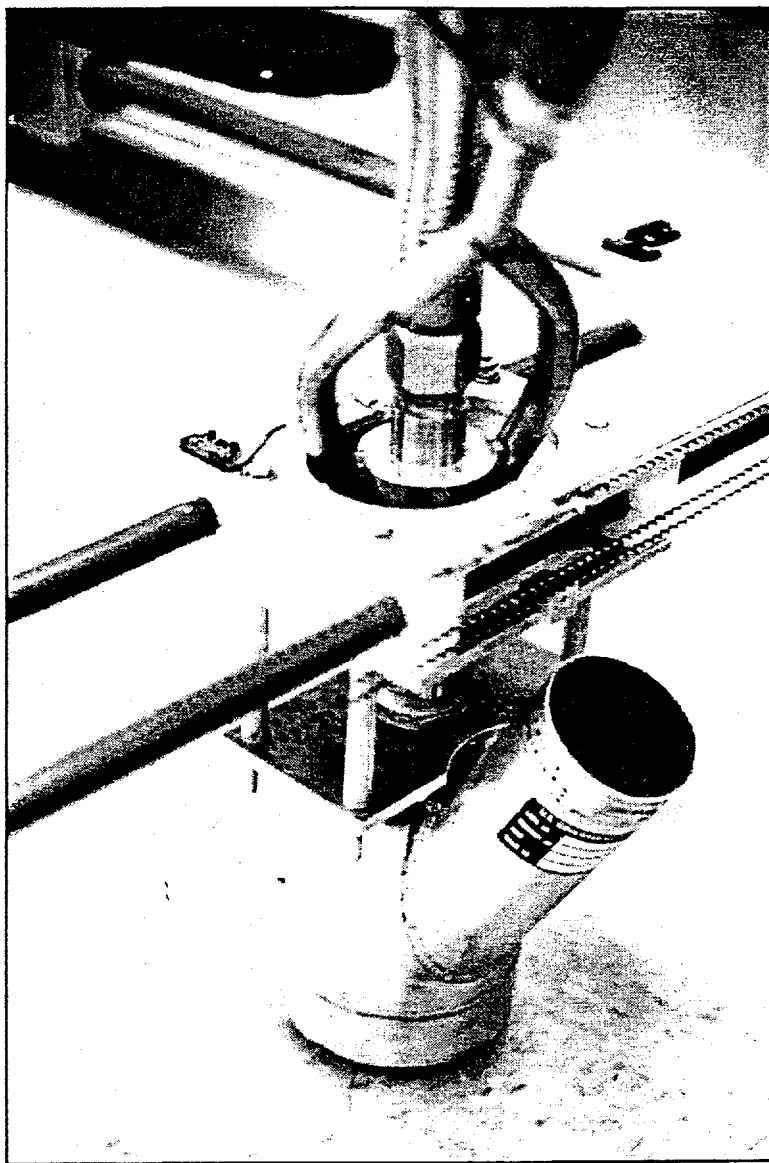


Figure 8 Work-head with nozzle in the COYOTEE cursor — the vacuum hose attaches to the opening

2.2.2.2 Performance Specification

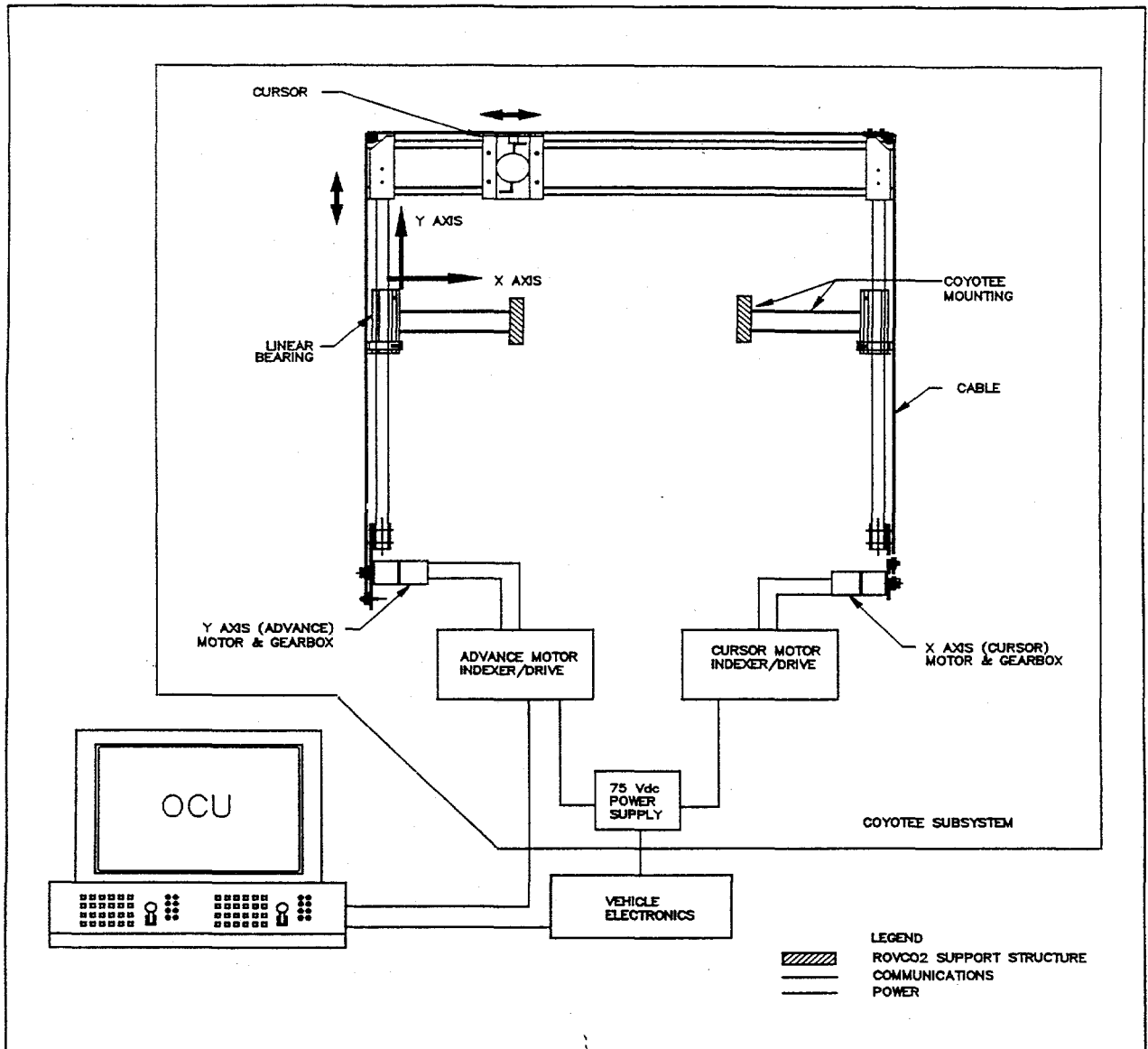


Figure 9 COYOTEE Subsystem Diagram

- Two (2) axis positioning subsystem independent axis control
- Supports work-head loads up to 35 lbs in any direction
- Configurable sweep area, presently 21.75" x 31.5"
- Cursor speeds: 0.1 - 9 in/s
- Positioning error 3.4% of motion
- Weight, approximately 35 lb., including mounting

-
- Drive Motors
 - Micro stepper motor
 - max. torque - 60 oz-in
 - 50 rev/s, max.
 - 75 VDC input
 - NEMA 23 frame
 - X axis
 - 10:1 gear box
 - Torque - 190% of estimated normal operations
 - Y axis
 - Micro stepper motor
 - max. torque - 60 oz-in
 - 50 rev/s, max.
 - 75 VDC input
 - NEMA 23 frame
 - 20:1 gear box
 - Torque - 222% of estimated normal operations

2.2.2.3 Components

The components of the COYOTEE are listed below:

- Drive Elements
 - Micro-stepper motors and indexes (2): Compumotor OEM650X
 - Gearboxes (2): Compumotor
 - Cursor (X axis) - 10:1
 - Advance (Y axis) - 20:1
 - Power supply: Compumotor OEM300 - 75 VDC
 - Drive cable: 0.134" Synchronesh Cable
 - Drive and idler pulleys: Synchronesh
- Structure
 - Mounting frame
 - Linear bearings
 - Cursor rails
 - Advance rails
 - Rail end blocks
 - Advance motor assembly
 - Cursor motor assembly
 - Cursor
- Control
 - The electrical block diagram for the COYOTEE is shown in Figure 10

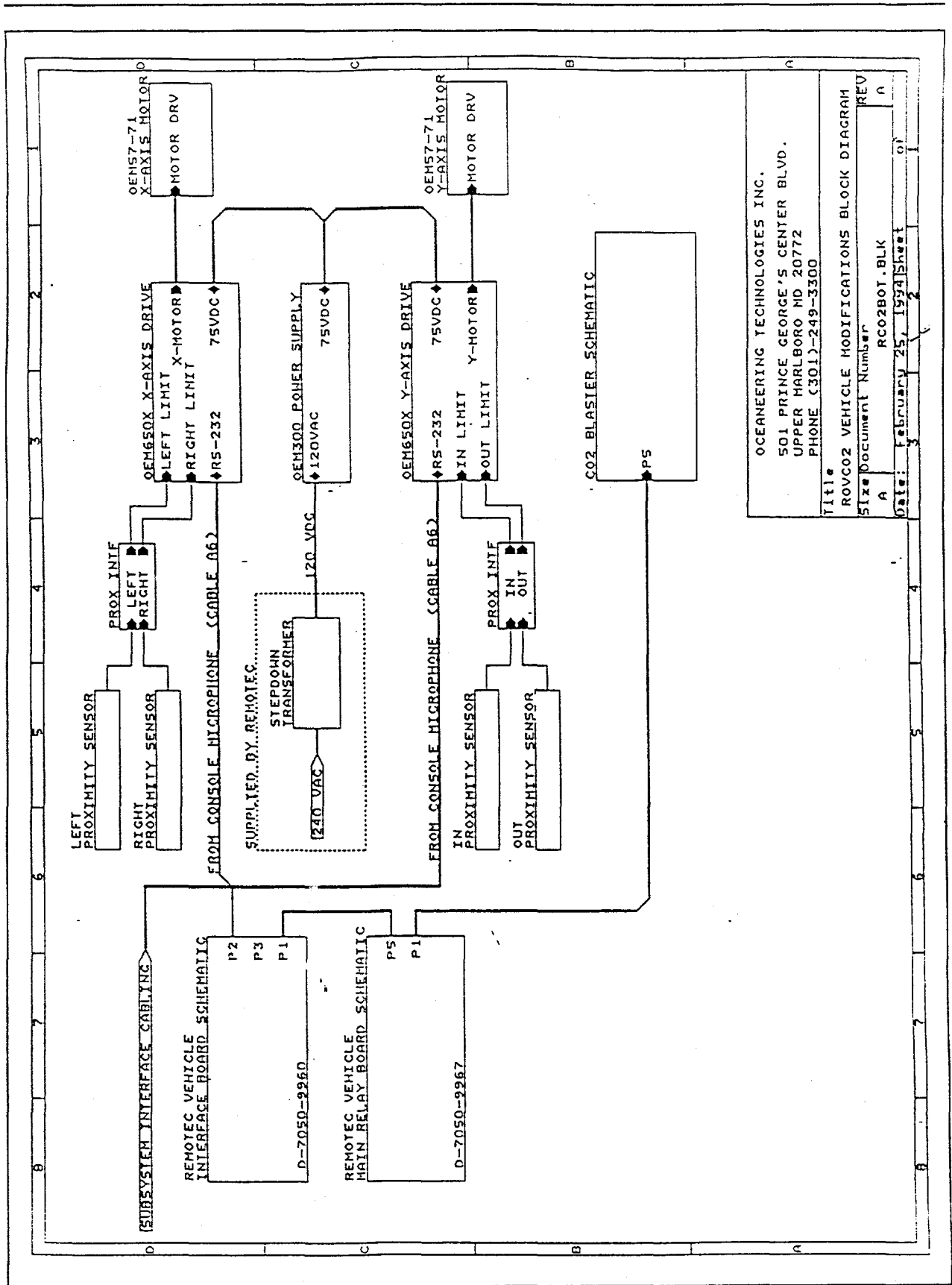


Figure 10 ROVCO₂ Vehicle Modifications Block Diagram

2.2.3 Vehicle Subsystem

The ROVCO₂ Vehicle, pictured below, is a six-wheeled, remote controlled vehicle which provides the transport and power required by all vehicle-mounted subsystems and equipment. The vehicle was procured from a commercial vendor. Following delivery, modifications were performed during system assembly to integrate it into the ROVCO₂ system.

The vehicle's 300 foot umbilical provides command, data, and power transfer between the vehicle and the control subsystem. Each wheel is driven separately and all are coordinated to provide skid steering which allows the vehicle to turn in place. Two camera/light assemblies, one black and white fixed-position and one color mounted on a pan and tilt unit, provide viewing for navigation, obstacle avoidance, and operations. The vehicle has the following characteristics:

- Six-wheeled, each driven separately;
- Skid steering (wheels counter rotate);
- Remotely controlled;
- 1,200 lb. payload capacity;
- 56" x 30" footprint;
- 300 foot umbilical;
- 240 VAC and 24 VDC available on vehicle for subsystems;
- Sealed for decontamination;
- One color pan and tilt video camera;
- One black and white video camera;
- Portable control console;
- Encoder position readout; and
- Spare sensor channels.

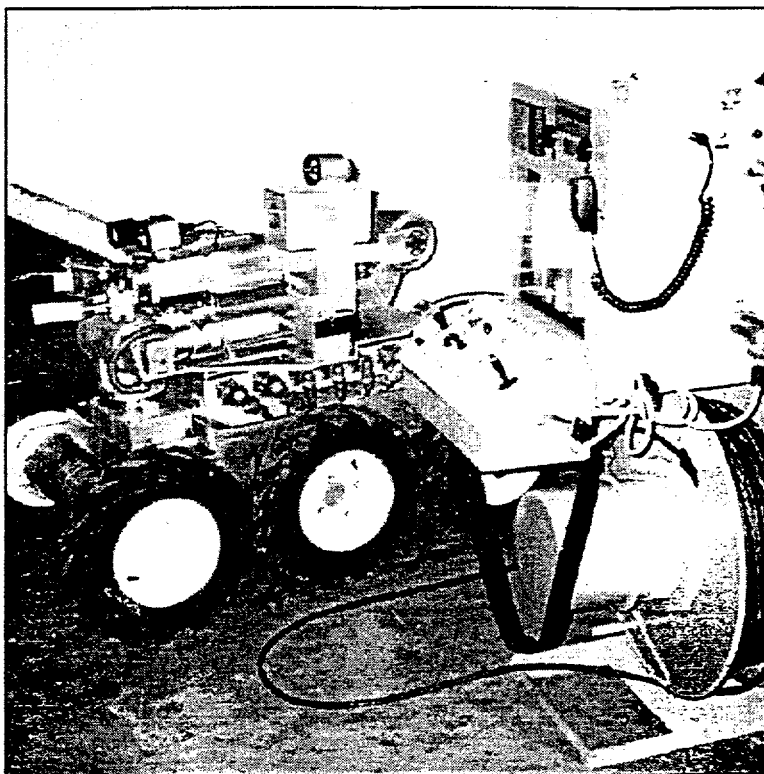


Figure 11 Vehicle Subsystem (arm not purchased for ROVCO₂)

2.2.3.1 Trade Studies

For the vehicle subsystem, the prime alternatives considered were a wheeled versus a track-type vehicle. The vehicle procurement required several steps including:

- Development of a vehicle specification based on the requirements allocated by System Engineering,
- Preparation of the Request for Proposal (RFP),
- Distribution of the RFP, and
- Evaluation of the proposals.

A copy of the RFP was previously submitted to DOE.

The drivers for the vehicle selection in order of importance were:

- Payload Capacity,
- Payload Footprint,
- Longitudinal Precision/Stopping Distance,
- Decontaminability/Sealing,
- Operator Control Unit (OCU),
- Reliability,
- Power, and
- Umbilical Length.

After receiving the vendor responses and comparing these to the specification, only one vendor met nearly all specifications. That proposal, from Remotec Inc., offered either of two vehicles: the ANDROS 6x6 six-wheeled vehicle, or the ANDROS Mark V-A, a track-type vehicle. Either vehicle was a very good candidate.

The advantages for the Mark V-A were:

- Proven reliability,
- Longer wheel base, and
- Wider wheel base.

The Mark V-A has undergone reliability testing by the US Army, and the resulting Mean Time Between Failure (MTBF) exceeds the ROVCO₂ specification. The longer wheel base was expected to provide more stability with respect to climbing obstacles. However, given the obstacles expected at a typical DOE site, either vehicle provided adequate climbing performance.

The advantages of the 6x6 over the Mark V-A were:

- Higher payload capacity, and
- Larger payload footprint.

The 6x6 uses the same motors as the Mark V-A, however for the 6x6 each wheel is driven separately providing six motors versus four for the Mark V-A. These additional motors provide added payload capacity. Considering the fluctuating payload weight during ROVCO₂ operations and the potential for an increase in vehicle payload in Phase 2, the team decided the 6x6 was preferred. The decontamination of the 6x6 was also expected to be less labor-intensive and possibly less expensive than the Mark V-A due to fewer exposed parts. Also, the 6x6 chassis provided a larger base upon which to mount the ROVCO₂ payload.

The only major advantage of the Mark V-A track vehicle was that reliability testing had been previously performed. But, since the 6x6 uses many of the same components, it is expected to have a comparable MTBF. The 6x6 was selected as the vehicle base unit for ROVCO₂.

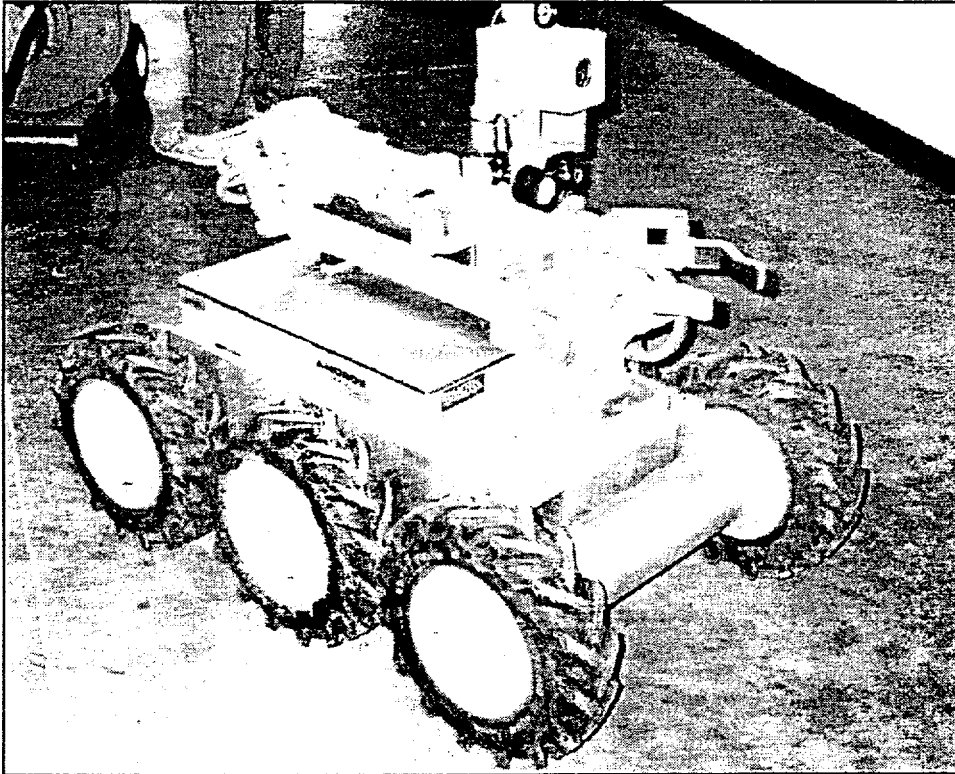


Figure 12 ANDROS 6x6 Vehicle, shown with manipulator arm

2.2.3.2 Performance Specifications

The performance specifications for the ROVCO₂ vehicle are provided below:

- Six wheels, each driven separately (6x6)
- Payload Capacity — 1,200 lbs.
- Overall Size — 56" X 30" X 20" (L x W x H)
- Longitudinal Precision — encoder resolution 0.1", stopping precision <0.1"
- External Power — 110 VAC, 15 Amps (plugs in wall socket)
- Vehicle Power — 240 and 24 VDC, 300 W maximum

-
- Umbilical:
 - 328' long
 - Transfer of power, command/data/video signals for vehicle, Cryogenesis, and Vacuum Subsystems

 - Maneuverability/Obstacles:
 - Crosses 6" trench
 - Climbs 8" ledge
 - Skid steering, turn in 66"
 - Video for obstacle avoidance

 - Decontaminability:
 - Made of 6061 aluminum
 - Enclosures for electronics and cameras
 - Exposed castings vacuum impregnated, hard anodized
 - Smooth surface features

 - Operator Control Unit:
 - Provides command for vehicle, cameras, and spare channels for ROVCO₂ equipment
 - Processes and displays vehicle and user data signals
 - Displays camera views
 - Portable — mounted on a hand truck

 - Cameras:
 - One black and white camera/light
 - fixed mount
 - fixed focus
 - auto iris

 - One color camera and light
 - pan/tilt unit, ± 180 degrees pan, ± 90 degrees tilt
 - 6:1 zoom
 - variable focus

 - Reliability:
 - Track version (ANDROS Mark V-A) successfully tested by NAVEODTECHCEN to criteria exceeding the specification

 - ANDROS 6x6 uses a significant number of the same components and is built to the same MIL-STD-45208A
-

2.2.3.3 Components

The major components of the ROVCO₂ vehicle are listed below:

- Vehicle:
 - Chassis
 - Electronics
 - Umbilical
 - Electrical
 - Air/N₂
 - Video Cameras
 - Positionable
 - Fixed
- Control Console:
 - Video Display
 - Vehicle Joystick and Switches
 - Camera Joystick and Switches
 - Vehicle Power Supply
 - Umbilical Reel

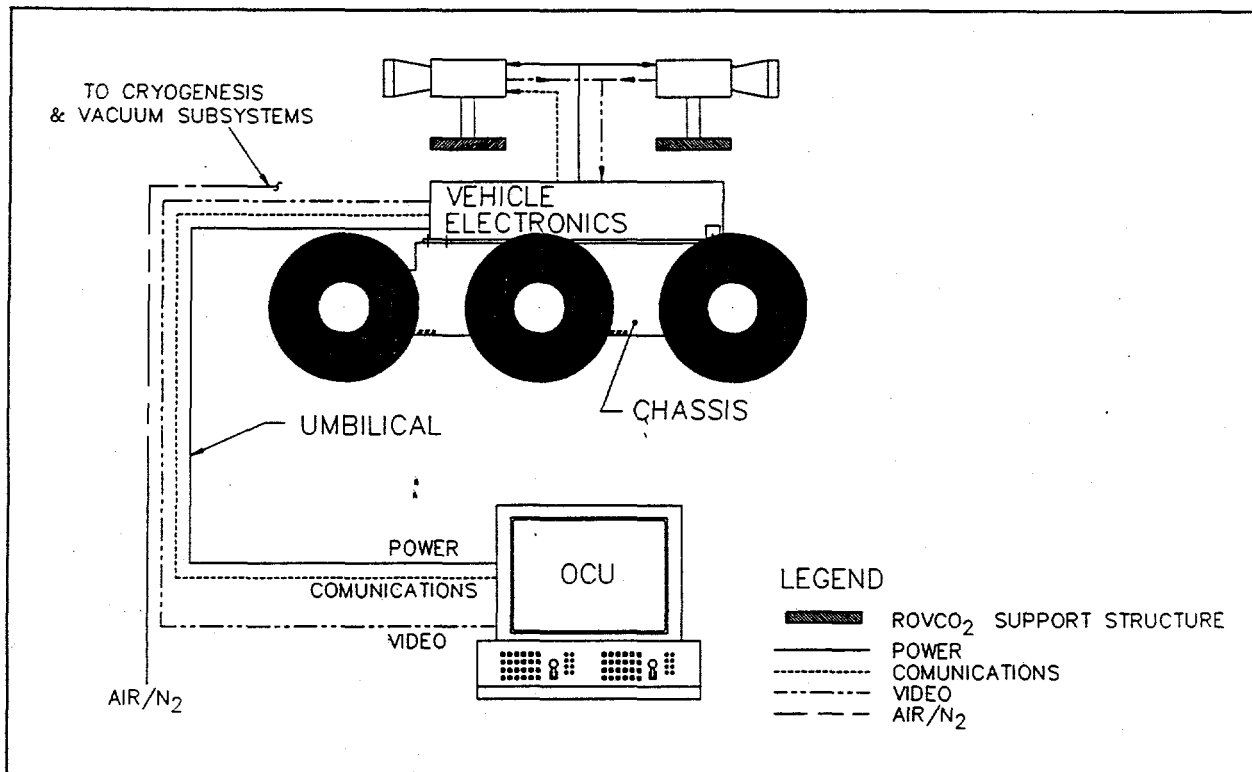


Figure 13 Subsystem Diagram

2.2.4 Vacuum and Filtration Subsystem

The Vacuum Subsystem provides filtration and containment of the debris generated by the CO₂ blasting. The subsystem is actually part of the ROVCO₂ Phase 2 equipment; however, engineering was performed to determine the sizing of components to allow enough volume and payload on the vehicle during the design of the support structure. The main drivers for the design of the Vacuum Subsystem are provided below:

- Minimize escape of contaminated debris from work-head,
- HEPA filtration,
- Sized for 55 gallon drum,
- Safe and simple material recovery drum change-out,
- Safe and simple filter change-out,
- Maximize use of off-the-shelf system or components, and
- Fit within available footprint.

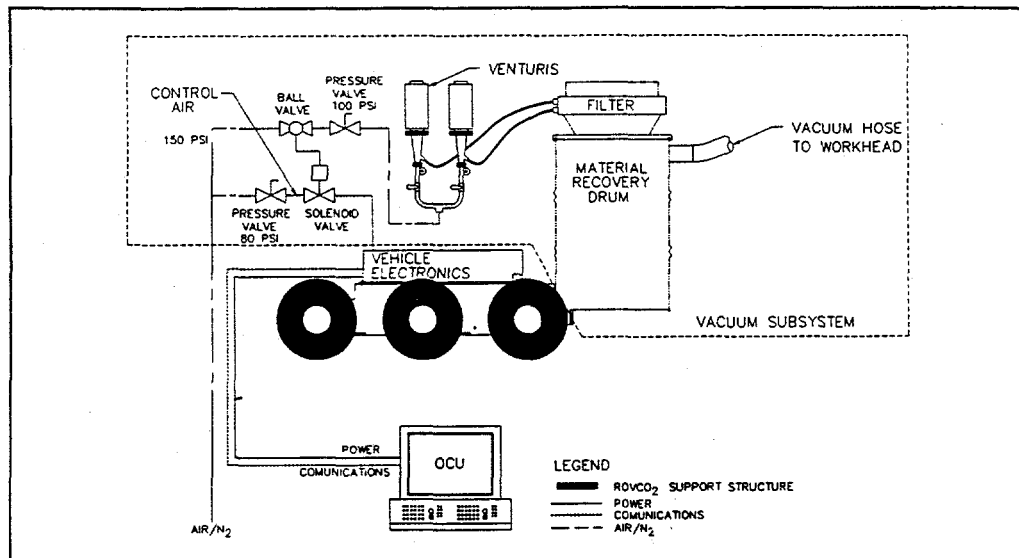


Figure 14 Vacuum Subsystem Diagram

2.2.4.1 Trade Study

The objectives of the Vacuum and Filtration Subsystem are:

- To collect and contain the waste being created by the blasting work-head,
- To facilitate removal of the waste from the ROVCO₂ system, and
- To be readily maintainable.

There are not a lot of alternatives to meet these objectives. To contain the blasting debris in the work-head, a high vacuum flow rate of over 500 scfm is recommended. To facilitate removal of the waste from the ROVCO₂ system, a standard containment vessel, a 55 gallon drum with access to support bag in/bag out operation, should be used. Finally, to be readily maintainable, the subsystem or its components should be commercial-off-the-shelf products.

2.2.4.2 Performance Specifications

The specifications for the Vacuum Subsystem are provided below:

- Integrated material recovery and filter:
 - Sized for 55 gallon drum
- Vacuum:
 - Double Venturi
 - Inlet (compressed air/N₂): 400 scfm @ 100 psig
 - Vacuum side: 650 scfm @ 5.9 psig (vacuum)
- Valving:
 - On/off (air supply to Venturi) controlled from OCU
 - Ball valve, air actuated
 - Control air provided by solenoid valve
- Filter/Material Recovery:
 - Change out filters or recovered material separately
 - HEPA filter slides out
 - Material recovery
 - Bag in/ Bag out

2.2.4.3 Components

The components for the Vacuum Subsystem are listed below. This system is in the preliminary design phase and some components are subject to change.

- Vacuum:
 - Venturi (2): procured in Phase 2
 - Vacuum hose - 3": procured in Phase 2
 - Control valves
 - Numatics 24 VDC solenoid valve
 - (1) AVCO SVF 1" Ball valve
- Material Recovery (Figure 15):
 - 55 gal. drum
 - Quick release strap
- Filter: procured in Phase 2:
 - Screen
 - Prefilter
 - HEPA filter

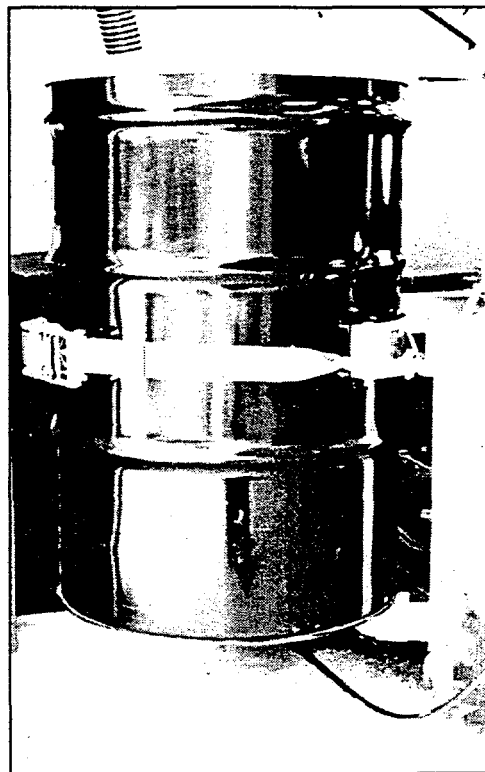


Figure 15 The Material Recovery Drum is easily accessible

2.2.5 Support Structure

The ROVCO₂ Support Structure provides support for the Cryogenesis, COYOTEE, and Vacuum Subsystems. Finally, the structure embodies the ROVCO₂ vehicle/equipment layout which was given significant consideration. The main drivers for the structure are provided below:

- Light-weight,
- Provide support and restraint of equipment,
- Provide maintenance access and allow removal/installation of equipment,
- Ease of decontamination,
- Low Center of Gravity,
- Simplify drum change-out,
- Distribute equipment weight evenly,
- Allow volume and mounting for Phase 2 equipment,
- Minimize modifications to existing equipment to allow attachment,
- Provide 4" Curb/Obstacle Clearance, and
- Provide collision protection for COYOTEE.

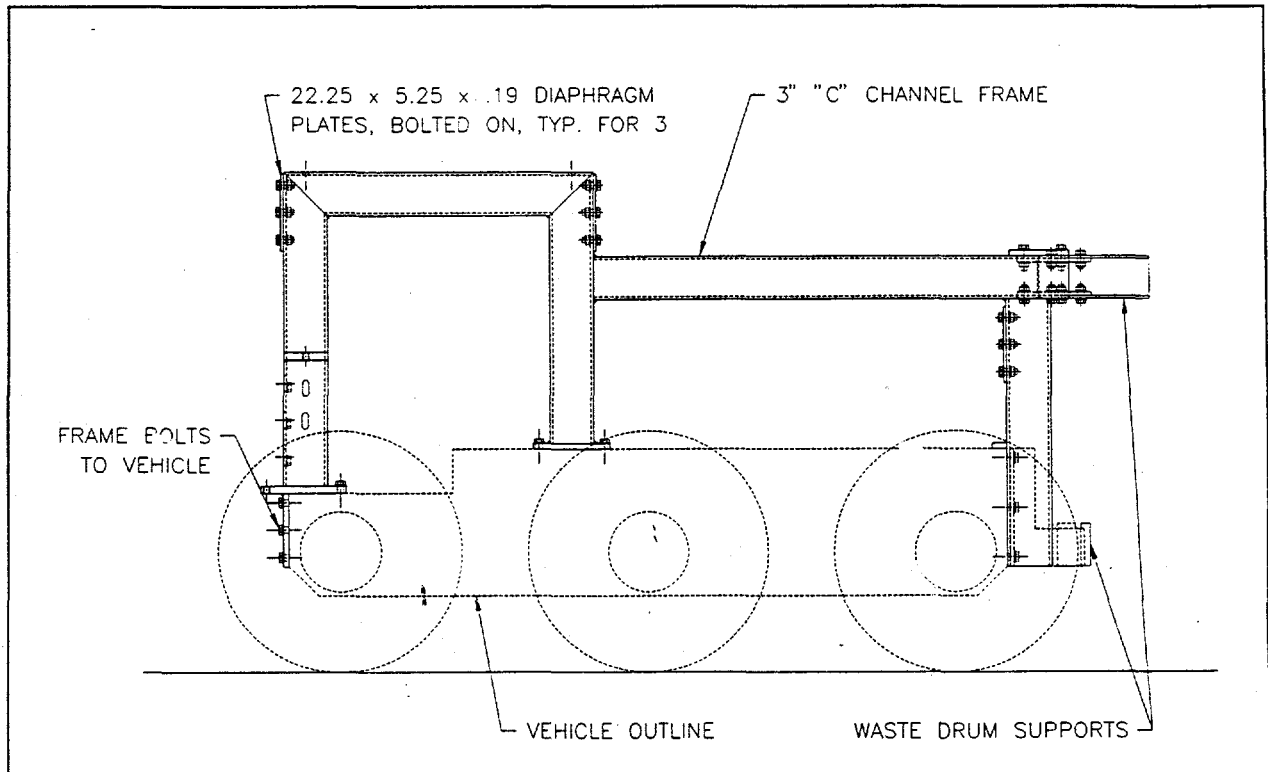


Figure 16 ROVCO₂ Support Structure Elevation

The basic structure consists of two weldments (left and right sides) with three bolted cross members; 6061 Aluminum is used for all structures. The two weldments are constructed using 3" channel, and 1/4" plate is used for the cross members. The structure is bolted directly to two vertical chassis members on the vehicle.

The ability to decontaminate the vehicle was considered throughout the design. The use of open structural elements allows access to the entire surface for decontamination. All weld joints are welded completely and the bolt-on construction allows all ROVCO₂ equipment and support structure to be easily removed, as required, for decontamination, maintenance, and inspection.

The frame design provides access to ROVCO₂ equipment and allows removal of the cross members for additional access as required. The valve manifold is mounted to provide full access to all valving. The lowered, rear-mounted drum is height adjustable and allows changeout using a hand truck. The drum location provides valuable payload volume for Phase 2 or other equipment.

The camera mounts bolt to the horizontal channel near the front of the structure. These can be interchanged as needed, and can be relocated along the structure.

COYOTEE collision protection is provided by a bumper. The bumper surrounds the COYOTEE and prevents damage due to potential collisions with walls and other objects during vehicle maneuvering. The bumper bolts directly to the sides of the vehicle chassis and can be quickly removed.

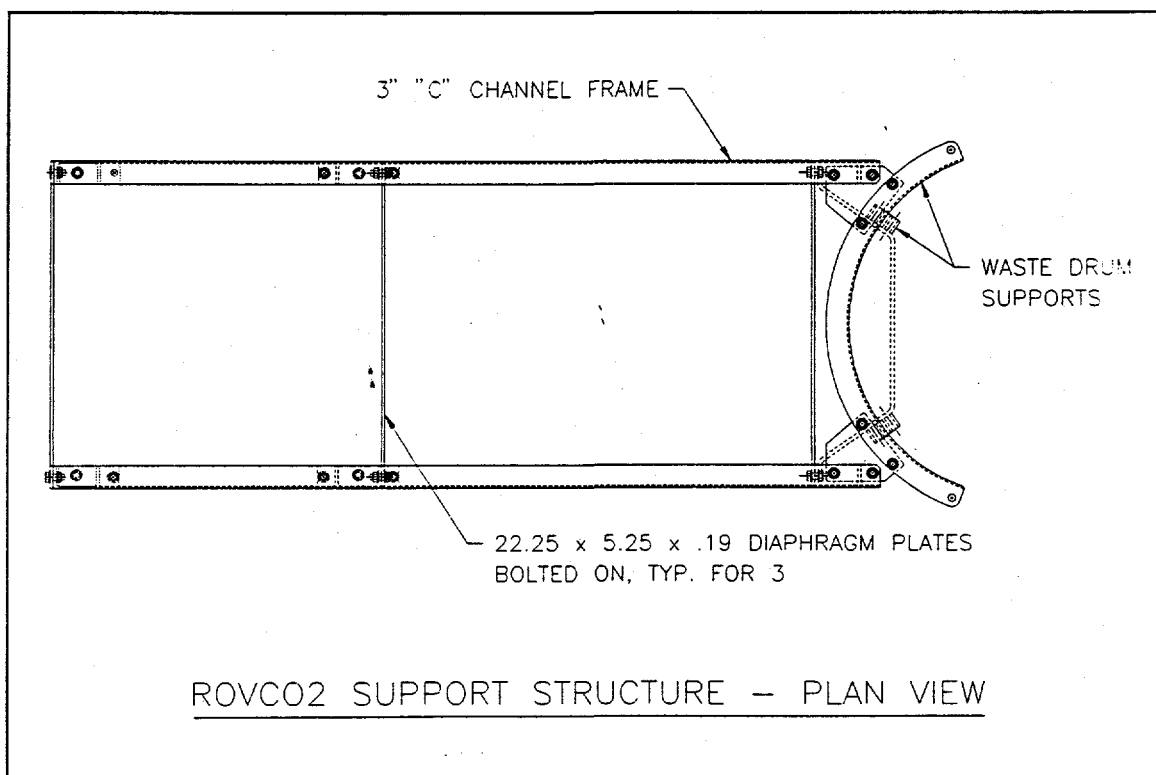


Figure 17 ROVCO₂ Support Structure Plan View

2.2.5.1 Trade-offs

There were several trade-offs which were made during the design of the support structure including:

- Type of structure, i.e., rolled plate versus structural shapes, impacts included.
 - Simplified decontamination
 - Weight
 - Fabrication cost
- Type of fabrication, i.e., single welded structure versus bolted construction, impact included.
 - Fabrication costs
 - Maintenance access
 - Decontamination access
- Type of layout, i.e., material recovery drum on top versus rear mount.
 - Additional payload footprint or shorter overall length
 - Lower CG & height
 - Change-out of drum

Tubular frames were not considered due to decontamination and verification problems. The open box structure was expected to provide the best surface for decontamination, however fabrication costs were estimated to be high. The channel frame was expected to require only slightly more effort for decontamination, but the fabrication costs were estimated to be significantly lower than the other concepts. In addition, the channel frame provided better access to equipment. After consideration, the bolted channel frame was selected due to low cost, ability to decontaminate, and accessibility for maintenance.

Another design consideration was the vehicle layout, specifically, whether to mount the material recovery drum on top of the vehicle or hang it off the rear of the chassis. The rear mount gave better access, saved payload footprint, and lowered the overall Center of Gravity (CG). On the downside, the rear mount increased the vehicle length, reducing maneuverability. The top mount provided a shorter layout raising the height and CG, as well as reducing camera visibility and substantial payload footprint. The rear mount was chosen as more advantageous.

2.2.5.2 Specifications

- All frame members are 6061-T6 aluminum
- Factor of Safety over static load - 10
- Dynamic loading case - 4" curb drop with a safety factor of 2.5
- Provides volume for Phase 2 equipment

-
- Can be disassembled for decontamination
 - Drum mounting
 - Layout simplifies drum change-out
 - Drum is low to the ground for safer change-out operation
 - Provides support for all vehicle mounted ROVCO₂ equipment
 - Cryogenesis Subsystem
 - Vacuum Subsystem
 - Coyotee Subsystem

2.2.5.3 Components

- Support frame
 - Side frame (2) - 3" aluminum channel
 - Cross members (3) - 1/4" aluminum plate
- Camera Mounts
 - Pan/Tilt Stand
 - Fixed Camera Bracket
- COYOTEE mounting assembly
- Drum mounting structure
 - Drum stop
 - Drum channel
 - Drum wing

2.2.6 Control Subsystem

For ROVCO₂, an integrated, single operator control system was desired. It was recognized early in the development that to achieve this, the ROVCO₂ system would have to be integrated with the vehicle subsystem's control system. To this end, the detailed design of the control system was delayed until the vehicle was selected and its control schematics procured. The result is an integrated operator control unit that has the vehicle's joystick controls and video display, and ROVCO₂'s programmable interface and on-screen data display.

In this section are discussions on the vehicle controls, sensors, and the programmable interface that controls the rest of ROVCO₂.

2.2.6.1 Vehicle Controls

The vehicle controls have been kept as hardware switches and a joystick for effective movement control. While much of the control for ROVCO₂ operation is serial and programmable, the vehicle control requires adaptive, responsive control in operation. The vehicle controls include:

- Joystick controlling rate and direction of vehicle movement with a deadman switch brake button;
- Enable/disable switches for the vehicle and tool circuits (the tool circuits were used for blasting control);
- Vehicle speed selection switch (fast/slow);
- Pan and tilt camera joystick, zoom, focus, and iris controls;
- Camera selection switch; and
- Video data display on/off switch.

The vehicle also came with three spare control circuits connecting the Operator Control Unit (OCU) with 24 VDC circuits in the vehicle electronics housing. These have been used for control of the Cryogenesis and Vacuum Subsystems.

2.2.6.2 Sensors

The control system uses two cameras and a temperature and a pressure sensor. The temperature and pressure sensors monitor Cryogenesis operation, and are displayed in the video overlap.

The fixed camera is mounted on the left side and is front facing to provide a wide angle view of the forward direction. This is useful for orientation and alignment of the vehicle with respect to the worksite. The pan/tilt mounted camera is bolted on the opposite side and provides views of the work-head, vehicle, and surroundings. This camera can also be panned to view the umbilical during turns and when backing up. Either camera can serve as the drive camera depending on the operator's preference.

2.2.6.3 Programmable Interface

The programmable interface consists of a 40 character by eight line LCD display and a keypad with 30 keys. Software written for ROVCO₂ is resident in the programmable interface. Control of the blast and COYOTEE units, automated operation of the ROV, and definition of operational parameters are all accomplished via the programmable interface.

The three components of the blast unit — the vacuum, air gun, and CO₂ blast — are all controlled via the programmable interface. Each device can be turned off and on with specific keys, but a predefined sequence is enforced by the software. The vacuum must be turned on first, followed by the air gun, then the CO₂. Shutdown of each unit follows the reverse order. An attempt to turn a device on (or off) out of sequence is not treated as an error condition. Instead, the software will perform the desired operation once the devices required to maintain the proper sequence have been turned on or off automatically.

Operation of the COYOTEE consists of five basic modes of sweep operation. The operator can choose to move to HOME, move to HOME OUT, SWEEP OUT, SWEEP IN, or JOG. Move to HOME and HOME OUT are preprogrammed moves designed to advance the blast nozzle to a specific point within the blast area. SWEEP IN and SWEEP OUT are calculated moves that advance the blast nozzle a specific distance in each direction from its current position. JOG gives the operator complete control over the COYOTEE operation. Arrow keys on the keypad are used to move the blast nozzle in the direction indicated by the arrow.

Operation of the ROV is accomplished primarily via manual controls on the operator's console, but the programmable interface does provide for one automated mode of operation. In this mode, operation of the vehicle, COYOTEE, and CO₂ blast is controlled by software. The blast nozzle is moved to HOME, the CO₂ is turned on, a SWEEP OUT is performed, the CO₂ is turned off, and the vehicle is advanced in a straight line. This process continues until a predefined distance is covered. Due to a mismatch in communications timing between the vehicle computer and the programmable interface, this feature had an unacceptably high error on vehicle movement (approximately 6") and was disabled. The movement error may be corrected in Phase 2 by adding position feedback and speed control.

There are a variety of parameters the operator can define which will govern the operation of the vehicle and its subsystems. Movement of the blast nozzle by the COYOTEE system is defined in terms of a Cartesian plane. Movement along the X-axis is from left to right, with positive X distance being left and negative X distance being right. Displacement along the Y-axis represents movement of the blast nozzle in toward the ROV (+Y) or out from the ROV (-Y). The speed of motion along each axis and distance along each axis for sweep operations are defined by the operator via the programmable interface. In addition, the overall travel of the ROV when operating in automatic mode can be defined by the operator, as can the amount of overlap that should be used in successive sweep operations. When turning the blast components on or off in sequence, time delays are used between the activation (or deactivation) of one device and the activation of the next. These time delays are also defined by the operator via the programmable interface.

- Software Specification:

- Target System

- Eason Technologies Model 1000 Smart Operator Interface w/ 64KB memory option
 - (2) Compumotor OEM650X Drives/Drive Indexers

The Eason Smart Interface 1000 requires the use of a proprietary version of GWBASIC. Eason Technologies refers to their version of GWBASIC as EASON BASIC (rev 1.3).

- Stepper Motors

The Compumotor OEM650X drives and indexers, used on COYOTEE, use a proprietary language referred to as the X Series Language. The X Language allows control of each motor's acceleration, velocity, distance of travel, and sequencing of motions.

- Software Requirements:

The software for the programmable interface was specified in terms of operator interface effecting actions (the specification is in Appendix C). The interface was organized by function including operating parameters, COYOTEE operation, blasting operation, vehicle operation, and general operations. The program was developed using the tools of the programmable interface to simplify and reduce program coding.



Figure 18 Operator Console

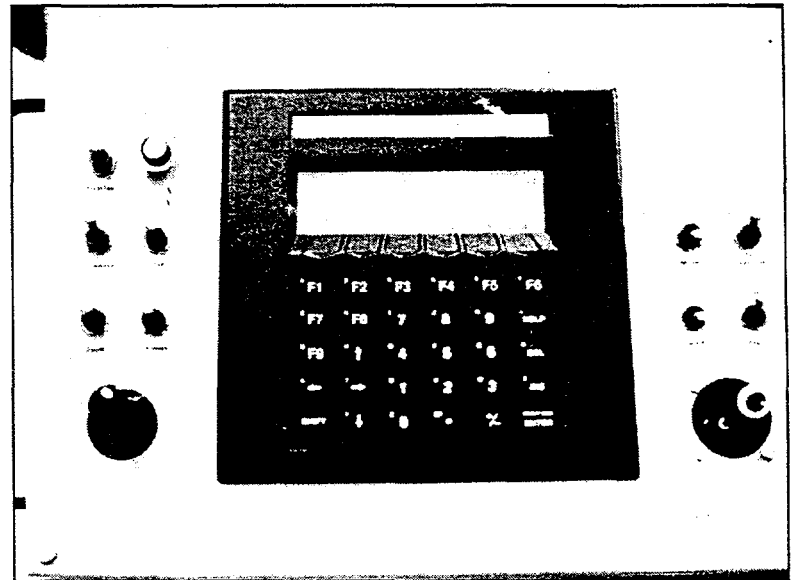


Figure 19 Operator Panel

3.0 SUBSYSTEM TESTING, RESULTS AND CONCEPT DEMONSTRATION

Testing was conducted at the end of the subsystem development to measure the performance of the subsystems against the Success Criteria. In addition, the Phase 1 subsystems were assembled and operated as a demonstration of the ROVCO₂ System concept. A video tape of the demonstration was produced and provided separately.

This section describes the methodology and results of the testing and demonstration.

3.1 Test Safety

The operation of the ROVCO₂ system has many safety issues even during testing at a non-radioactive site. In addition to OSHA regulations, OTECH produced and followed a safety plan for ROVCO₂. A copy of the plan is in Appendix B.

3.2 Concept Demonstration

To demonstrate and verify the integrated operation of the Cryogenesis blasting, ROV, and COYOTEE, a concept demonstration was run at the end of Phase 1 development. This demonstration verified that the subsystems would function in concert as designed and validated the concept of operation. Two demonstrations of several hours each were run with representatives from METC and Oak Ridge at the first.

Expendable materials required for the concept demonstration included drice (~150 lbs/hr) and dry compressed gas (~250 scfm @ 150 psi). The drice was shipped from WMC in 600-lb insulated containers. The shelf life of the drice in unopened containers is about three days before it becomes too soft for aggressive blasting. The gas was supplied by an air compressor, without a dryer, for the first demonstration. The wet air from the compressor condensed to ice in the blasting nozzle, disrupting the aerodynamics and clogging the CO₂ pellet hose. For the second concept demonstration, a trailer of compressed N₂ tanks, with very low humidity, was used as a supply without problems.

In lieu of the containment and filtration subsystems, the concept demonstration was conducted in OTECH's paint area. The floor of the paint area was coated with the test coatings, agreed upon by Oak Ridge and METC, for the demonstration.

For an ongoing operation, the drice would be supplied by a pelletizer and CO₂ tank at the site. The compressed gas could either come from a compressor with a dryer or large liquid N₂ tanks and a gasifier, whichever is least costly for the site.

- Procedure:

For the concept demonstrations, an operator sat at the control console out of sight of the vehicle in a painting/blasting area. The operation consisted of:

1. Setting the COYOTEE sweep speed and area parameters for the coating to be removed.

2. Driving the ROV into position to clean the designated area.
3. Turning on the Cryogenesis Blasting.
4. Starting the COYOTEE sweep operation. The operator makes an initial check through the ROV camera that the coating is being completely removed.
5. At the end of the sweep operation, the vehicle is incremented forward to an encoder distance 0.1" less than the Y sweep distance. If auto CO₂ control is enabled, the CO₂ pellet feed will automatically pause while the COYOTEE is stopped.
6. Start the COYOTEE sweep in the opposite direction. If AUTO is enabled, the CO₂ pellet feed will be started before the COYOTEE movement.
7. Repeat steps 5 and 6.

The demonstration was run on two coatings: a two-part polyamide-epoxy paint and a water emulsion, metal interlock, acrylic copolymer sealant. Several cycles of sweeps and moves were run on each coating.

- **Results:**

Tests of full sweeps by COYOTEE and incrementing the vehicle to the next position were run in the demonstration. The tests were video taped (a summary tape has been provided) and showed that the ROVCO₂ system will perform as designed. Contiguous swaths of floor can be cleaned with a minimum of overlap. The verified functions included:

- The ROVCO₂ system cleaned the coatings from the floor as it was designed to do.
- The operator at the OCU was able to effectively remove swaths of coating from designated areas of the floor.
- The control system provided useful automation of otherwise tedious tasks such as sweeping the work-head back and forth.
- The subsystems worked in concert as orchestrated by the control system, such as the automatic shut-off of the pellet feed auger whenever COYOTEE was stopped in order to conserve drice.

3.3 Blasting Tests

Two sets of blasting tests were conducted. The initial tests were nozzle tests, operated manually, at WMC. The final tests were stripping rate tests, with the nozzles mounted on COYOTEE and ROVCO₂, at OTECH.

3.3.1 Nozzle Tests

The three nozzles produced, the 380 and 450 round and 250 flat nozzle, were tested by WMC for operation and effectiveness. The testing used expendable supplies of drice and N₂ from WMC's on-site supplies.

3.3.1.1 Operation Tests

The operational test checked the integrity and function of the nozzles. The test consisted of the following for each nozzle.

- Data:
Pass/Fail of each nozzle.

- Procedure:
 1. Connect the nozzle to the supply lines and clamp them down.
 2. Slowly turn on the gas supply valve, while observing the nozzle for adverse reactions, until low (80 psi) and then high (200 psi) is reached.
 3. Decrease gas supply pressure from 200 to 0 while observing the suction pressure on the CO₂ inlets.

- Results:
Of the three nozzles fabricated, the two round ones passed the operation test and the flat nozzle failed. The round nozzles functioned smoothly with nearly constant CO₂ supply line suction from 80 to 200 psi.

The operation of the flat nozzle produced large, fluctuating forces apparently due to the shock wave entering and exiting the discharge end of the nozzle. The cause of the problem has not been determined and further work on the flat nozzle was discontinued in this phase.

3.3.1.2 Effectiveness Tests

The effectiveness test checks the blast pattern and aggressiveness of the nozzles. The blasting for the tests was performed manually using a standard Cryogenesis unit. The blasting was on metal surfaces removing automotive (enamel) paint and, in a separate test, oil/grease. The test consisted of the following steps for each nozzle carried out by two people, a timer and an experienced blaster.

- Data:
For each nozzle: pressure, distance off surface, and the width and length of the swath.

- Procedure:
 1. Set up the Cryogenesis system for blasting with the nozzle to be tested. A CO₂ pellet feed rate of 2.5 lb/min was used.
 2. The pressure regulating valve is set for the test pressure.
 3. The blaster holds the nozzle and measures to find the appropriate distance off the surface.

-
4. The timer gives a go signal and the blaster cleans a straight line, marked on the surface, for 30 seconds, stopped by the timer's signal. Blast height was manually maintained by eye. The blaster maximized speed limited only by leaving a clean trail.
 5. The pattern width and the distance covered is measured and recorded.

Steps 3 - 5 are repeated for standoff distances of 2", 4", and 6" for each pressure. Steps 2 - 5 are repeated to test each functional nozzle at 80 to 150 psi in 10 psi steps. The timing was made with a quartz watch and the measurements with a carpenters tape measure.

- **Results:**

The results of the effectiveness testing are in the following tables. They show that the 380 gun is more aggressive and faster than the 450 for practically all sets of conditions even though it has a smaller blast pattern. This agrees with the analysis which predicted the 380 would have faster pellet velocities.

PSI	BLAST WIDTH			.450 GUN REMOVING: AUTOMOTIVE PAINT CLEANING RATE (SQ. IN./MIN.)		
	at 2"	at 4"	at 6"	at 2"	at 4"	at 6"
80	1 ¼"	1 ½"	1 ¾"	12	11	7.5
90	1 ¼"	1 ½"	1 ¾"	14	16	14
100	1 ¼"	1 ½"	1 ¾"	24	24	20.25
110	1 ¼"	1 ½"	1 ¾"	22.5	37.75	46
120	1 ¼"	1 ½"	1 ¾"	43	52	55
130	1 ¼"	1 ½"	1 ¾"	67	64.75	59
140	1 ¼"	1 ½"	1 ¾"	59	69	83
150	PATTERN	REMAINS	CONSTANT	78	82	100.5

PSI	BLAST WIDTH			.450 GUN REMOVING: OIL/GREASE BUILD-UP CLEANING RATE (SQ. IN./MIN.)		
	at 2"	at 4"	at 6"	at 2"	at 4"	at 6"
80	1 ¼"	1 ½"	1 ¾"	93.75	100.2	110.5
90	1 ¼"	1 ½"	1 ¾"	93.75	100.2	110.6
100	1 ¼"	1 ½"	1 ¾"	100	120	123.5
110	1 ¼"	1 ½"	1 ¾"	115.25	163	161.5
120	1 ¼"	1 ½"	1 ¾"	136.25	163.5	161.5
130	1 ¼"	1 ½"	1 ¾"	136.25	163.5	161.5
140	1 ¼"	1 ½"	1 ¾"	150	200	210
150	PATTERN	REMAINS	CONSTANT	166.75	200	210

PSI	BLAST WIDTH			.380 GUN REMOVING: AUTOMOTIVE PAINT CLEANING RATE (SQ. IN./MIN.)		
	at 2"	at 4"	at 6"	at 2"	at 4"	at 6"
80	15/16"	1 ¼"	1 ½"	32	26	16.5
90	15/16"	1 ¼"	1 ½"	36	30	16.5
100	15/16"	1 ¼"	1 ½"	68	63	60
110	15/16"	1 ¼"	1 ½"	47	51	66
120	15/16"	1 ¼"	1 ½"	58	68	80
130	15/16"	1 ¼"	1 ½"	64	67	75
140	15/16"	1 ¼"	1 ½"	76	76	73
150	PATTERN	REMAINS	CONSTANT	89	90	92

PSI	BLAST WIDTH			.380 GUN REMOVING: OIL/GREASE BUILD-UP CLEANING RATE (SQ. IN./MIN.)		
	at 2"	at 4"	at 6"	at 2"	at 4"	at 6"
80	15/16"	1 ¼"	1 ½"	112.5	125	120
90	15/16"	1 ¼"	1 ½"	112.5	125	127.5
100	15/16"	1 ¼"	1 ½"	112.5	136.25	163.50
110	15/16"	1 ¼"	1 ½"	140.625	150	163.50
120	15/16"	1 ¼"	1 ½"	187.5	214.25	225
130	15/16"	1 ¼"	1 ½"	225	300	300
140	15/16"	1 ¼"	1 ½"	225	300	360
150	PATTERN	REMAINS	CONSTANT	281.25	330	450

3.3.2 Blasting Strip Rate Test

The Blasting Strip Rate Testing during the concept demonstration went beyond the requirements to substantiate the Phase 1 Success Criteria. OTECH decided to use this opportunity to better document the capabilities of the Phase 1 system. Budget limitations restricted the amount of testing, and therefore the scientific rigor of this test. The results of the testing have been included in this report for information. The testing was not adequate to definitively determine the ROVCO₂ system productivity.

The coatings for the test were:

- A two-part polyamide-epoxy paint commonly used at the Oak Ridge K-25 site for painting over contaminants. The paint was applied to sealed concrete by spraying.
- An acrylic copolymer sealer judged similar to the sealant applied to the vast majority of the concrete floors at K-25. The sealant was applied to clean concrete by mopping.

The selection of these coatings was coordinated with Oak Ridge K-25 and METC.

This testing required the COYOTEE and Cryogenesis subsystems. The testing measured blasting effectiveness for the 380 nozzle (the 450 nozzle was tried on the epoxy paint, but was much less effective). A Simpson's approach was used to determine the fastest X sweep rate at which paint could be removed from a concrete surface. The maximum X sweep rate for paint removal was determined for a given air pressure and CO₂ rate. The amount of paint removal was measured by visually comparing results from other test runs.

- Data:
Photographs of test runs, run #, desired ips, time, distance, motor/indexer commands, blast air/N₂ pressure, and CO₂ rate.
- Procedures:
Initial experimentation blasting with the 380 nozzle determined that close up operation (~1"), closer than comfortable for a continuous manual operation, produced the best results.
 1. For these tests the full Phase 1 ROVCO₂ system was employed with a compressed gas supply and a cooler with 600 pounds of drice. The tests were run in OTECH's large structure painting area to contain the blasting debris.
 2. Test equipment included a pressure gauge and an orifice-type flow meter for the compressed air line, a scale and stop watch for measuring and correlating the drice feed rate, and a set of spacers for setting and checking nozzle height off the floor.
 3. The Cryogenesis supply unit's auger rotation speed was correlated to pounds of drice per minute by putting a weighted amount of drice in the hopper and timing both the auger rotation speed and the time to exhaust the drice.
 4. The ROVCO₂ system would be driven into position for each test run with the blasting and COYOTEE systems off.

5. The COYOTEE sweep speed and distance parameters are set for the test run. The nozzle height would be set or checked.
6. The blasting system would be started and allowed 20 seconds to achieve steady operating conditions. The gas flow rate and pressure would be recorded.
7. The COYOTEE sweep was started and observed until complete. During operation the drice feed rate would be checked by timing the auger rotation speed.
8. The blasted area would be observed, evaluated, and photographed.

● Results:

The overall ROVCO₂ system operated well above the design requirements, providing an effective platform for the test. On the sealant, the CO₂ blasting performed above expectation, averaging 100 sqft/hr. On the epoxy paint, the CO₂ blasting was below the expectations, averaging only 10 sqft/hr. The enhancements in Phase 2 are expected to improve both blasting rates.

CONCEPT TESTING RESULTS		
MATERIAL	DECONTAMINATION RATES ³ (SQFT/HR)	
	MINIMUM	BEST
Concrete Sealant ¹	85	115
Epoxy Paint ²	8.7	12.5

Notes:

- 1) A water emulsion, metal interlock, acrylic copolymer sealant.
- 2) A two-part polyamide-epoxy paint.
- 3) Removal rates varied within a coating, probably due to variation in thickness.

Parameters:

- The Cryogenesis 380 nozzle was used at 1.25" off the surface. Nozzle heights were varied from 0.75" to 2", with 1.25" performing the best.
- Blasting gas flow was kept at 245 scfm. Testing was run from 200 to 275 scfm with little improvement above 240 scfm.
- Drice pellet feed rate was at 2.9 lbs/min. The high rate was used to test, successfully, a new anti-clogging CO₂ hose. Testing was run from 2.0 to 2.9 lbs/min with little improvement above 2.5 lbs/min.
- Success of coating removal was judged visually by the lack of coating left on the surface.

During the first concept demonstration (runs 1 - 10), wet air (a rainy day) and lack of an air dry on the compressor (budget savings against WMC's recommendation) caused ice build-up in the Cryogenesis nozzle decreasing the nozzle velocity and the suction on the CO₂ pellet feed line. The decreased suction limited the CO₂ pellet feed rate, further degrading performance.

For the second concept demonstration, dry N₂ was used for the compressed gas which eliminated the ice build-up and allowed CO₂ pellet feed rates up to 2.9 lb/min. The focus of the second demonstration was ROVCO₂ System operation rather than the blasting rate test.

Budget limitations prevented OTECH from running a complete complement of blasting rate tests. The first objective of the concept demonstration was to show the integrated operation of the ROVCO₂ system. The runs completed are summarized and documented in the following tables.

Description	CO ₂ BLASTING TEST DATA				
	Run #1	Run #2	Run #3	Run #4	Run #11
Coating	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy
X sweep velocity (ips)	1	1	0.5	---	.4
Volume (scfm)	255	255	250	---	250
CO ₂ Rate lbs/min	2.08	2.08	2.08	2.08	2.75
Pressure (psi)	135	139	139	---	145
Nozzle height off floor (inches)	1.5	1.5	0.75	3.5	1
Nozzle size	380	380	380	450	380
Step size	1	1	1	1	.7
% Coating Removed	20	20	75	---	100

Description	CO ₂ BLASTING TEST DATA					
	Run #5	Run #6	Run #7	Run #8	Run #9	Run #10
Coating	Sealant	Sealant	Sealant	Sealant	Sealant	Sealant
X sweep velocity (ips)	0.5	0.5	2	5	7.5	6
Volume (scfm)	370	255	255	260	260	257
CO ₂ Rate lbs/min	2.08	2.08	2.08	2.08	2.08	2.08
Pressure (psi)	125	145	145	145	145	145
Nozzle height off floor (inches)	3.5	1	1	1	1	1
Nozzle size	450	380	380	380	380	380
Step size	1	1	1	1	1	1
% Coating Removed	25	100	100	100	85	95

3.4 COYOTEE Tests

The operation and function of COYOTEE was tested for accuracy of motion and speed. The range of COYOTEE speeds was increased (from 1.15 to 5 ips) to maintain productivity with the decrease in nozzle width (from 3" to ~1").

The objectives of the manipulation tests are to verify the COYOTEE's ability to position and translate the Cryogenesis work-head at a specified rate, and to maintain accuracy within its workspace. Testing can be performed with COYOTEE mounted on the vehicle or bench top. When blasting, the reaction from the nozzle actually reduces the loads on COYOTEE by cancelling the nozzle, work-head, and cursor weight.

- Data: For time measurement a stop watch will be used. The stop watch estimated error is ± 0.1 s or 1.1% (assuming max. cursor speed of 3.5 ips and 33" distance).

The distances will be measured with a tape measure with an estimated error of ± 0.125 " or 0.5% (over 30").

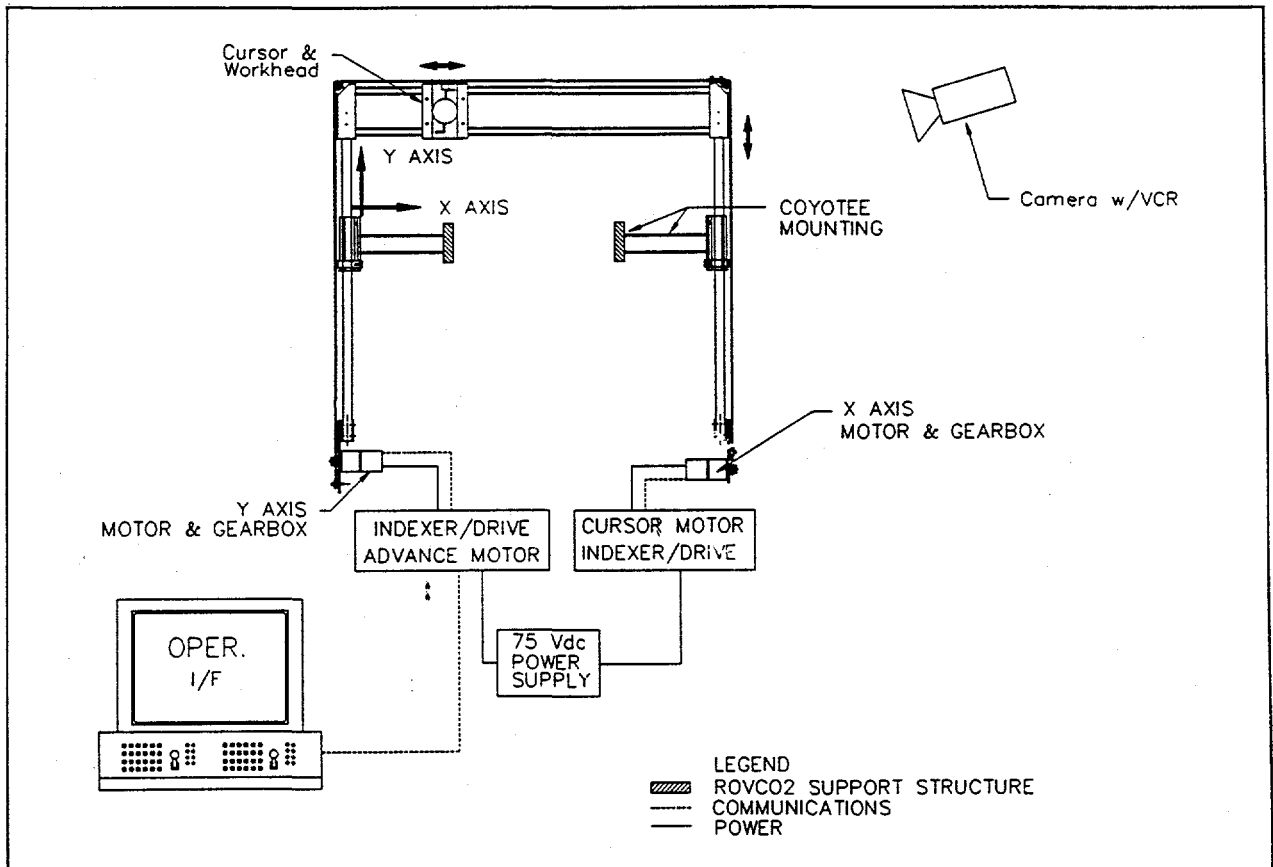


Figure 20 COYOTEE Testing Setup

3.4.1 COYOTEE / Work-head Motion Test

This is a test of the effective deployment of the work-head by COYOTEE. COYOTEE will be run with a marker attached to the work-head, drawing the work-head motion on a paper taped to the floor.

- Data:
Sweep Parameters, Pattern measurement.
- Procedures:
 1. Set-up test (See Figure 20):
 - Power up COYOTEE and OCU,
 - Position work-head to start location, and
 - Set COYOTEE sweep parameters.
 2. Send sweep command.
 3. Measure sweep distance.
 4. Record test personnel comments.

Repeat for three test runs.

- Data Analysis:
Compute average position error.
- Results:
The COYOTEE subsystem was designed for use with a manipulator as well as on floors so it is light-weight and therefore elastic. The motion errors are attributable to the elasticity of the drive wires and the frame. For moves in the Y direction, the COYOTEE frame is slightly racked as the drive wires pull the COYOTEE's following side. The racking is a systematic error introduced when the direction is reversed.

COYOTEE MOTION TEST			
Motion	Distance	Avg. Error	% Error
X Sweep Distance	30"	0.09"	0.29%
Y Increment Distance	1"	0.06"	6.25%
Y Total Distance	20"	0.71"	3.6%

In the testing, the X Sweep and Y Total motions were started from a stop (usually HOME), reversing the previous direction. The large Y Total error is a result of the COYOTEE frame's elasticity during a direction reverse. The Y error in operation can be corrected by altering the HOME function to include a small move back outward to take up the system elasticity.

The Y Increment error was measured from adjacent sweep lines, so there was no prior reversing of direction. The error value is very small (0.06"), though the percentage is larger than the others.

3.4.2 Work Area Measurement

Measure the extent of COYOTEE's work-head movement. COYOTEE, with the marker of the previous test attached, will be run to its four corners.

- Data:
 - Initial final position, comments.
- Procedures:
 1. Set-up test:
 - Mount marker on work-head and paper on floor,
 - Power up COYOTEE and OCU, and
 - Position work-head to start location.
 2. Move the work-head to each corner with the JOG commands.
 3. Measure area traversed by work-head.
 4. Record test personnel comments.

- Results:

COYOTEE WORK AREA TEST		
Axis	Measurement	Target
X	31.5"	30"
Y	21.75"	24"

Note: The Y-axis fell short of the target due to a 3" error in specifying the length of the Y tubes in the fabrication of COYOTEE. With longer tubes we can exceed the 24" target.

The COYOTEE's blasting area is recessed 4.5" from the sides and 3" from the end of the COYOTEE frame. A modification proposed for Phase 2 would eliminate the recess from one side and the end.

3.4.3 Sweep Rate Control

Test the COYOTEE's work-head speed accuracy in the X sweep direction. Measure the distance and time during the constant speed portion of the sweep.

- Data:
Run#, time, distance, sweep command parameters (X & Y rates and distances), comments.
- Procedures:
 1. Set-up test:
 - Power up COYOTEE and OCU,
 - Position work-head to start location,
 - Set the X & Y sweep speed and distance, and
 - Attach pen to work-head and paper to floor.
 2. Sweep COYOTEE
 - After acceleration ends, mark a start time and the position on the paper;
 - Before deceleration starts, mark an end time and the position on the paper; and
 - Record distance between start and end X marks and the time elapsed.
 3. Record test personnel comments.

Perform for minimum two runs at five speeds from 0.6-5 ips

- Results:
The COYOTEE performs quite accurately, except at the slowest speed tested.

COYOTEE SWEEP RATE TEST			
Set Speed ips	Computed ips	Error ips	Error %
0.6	0.758	0.16	26.33%
0.6	0.767	0.17	27.83%
1.5	1.51	0.01	0.67%
1.5	1.52	0.02	1.33%
2.5	2.65	0.15	6.00%
2.5	2.63	0.13	5.20%
3.5	3.24	0.26	7.43%
3.5	3.41	0.09	2.57%
5	4.77	0.23	4.60%
5	4.82	0.18	3.60%
Average		0.14	8.56%
Standard Deviation		0.08	

It is important to note that the deviation of the error in ips is small. The high percentage error at 0.6 ips is due to the systematic error becoming a large part of set speed. The cause of the systematic error remains unresolved despite attempts to adjust and calibrate the subsystem. The errors reversing trend, running fast at slow speeds, and running slow at fast speeds are also anomalous given the linear nature of the stepper motors and drive system. These speed errors have been corrected for in the blasting tests.

3.5 Vehicle Tests

The Vehicle Subsystem was tested carrying the ROVCO₂ system by three tests: positioning, incremental, and maneuvering. The testing was designed to measure the vehicle subsystem's ability to deploy the ROVCO₂ system verifying the positioning of the COYOTEE and gross movement to area to be cleaned. In all the vehicle tests, the operator worked solely from the OCU and was prevented from directly viewing the vehicle or its vicinity during the test.

The vehicle was tested in both full and empty conditions. In the full condition, weights were added to the waste drum and drice hopper to simulate the weights of the filter, vacuum, debris in the drum, and the drice in the Cryogenesis hopper.

3.5.1 Vehicle Positioning and Alignment Test

This test measured the ability of the system and operator to track along a straight path as planned for a ROVCO₂ decontamination operation. The line to be tracked was positioned at the edge of the adjacent cleaning line. The test was run in both fully loaded and empty conditions.

- Data:
Start and end positions, time, video of test.
- Procedures:
 1. Set up: Mark floor with track line, start and end points 30' apart.
 2. Position the vehicle at the start point and measure the position normal to the track line (X_i).
 3. Drive the vehicle along the track line from start point to end point. The operator makes mid-course corrections to continuously maintain the vehicle's position relative to the track line.
 4. Measure the vehicle position normal to the track line (X_i).
 5. Record data and operator comments.

Repeat the test a minimum of three times with a different operator each time.

- Results:
The ROVCO₂ vehicle was relatively easy to drive along a track with a tolerance of 2" by experienced ROV pilots. The operators commented that a gun sight working with the pan and tilt camera would improve accuracy even more.

ROVCO₂ POSITIONING AND ALIGNMENT TESTING

Test #	Positioning Test: ROVCO ₂ fully loaded Description	Data		
		Run #1	Run #2	Run #3
1	Operator	Pilot 1	Engineer	Pilot 2
	- distance (ft)	30'	30'	30'7"
	- time (seconds)	33.54	35.16	37
	- final: desired position X _i (inches)	3	4	6.5
	X _f	4	1.5	6.75
	Y	30	30	30
	$\Delta X = X_f - X_i = >$	1	-2.5	.25
Test #	Positioning test: ROVCO ₂ empty Description	Data		
		Run #1	Run #2	Run #3
2	Operator	Pilot 1	Engineer	Pilot 2
	- distance (ft)	29'7"	30'7"	30'5"
	- time (seconds)	34.85	35.84	35.11
	- final: desired position X _i (inches)	6.5	7.0	8.0
	X _f	7	5.5	11.5
	Y	30'	30'	30'
	$\Delta X = >$	0.5	-1.5	3.5

The average ΔX for all tests was 1.54", which is 0.24° over 30'. The maximum error was 0.6°.

3.5.2 Vehicle Indexing Test

This test measured the ability of the system and operator to move forward an incremental distance along a straight path as planned for ROVCO₂ decontamination operation. The increment was 21" to match the current sweep of COYOTEE. The test was run in the fully loaded condition. The operator relied on the encoder for distance.

- Data:
Start and end positions, time, video of test.
- Procedures:
 1. Set up: Mark floor with track line.
 2. Position the vehicle and mark the start point relative to a fixed pointer attached to the vehicle.

3. Drive the vehicle straight forward to 21" on the encoder. To document possible total error, the overshoots were not corrected.
4. Mark and measure the vehicle position again by the fixed pointer.
5. Record data and operator comments.

- Results:

VEHICLE INDEXING TEST RESULTS					
Run	Target in.	Encoder in.	Measured in.	Error in.	Error %
1	21	21	20.4	0.6	2.7%
2	21	21.1	21.3	0.3	1.2%
3	21	21	20.9	0.1	0.6%
4	21	21.1	20.8	0.3	1.2%
5	21	20.9	21.0	0.0	0.0%
Mean				0.2	1.1%

The calculated error includes operator error in stopping the vehicle.

3.5.3 Vehicle Maneuvering Test

The ability of the ROVCO₂ system to work around obstacles was tested subjectively by the operators positioning the vehicle at a target beyond two obstacles and in positioning the vehicle for the concept demonstrations. The maneuvering test was conducted fully loaded. As in all the vehicle tests, the operator worked solely from the OCU and was prevented from directly viewing the vehicle or the obstacle course during the test. The umbilical was manually handled solely from a position behind the vehicle's initial position simulating the umbilical management system.

- Data:
Video and operator comments.
- Procedure:
 1. Set up (Figure 21): Obstacles were set in an aisle requiring the vehicle to snake around them to progress up the aisle. Two targets were placed in a cross aisle.
 2. The vehicle was moved from an initial position around the obstacles to one of the two targets.
 3. The vehicle was returned to the initial position.

Each of the three operators drove once to each target.

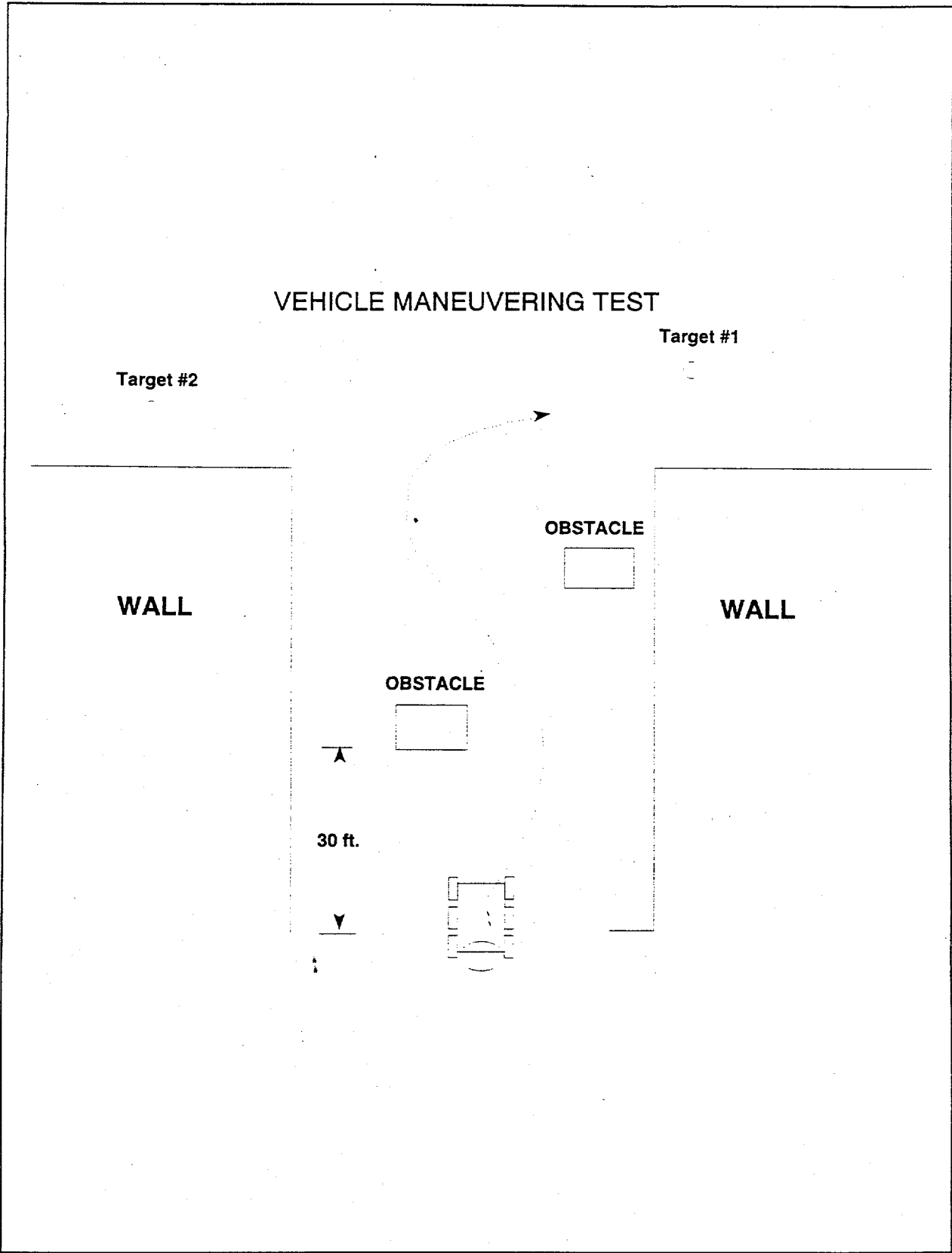


Figure 21 Vehicle Maneuvering Test

- Results:
All of the operators were successful in reaching both targets, without snagging, on the first try. Comments were favorable; the vehicle's ability to turn on a range of radii (from in place to a sweeping turn) was found to be very useful.

Suggestions from the maneuvering test focused on adjusting the positions of the fixed camera and umbilical. All the operators agreed that the fixed camera which was facing back observing the umbilical should face forward as a drive camera. With the fixed camera pointing forward, the umbilical should switch sides to allow observation by the pan and tilt camera. These recommendations were subsequently enacted and used during the concept demonstration.

Comments from the concept demonstration were also favorable with fewer recommendations. The two note-worthy comments recommended switching the COYOTEE home position to below the camera and setting up some gun sights for the camera to aid in positioning for blasting.

3.6 Operator Control Unit Tests

The objectives of the Operator Control Unit (OCU) Tests are to verify that operator commands are properly implemented by the subsystems. The tests will also verify the accuracy and adequacy of the visual and sensor feedback to the operator.

The operator interface proved to be easy to teach to new personnel and efficient in carrying out the testing and concept demonstration. The display provided the operator all the information required for ROVCO₂ operation.

The tests were performed separately for the vehicle controls and the programmable interface that controls all other remote functions. In this section are the tables of the test results and notes.

3.6.1 Programmable Interface Tests

ROVCO ₂ PROGRAMMABLE INTERFACE RESULTS			
TEST PERFORMED	PASS	FAIL	NOTE
User Interface:			
Verify progression through menu hierarchy	X		
Verify F9 returns to main menu from any point	X		
Verify correct key identifiers displayed at each level	X		
Verify content of status display	X		
Verify update validity of status display	X		
Verify correct prompts displayed during user input	X		

ROVCO₂ PROGRAMMABLE INTERFACE RESULTS

TEST PERFORMED	PASS	FAIL	NOTE
Verify correct formatting of user input	X		
Verify correct ranging of user input	X		
Verify correct storage of user input	X		
Verify accuracy of error messages during input	X		
Verify ability to perform ops with only Eason keypad	X		
Verify conversions between in/sec, steps, revolutions	X		1
Blast Functions:			
Verify correct I/O pin used for each device	X		
Verify correct logic level on I/O pin for On/Off	X		
Verify function keys map to correct device	X		
Verify correct ON sequence used for each device	X		
Verify correct OFF sequence used for each device	X		
Verify sequence uses the user-defined time delays	X		
Verify operation of AUTO CO ₂	X		
Verify all devices off in response to ASTOP	X		
Coyotee Functions:			
Verify appropriate strings downloaded to indexers	X		
Verify initialization of drives/indexers	X		
Verify speeds change in response to user input	X		
Verify distances change in response to user input	X		
Verify rotational direction of motors	X		2
Verify proper sequence selection for HOME	X		3
Verify proper sequence selection for HOME OUT	X		3
Verify ability to detect normal finish of HOME moves	X		4
Verify ability to detect activation of limit switches	X		4
Verify proper sequence selection for SWEEP IN	X		5

ROVCO ₂ PROGRAMMABLE INTERFACE RESULTS			
TEST PERFORMED	PASS	FAIL	NOTE
Verify proper sequence selection for SWEEP OUT	X		5
Verify iteration calculations for sweep operations	X		6
Verify last X pass on sweep operations	X		6
Verify detection of normal sweep finish	X		
Verify detection of sweep trigger limit switches	X		
Verify motor rotation direction for sweep operations	X		
Verify able to switch between HOME and SWEEP ops	X		
Verify CSTOP provides smooth shutdown of Coyotee	X		7
Verify ability to resume operations from CSTOP	X		
Verify CSTOP can be activated from any point	X		
Verify ASTOP does immediate shutdown of motors	X		7
Verify ASTOP can be activated from any point	X		
Verify rotation direction of motors in JOG mode	X		2
Verify JOG speed changes in response to SHIFT key	X		8
ROV Functions:			
Verify correct I/O references	X		9
Verify enable/disable logic levels	X		9
Verify ability to read manual speed switch level	X		
Verify automove sequence of operations	X		
Verify automove won't start if speed switch = FAST	X		10
Verify automove terminates if speed switch = FAST	X		10
Verify ROV time calculations	X		11
Verify ROV distance calculations	X		12
Verify ROV move time proportional to distance	X		
Verify operation of ROV STOP			13
Verify operation of ROV RESUME			13

ROVCO₂ PROGRAMMABLE INTERFACE INTEGRATION

TEST PERFORMED	PASS	FAIL	NOTE
Blast Operations:			
Verify I/O pin designations	X		14
Verify On/Off operation for each device	X		
COYOTEE Operations:			
Verify communications between indexers & EASON	X		
Verify proper initialization of drives/indexers	X		
Verify drives stop on limits	X		
Verify ability to JOG in slow speed	X		
Verify ability to JOG in fast speed	X		
Verify HOME moves to inside left corner of grid	X		
Verify HOME OUT moves to outside right corner	X		
Verify SWEEP IN drive sequencing	X		
Verify SWEEP OUT drive sequencing	X		
Verify CSTOP operation	X		
Verify RESUME operation	X		
ROV Operations:			
Verify I/O pin designations	X		9,14
Verify I/O logic levels to actions	X		9
Verify ROV automove disabled if speed is FAST	X		10
Verify proper ROV brake operation	X		
Verify proper ROV automove operation		X	15
Calibration Operations:			
Verify proper X-axis conversion ratio	X		
Verify proper Y-axis conversion ratio	X		
Verify ROV move time / distance ratio		X	15

ROVCO ₂ PROGRAMMABLE INTERFACE INTEGRATION			
TEST PERFORMED	PASS	FAIL	NOTE
Verify Y-axis step distance (1")	X		
Verify sweep distances (X and Y)	X		
Verify blast on/off sequence timing	X		

Notes:

1. All user input is based on inches per second, but all motor commands are expressed in either revolutions per second or steps.
2. X-Axis: Left = Clockwise Right = Counter Clockwise
Y-Axis: In = Clockwise Out = Counter Clockwise
3. HOME moves are accomplished by running sequences stored in the drive indexers at initialization. HOME IN runs sequence number 1 in each indexer and HOME OUT runs sequence number 2 in each indexer.
4. HOME moves are accomplished by setting the drive distances to some value slightly higher than the maximum range for their respective axis. Normally, the move will be completed when the limit for both motors is active. If a limit switch fails, the motor will stall while attempting to move the set distance. The software should be capable of detecting either condition.
5. SWEEP operations (IN or OUT) involve running sequence number 3 in each indexer. Outputs 1 and 2 of each indexer are fed to trigger inputs 1 and 2 of the opposite indexer. The sequences used to accomplish SWEEP operations are cooperative in that commands in one sequence will be used to trigger operations in the other.
6. The sequences used to accomplish SWEEP operations are based on looping structures. The X-axis essentially uses an infinite loop. Each time it receives a trigger it will move the established X distance, reverse direction, trigger the Y indexer, and wait on its next trigger. The Y indexer, in turn, will move in/out one inch then trigger the X sequence. Once the desired Y distance is covered, the X motor will make one last pass.
7. C STOP (COYOTEE Stop) should stop movement of the blast nozzle in an orderly fashion. The active motor will complete its current move and then the movement will stop until the operator selects RESUME or initiates a new operation. A STOP (ALL Stop), on the other hand, brings all systems to an immediate halt.
8. There are two different JOG speeds defined by the user. Just pressing an arrow key will move the blast nozzle in the desired direction at the slow speed. If the SHIFT key is pressed in conjunction with the arrow key, fast speed will be used.

9. This system uses two I/O pins to control ROV automove operations. The ROV brake is pin 9 and the ROV move is pin 17 (refer to interface control document). To move the ROV, the brake must be released by placing a logic high (1) on pin 9 and then the ROV will move as long as a logic high appears on pin 17. To stop the ROV, output a logic low (0) on pin 17 and then reset the brake by placing a logic low on pin 9.
10. This system uses a manual ROV speed switch on the operator's console. If that switch is set to FAST, the ROV automove function should be disabled.
11. The automatic movement of the vehicle is based on a time/distance relationship. The amount of time the automove is enabled is calculated from the ratio of seconds/inch for the ROV. This value is adjustable via the calibration menu.
12. The normal sequence for automove operations is move blast nozzle to HOME, SWEEP OUT, move the ROV, and repeat. This continues until the distance defined by the operator is covered. The amount that the vehicle moves with each iteration is a function of the current Y-axis distance and the desired overlap between sweeps: ROV distance = Y distance - Overlap
13. Bench testing of these functions was not possible because the drives/indexers were not available.
14. Refer to interface control documentation.
15. Testing revealed a problem in attempting to move the ROV based on some time value. In attempting to calibrate the time conversion, sometimes one second would move the ROV one inch and sometimes it would move it six inches. The cause was traced to the period of the OCU to vehicle communication telegram being 48.4 msec, much longer than the acceptable tolerance. The automove operation was removed from the specifications due to insufficient time and funds.

3.6.2 Vehicle Control Verification

VEHICLE CONTROL TEST RESULTS			
TEST PERFORMED	PASS	FAIL	NOTE
Vehicle Motion:			
Verify joystick to wheel relation	X		
Verify straight ahead	X		
Verify joystick brake	X		
Verify vehicle disable	X		

VEHICLE CONTROL TEST RESULTS			
TEST PERFORMED	PASS	FAIL	NOTE
Verify fast/slow functions	X		
Verify auto/manual functions	X		1
Camera Functions:			
Verify joystick to pan & tilt relation	X		
Verify camera selection	X		
Verify focus in/out	X		
Verify iris open/close	X		
Verify zoom in/out	X		
Verify lights dim/bright	X		
Verify overlay off/on-reset	X		

Notes:

1. The auto/manual switch worked. The ability to control vehicle motions forward was too crude, as noted under programmable interface testing Note 15, the function disabled.

3.6.3 OCU Display & Sensor Tests

DISPLAY & SENSOR TESTS			
TEST PERFORMED	PASS	FAIL	NOTE
Video display usable to operator	X		
Encoder useful for distance control	X		1
Temperature sensor	X		2
Temperature display	X		
Pressure sensor	X		
Pressure display	X		

Notes:

1. The encoder's accuracy was 1.2% was measured as part of the Vehicle Indexing test.

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2. The temperature sensor was successfully tested during system integration. During the concept demonstration, it stopped working, apparently for electrical reasons, and has not been repaired.

3.7 Decontamination and Sealing

The Decontamination and Sealing of the ROVCO₂ system was accomplished by ensuring that each of the components was decontaminated and sealed. Most of these components are sealed or solid with metal surfaces that aid decontamination. Some pieces, such as the tires, would have to be scraped to get the system fully decontaminated.

In discussions with Oak Ridge, it was learned that decontamination to free release is a problematic and unwarranted goal. Decontamination tools such as ROVCO₂ are often kept in Radioactive Control Areas (RCA's) and transported as contaminated equipment rather than going through the effort and cost of full decontamination. The change to a goal of aiding and being impervious to decontamination processes reduces the ROVCO₂ system cost and complexity.

The ROVCO₂ system is fully decontaminable with a minimal amount of sacrificed pieces as waste, these being mostly rubber seals and tires. The majority of the system can be decontaminated by the Cryogenesis blasting system with the exception of small tubes and the Cryogenesis unit itself.

Below, the specifics of decontaminating each subsystem are discussed.

- Vehicle Subsystem:

The ANDROS 6x6 has been successfully used in radioactive control areas and previously released after decontamination according to Remotec, the manufacturer. The enclosures are fully sealed against intrusion. Made of 6061 aluminum, it can support most types of decontamination. The rubber tires and seals are the exception, and must be disposed of as waste if complete decontamination is to be achieved.

- Cryogenesis CO₂ Blasting Subsystem:

The Cryogenesis subsystem is made of stainless steel that would tolerate decontamination. The supply unit does have a number of parts that would require disassembly for full decontamination.

The control valves are sealed to NEMA-4 specifications and can also be disassembled. The rubber seals would be disposed of as waste in a complete decontamination.

- COYOTEE Subsystem:

The COYOTEE Subsystem is made of 6061 aluminum and will tolerate disassembly and decontamination. Some of the drive components, such as the idler pulleys and drive wire, would be disposed of as waste in a complete decontamination.

- ROVCO₂ Support Structure:

The ROVCO₂ frame is bolted together from 3" C channel and plate of 6061 aluminum. The bolt together design allows disassembly for easy access during decontamination.

C

4.0 CONCLUSIONS AND DISCUSSION

Phase 1 of the ROVCO₂ program has resulted in the development of a system that has been tested and demonstrated to remotely remove coatings from floors. With few exceptions, the ROVCO₂ system exceeds its contractual Success Criteria and works as proposed (see the Success Criteria Results table below). The greatest success for OTECH is having again produced a remote work vehicle that functions as specified. This success is clearly illustrated in the concept demonstration video tape.

In the ROVCO₂ Phase 1 work, the following have been achieved:

- Technical Achievements:
 - The system requirements have been specified and allocated to the subsystems and components. The ROVCO₂ system layout has been optimized to meet the requirements by mounting the blasting and vacuum subsystems on the vehicle with remote controls.
 - The Cryogenesis CO₂ blasting subsystem has been adapted to the ROVCO₂ system including automated remote control and mounting on the vehicle.
 - An improved Cryogenesis nozzle was developed and tested. The new nozzle provides extremely aggressive CO₂ blasting with calculated pellet velocities of up to 1,100 fps.
 - A vacuum work-head was selected, adapted to accept the new Cryogenesis nozzle, and mounted on the COYOTEE.
 - A COYOTEE was produced and tested. The test results show that the COYOTEE exceeded Success Criteria and specification for manipulation in accuracy and speed.
 - A vehicle subsystem was selected and integrated into the ROVCO₂ system exceeding the Success Criteria for mobility.
 - An integrated control system was developed based on a programmable interface that integrates and functionally automates ROVCO₂ operation meeting the Success Criteria. Sensors were selected and integrated into the control system.

- Milestones and Deliverables:

All the contract milestones and deliverables have been completed and delivered.

- The Kickoff meeting at METC was held on December 15, 1993,
- The Design Review meeting was held March 10, 1994,
- Development was completed May 17th,

- The Test Plan was delivered May 5th,
- The Subsystem Testing was completed May 20th,
- The Concept Demonstration was completed June 10th, and
- The draft Topical Report was delivered July 27th.

OTECH has not been asked to prepare a briefing for the mid-year review. The Robotics University and Industry forum was held in August this year and OTECH attended for the ROVCO₂ program.

4.1 Success Criteria Performance

The performance of the developed ROVCO₂ system to each of the success criteria is tabulated below.

TABLE OF SUCCESS CRITERIA PERFORMANCE	
SUCCESS CRITERIA	PERFORMANCE
1.1 Mobility	
1.1.1 The ROVCO ₂ vehicle shall be capable of traversing smooth concrete floors to grossly position the CO ₂ blasting system.	In the Vehicle Positioning Test and the Maneuvering Test, the ROVCO ₂ system was shown to easily maneuver on concrete floors including avoiding obstacles. It was also shown to climb 4" curbs and cross 6" trenches.
1.1.2 The ROVCO ₂ vehicle shall be capable of indexing forward, under manual control, to sequential blast areas to a tolerance of ± 5 ".	The Vehicle Indexing Test found an average indexing tolerance of 0.2" or 1.1% for the ROVCO ₂ vehicle. The error is random so it would not accumulate over sequential vehicle indexing.
1.2 Manipulation	
1.2.1 The ROVCO ₂ work arm shall be capable of effectively deploying the CO ₂ blasting nozzle and vacuum work-head.	The COYOTEE/Work-head Positioning Test and the Concept Demonstration proved that the work-head is effectively deployed by COYOTEE with average position accuracies of 3.4%

TABLE OF SUCCESS CRITERIA PERFORMANCE

SUCCESS CRITERIA	PERFORMANCE
1.2.2 The ROVCO ₂ work arm shall sweep an area 24"x 30" (720 sqin) without holidays in the pattern.	The Work Area Measurement found that COYOTEE only reaches an area 21.75" x 31.5" due to an error in specifying the Y tube length. The swept area is 0.8" larger due to the nozzle width so the swept area is 22.5" x 32.3" = 728 sqin, exceeding the specified sweep area. Y tubes of the correct length will be added in Phase 2.
1.2.3 The ROVCO ₂ work arm shall sweep at a controllable rate ranging from 0.6 to 3.45 inches per second (ips) in linear motion. [Modified with METC's consent in conjunction with 1.5.1. See Appendix A.]	The Sweep Rate Control Test found that the COYOTEE could sweep the work-head at rates from 0.6 to 5 ips with an average accuracy of 0.14 ips. The Sweep Rate Control Testing range was increased to accommodate the decrease in nozzle width from 3" to ~1".
1.3 Operator Control Unit (OCU)	
1.3.1 The OCU shall provide simple yet effective control of all ROVCO ₂ remote functions, including vehicle driving, CO ₂ blasting, and camera adjustment.	The Control Verification Tests verified that the OCU provides control of all ROVCO ₂ functions. In the Concept Demonstration, it was shown that a single operator can easily work the ROVCO ₂ system.
1.3.2 The OCU shall provide the operator with adequate visual and sensor feedback to perform and monitor vehicle deployment and CO ₂ blasting operations.	The OCU Feedback, including visual and sensor feedback, was evaluated by the operator during the testing and demonstration as very good. It allowed full monitoring of ROVCO ₂ systems during all operations.
1.4 Sensing	
1.4.1 ROVCO ₂ shall be equipped with driving and decontamination monitoring cameras.	This was verified by the operators in the testing and Concept Demonstration as described in 1.3.2 above.

TABLE OF SUCCESS CRITERIA PERFORMANCE	
SUCCESS CRITERIA	PERFORMANCE
1.5 CO ₂ Blasting	
1.5.1 ROVCO ₂ 's CO ₂ blasting nozzle, when deployed effectively by ROVCO ₂ 's manipulator, shall remove paint from a concrete surface at a productive rate. [Modified with METC's consent in conjunction with 1.2.3. See Appendix A.]	The CO ₂ Blasting Tests removed coatings from concrete very effectively. Removal rates of up to 115 sqft/hr for concrete sealant and 12.5 sqft/hr for epoxy paint were documented.
1.5.2 The ROVCO ₂ system shall function with blasting gas volumes ranging from 200 to 275 scfm and dry ice pellet rates of 2.5 lbs/min.	The Verification of Blast Parameters for the ROVCO ₂ system covered the range of 200 to 370 scfm of blasting gas and 2.1 to 2.9 lbs/min of dry ice pellets.
1.6 Decontaminability & Sealing	
1.6.1 The ROVCO ₂ vehicle/manipulator shall be sealed to prevent dust, dirt, or water infiltration of vehicle interior cavities.	The ROVCO ₂ system has been developed and demonstrated to be sealed against infiltration and to meet the requirements for decontamination of the system.

4.2 Conclusions

The Phase 1 development of the ROVCO₂ system was a great success. The hardware was designed and produced exceeding the Phase 1 Success Criteria and making substantial progress toward meeting many of the Phase 2 and 3 Success Criteria.

OTECH has devoted substantial effort conferring with the OTD and D&D personnel at the Oak Ridge K-25 site to ensure ROVCO₂ meets the real requirements at the site. The results of Oak Ridge's input can be seen, for example, in the positioning of the waste drum for easy handling. The ROVCO₂ system can be a valuable tool for D&D.

In Phase 2 of the ROVCO₂ program, the non-developmental components will be added, improvements made, and reliability and productivity testing conducted. The result will be a proven tool ready for the Phase 3 Integrated Demonstration and commercial use.

5.0 BIBLIOGRAPHY

The following documentation is related to, and required for, software development for ROVCO₂:

- Programmable Interface:
 1. Eason Technology Model 1000 Smart Operator Interface User's Manual, and
 2. Eason Basic User's Guide.
- Motors:
 1. Compumotor Software Reference Guide (OEM 650X), and
 2. Compumotor Drive/Drive Indexer User's Guide (OEM 650X).
- Vehicle:
 1. Remotec, ANDROS 6x6 Operation and Maintenance Manual.
- CO₂:
 1. Waste Minimization and Containment, Operations Manual for Cryogenesis Model 1350-2.

Appendix A — PHASE 1 SUCCESS CRITERIA

1.1 Mobility

- 1.1.1 The ROVCO₂ vehicle shall be capable of traversing smooth concrete floors to grossly position the CO₂ blasting system.
- 1.1.2 The ROVCO₂ vehicle shall be capable of indexing forward, under manual control, to sequentially blast areas to a tolerance of ± 5 ".

1.2 Manipulation

- 1.2.1 The ROVCO₂ work arm shall be capable of effectively deploying the CO₂ blasting nozzle/vacuum work-head.
- 1.2.2 The ROVCO₂ work arm shall sweep an area 24"x 30" without holidays in the pattern.
- 1.2.3 The ROVCO₂ work arm shall sweep at a controllable rate ranging from 0.6 to 1.15 inches per second in linear motion. [Modified with METC's acknowledgement in conjunction with 1.5.1 to a range of 0.6 to 3.45 ips.]

1.3 Operator Control Unit (OCU)

- 1.3.1 The OCU shall provide simple and effective control of all ROVCO₂ remote functions, including vehicle driving, CO₂ blasting, and camera adjustment.
- 1.3.2 The OCU shall provide the operator with adequate visual and sensor feedback to perform and monitor vehicle deployment and CO₂ blasting operations.

1.4 Sensing

- 1.4.1 ROVCO₂ shall be equipped with driving and decontamination monitoring cameras.

1.5 CO₂ Blasting

- 1.5.1 ROVCO₂'s CO₂ blasting nozzle, when deployed effectively by ROVCO₂'s manipulator, shall remove paint from a 3" strip of concrete surface at a pass. [Modified with METC's acknowledgement in conjunction with 1.2.3 to remove a 1" strip of paint at a pass.]
- 1.5.2 The ROVCO₂ system shall function with blasting gas volumes ranging from 200 to 275 scfm and dry ice pellet rates of 2.5 lbs/min.

1.6 Decontaminability & Sealing

- 1.6.1 The ROVCO₂ vehicle/manipulator shall be sealed to prevent dust, dirt, or water infiltration of vehicle interior cavities.

Appendix B — SAFETY FOR THE ROVCO₂ SYSTEM

- Hazards
 - Collision:
The ROVCO₂ vehicle will weigh up to one ton and is powered by six motors with high gear reductions. Collisions with personnel or property will cause damage!
 - Asphyxiation:
The ROVCO₂ blasting system uses CO₂ pellets and may use N₂ blasting gas. Personnel confined in an area with the operating blasting system could be asphyxiated.
 - Abrasion:
The ROVCO₂ blasting system shoots a very high velocity jet of CO₂ pellets and compressed gas to remove surface material. Personnel or property hit by the jet may be hurt.
 - Noise:
The ROVCO₂ blasting system uses high volumes of high pressure gas creating noise above acceptable levels. Personnel near the blasting could suffer hearing loss.
 - Dust:
The ROVCO₂ blasting system can blow up dust if the vacuum containment system is ineffective. Personnel in the area could be exposed to unacceptable levels of particulates.
 - Electrical:
The ROVCO₂ system is electrically powered and in a mishap has the potential to shock personnel in contact with the vehicle or console.
- Precautions
 - Operators:
The ROVCO₂ system is only to be operated by personnel thoroughly trained and familiar with the system and its hazards. The operator is responsible for ensuring that safety precautions are followed by all personnel working in the vicinity of the system.
 - Electric Power:
The ROVCO₂ system will only be operated from properly grounded power sources. Power will be shut off, locked or disconnected, and drained before performing any servicing.

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- **Vehicle Movement:**
The vehicle will only be driven either with an operator escort to warn traffic or in areas inaccessible to other traffic. When transversing traffic areas, the escort must be able to communicate with the driver.
 - **Blasting Operation:**
The blasting system will only be operated in areas with sufficient ventilation to ensure adequate O₂ supply to personnel or in isolated areas sealed and marked to prevent personnel entry. When operating with compressed air, operators may determine that the blasting air is sufficient ventilation.

The blasting system will be operated only when the nozzle is securely held in position, and with some contaminant system for the blast created debris.

Operators will ensure that all personnel in the area of blasting activity have personnel safety protection for hearing, eyes, and breathing.

Appendix C — ROVCO₂ CONTROL SOFTWARE SPECIFICATION

The ROVCO₂ control software shall provide the following services and meet the following specifications:

- Operational Parameters:
 1. Operator shall be able to define distance traveled along the X-axis during SWEEP operations.
 2. Operator shall be able to define distance traveled along the Y-axis during SWEEP operations.
 3. Operator shall be able to define the speed of travel along the X-axis during SWEEP and HOME operations.
 4. Operator shall be able to define the speed of travel along the Y-axis during SWEEP and HOME operations.
 5. Operator shall be able to define fast and slow speeds used during JOG operations.
 6. Operator shall be able to define total vehicle straight line travel during automatic mode operation.
 7. Operator shall be able to define amount of overlap between successive SWEEP operations when system is operated in automatic mode.
 8. Operator shall be able to define time delays used when sequentially enabling blast devices.
 9. Operator shall be able to define time delays used when sequentially disabling blast devices.
 10. Operator shall be able to enable/disable a feature which will automatically turn the CO₂ discharge off when blast nozzle motion is terminated.
 11. All user input shall be in terms of inches, seconds, and inches/sec. and then converted to appropriate step and revolution values.
 12. Operator shall be able to define described values at any time, unless conflicting operations are active.
 13. Operator input shall be validated to prevent out of range values from being entered.
 14. Ranges shall be prominently displayed during input operations.
 15. Automatic correction or meaningful error messages shall be displayed if out of range values are entered by the operator.
 16. Operator defined parameters shall be stored in nonvolatile memory to alleviate the need for redefinition each time the system is powered on.

- COYOTEE Operations:

1. The system shall provide four basic modes of blast nozzle positioning: HOME, HOME OUT, SWEEP IN, SWEEP OUT, and JOG.
2. Selecting HOME shall position the blast nozzle at the extreme inside left corner of the motion grid.
3. Selecting HOME OUT shall position the blast nozzle at the extreme outside right corner of the motion grid.
4. Selecting SWEEP IN shall advance the blast nozzle from its current position toward the HOME position. The distance traveled along each axis, and the speed of travel along each axis, shall be in accordance with those parameters defined by the operator.
5. Selecting SWEEP OUT shall advance the blast nozzle from its current position toward the HOME OUT position. The distance traveled along each axis, and the speed of travel along each axis, shall be in accordance with those parameters defined by the operator.
6. Normal operation shall be terminated with an appropriate error message if a limit is encountered during SWEEP operations.
7. With the exception of CO₂ auto-off at COYOTEE stop, the state of the blast devices shall be independent of nozzle positioning.
8. Unless operating in automatic mode, the system shall return to idle state upon completion of a SWEEP or HOME operation with the blast nozzle remaining in the stop position.
9. Operator shall be able to pause blast nozzle motion at any point by activating CSTOP feature. This is an orderly shutdown of the COYOTEE system. Any active move, along either axis, shall be allowed to complete before motion is stopped.
10. Operator shall be able to resume operation from a CSTOP action. Any interrupted SWEEP or HOME operation shall be resumed from the current position and complete as though it had not been interrupted.
11. CSTOP shall effect only movement of the blast nozzle. The vehicle state and blast devices shall be unaffected.
12. JOG mode operation shall provide the operator with keypad positioning of the blast nozzle. Activation of an arrow key on the programmable interface keypad shall move the blast nozzle in the associated direction until the key is released or a limit is encountered.
13. JOG mode positioning can be conducted at two rates of speed. If only an arrow key is pressed, the nozzle will move at the slow rate of speed defined by the operator. If the SHIFT key is pressed in conjunction with the arrow key, the nozzle will move at the fast rate of speed defined by the operator.
14. JOG mode operation is disabled during automatic mode operation but is independent of blast device state.

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- Blast System Operation:
 1. The operator shall be able to enable or disable each of the blast system devices.
 2. The state of each device is not independent of other devices. The vacuum must be on if the blast gun is on, and the gun must be on if the CO₂ is on.
 3. The system shall be capable of auto sequencing the blast system devices. If the operator attempts to enable a device when other devices that should already be enabled are not, then the system shall automatically enable those devices prior to enabling the selected device. This shall apply to the disabling of devices also.
 4. If automatic enabling or disabling of devices is employed, the time delays defined by the operator shall be used between enabling or disabling successive devices.
 5. If the operator has enabled the CO₂ auto-off feature, the CO₂ unit shall be disabled when blast nozzle movement is terminated.

 - ROV Operation:
 1. The system shall provide the operator with a totally automated means of operation. When operating in this mode the system shall run the following sequence:
 - a. Move the blast nozzle to HOME using the X- and Y-axis speeds defined by the operator.
 - b. Perform a SWEEP OUT in accordance with the operator defined parameters for speed and distance.
 - c. Move the vehicle forward in a straight line. The distance is calculated based on the current Y-axis SWEEP range and the amount of overlap defined by the operator.
 - d. Repeat A,B, and C until the total vehicle distance defined by the operator is covered.
 2. Automatic operation shall be disabled if the manual ROV speed switch is set to FAST.
 3. The operator shall be able to pause movement of the vehicle during automatic mode operation. Operational parameters may not be reset while the system is paused.
 4. The operator shall be able to resume automatic operation when the system is paused. The parameters established when automatic operation was enabled are used and the operation continues to a normal completion.

- General Operations:

1. The system shall provide an all stop (ASTOP) feature allowing the operator to immediately disable all systems. Blast nozzle movement will be immediately terminated, all blast devices will be disabled, and vehicle movement will stop.
2. Activation of ASTOP is unrecoverable. All operations are immediately halted and can not be resumed from the point of termination.
3. The operator shall be able to return to the main menu from any point in the program by pressing F9 on the keypad.
4. The operator shall be provided with a facility to reset the COYOTEE unit using the current operational parameters or the default values stored in the program.
5. The operator shall be able to reset the entire system. This will be especially useful should battery power be lost in the programmable interface.
6. The operator shall be provided with a facility for testing communications between the programmable interface and the drives/indexers.

- System Calibration:

1. The system shall provide a means of adjusting the slope and intercept of the linear transform used to convert for inches and inches/second to revolutions and steps.
2. Calibration of the X- and Y-axis transforms shall be independent of one another.
3. Movement of the ROV will be accomplished by enabling the automove output for some calculated amount of time. The amount of time is based on a ratio (inches/second) stored within the software. The system shall allow for the calibration of this time ratio.

Appendix D — LIST OF ACRONYMS AND INITIALISMS

CG	Center of Gravity
COTS	Commercial-off-the-shelf
COYOTEE	CO ₂ xY Orthogonal Translational End Effector
D&D	Decontamination and decommissioning
DOE	U.S. Department of Energy
Drice	Dry Ice
HEPA	High Efficiency Particulate Air
INEL	Idaho National Engineering Laboratory
IRAD	Internal Research and Development
METC	Morgantown Energy Technology Center
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
OCU	Operator Control Unit
OR	Oak Ridge
OTD	Office of Technology Development
OTECH	Oceaneering Technologies, Inc.
R&D	Research and Development
RCA	Radiological Control Area
RFP	Request for Proposal
ROVCO ₂	Remote Operated Vehicle with CO ₂ Blasting
WMC	Waste Minimization & Containment