DOE/MC/30165 -- 5256
(DE96011354)

Remote Operated Vehicle With CO2 Blasting (ROVCO2)
Volume 1

Final Report
September 1993 - July 1996

June 1996

Work Performed Under Contract No.: DE-AC21-92MC30165

For

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Oceaneering Technologies
501 Prince George's Boulevard
Upper Marlboro, Maryland 20772

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ABSTRACT

This report documents the second phase of the Remote Operated Vehicle with CO_2 Blasting (ROVCO_2) Program. The ROVCO_2 Program's goal is to develop and demonstrate a tool to improve the productivity of concrete floor decontamination. The second phase integrated non-developmental subsystems on to the ROVCO_2 system and performed quantitative decontamination effectiveness, productivity, and reliability testings. The report documents these development activities and the analysis of cost and performance. The results show that the ROVCO_2 system is a efficient decontamination tool.

ACKNOWLEDGMENTS

The ROVCO_2 team of Oceaneering Technologies, Inc. and Waste Minimization and Containment, Inc. would like to thank the personnel at the US Department of Energy's (DOE) Morgantown Energy Technology Center (METC), Oak Ridge Operations Office, Martin Marietta Energy Systems personnel at Oak Ridge, and Westinghouse Hanford Company personnel at the Hanford Site for their assistance in understanding the problem and focusing the ROVCO_2 development. The ROVCO_2 team is appreciative of the program funding by the DOE's Office Of Science and Technology under a Program Research and Development Announcement contract from METC.

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EXECUTIVE SUMMARY

Introduction

The Remote Operated Vehicle with CO_2 Blasting ($ROVCO_2$) Program has developed a tool for efficient decontamination of concrete floors. Oceaneering International, Inc. (Oceaneering) has led its team in the design, production, integration, testing, and demonstration of the critical subsystems of the $ROVCO_2$ system.

At the end of Phase 2 of the $ROVCO_2$ Program all but one of the success criteria were achieved. The $ROVCO_2$ system was shown in testing to effectively and productively remove coatings and contaminants from concrete floors achieving:

- Removal rates of 98% for smearable and 75% for the fixed contamination,
- Productivity rates averaging 52.5 square feet per hour on epoxy paint and concrete sealant,
- Tested availability of over 85%, and
- Estimated operational cost of $0.72 per square foot including waste disposal.

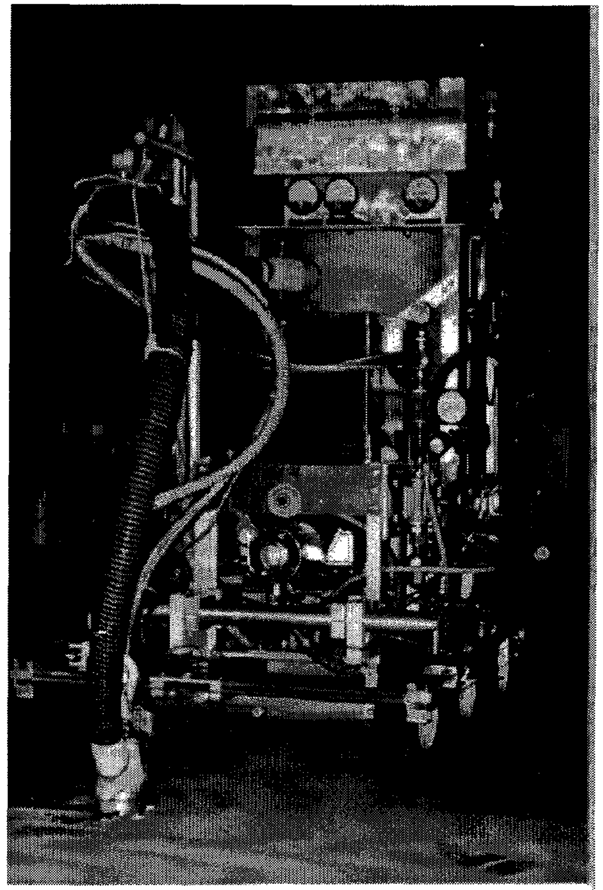

Figure EX-1: The $ROVCO_2$ vehicle in productivity testing at the end of phase 2.

In phase 2 the off-the-shelf subsystems consisting of Vacuum/Filter/Containment System and the Tether Management System (TMS) were integrated onto the $ROVCO_2$ system. The winch, slip ring, and vacuum/filter system were all procured form commercial vendors. Oceaneering's innovations kept the program within budget by inexpensively making the TMS umbilical in-house when vendors' bids were beyond the budget. When Oceaneering discovered in testing that the vendor's containment workhead would not perform as advertised we responded to keep the program on track. To correct the workhead containment Oceaneering revised the test schedule, designed a workhead based on a different principle, fabricated a prototype, tested the prototype, analyzed the test results, and developed a final containment workhead design that we propose for the next phase all within budget. The only success criterion we didn't achieve is a direct result of the non-performance of the commercial workhead.

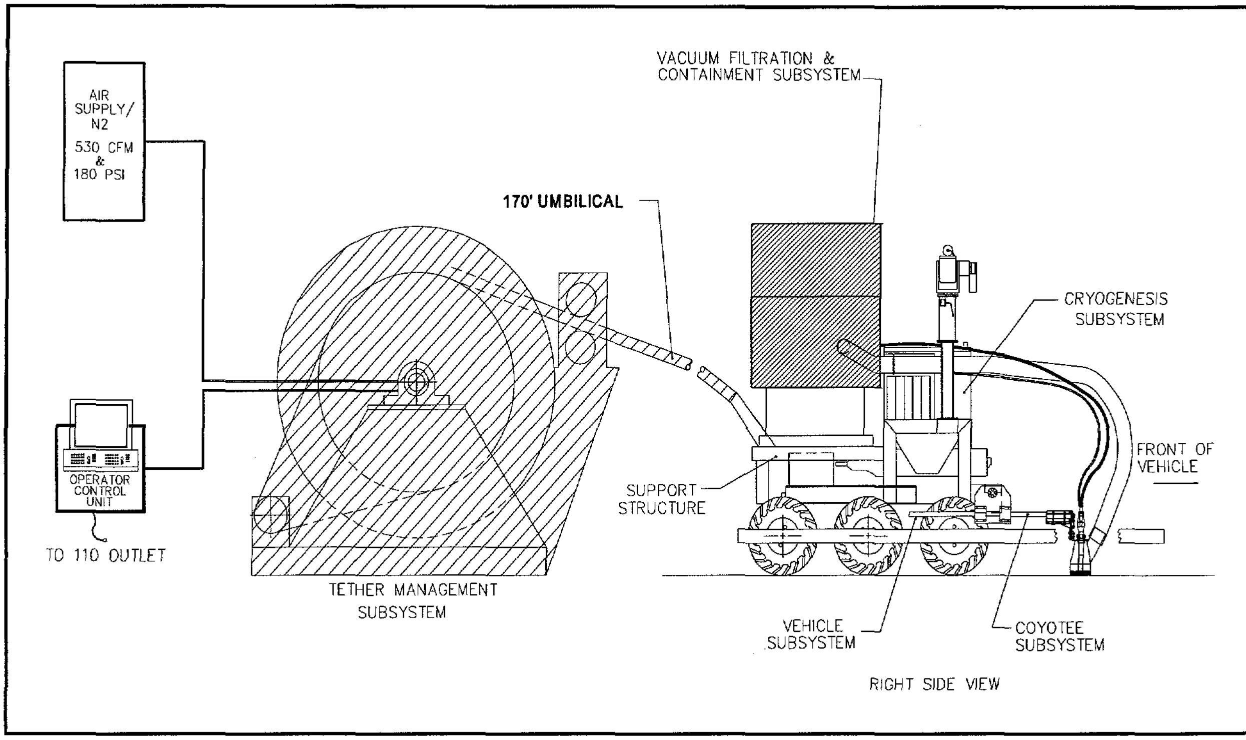

Figure EX-2: Subsystems integrated into the $ROVCO_2$ system during phase 2

The testing in Phase 2 quantified all $ROVCO_2$ performance parameters including:

- Decontamination effectiveness with laboratory tests measuring surrogate contaminants at realistic levels,
- Productivity with large area coating removal tests on both epoxy paint and concrete sealant, and
- Reliability and availability with analysis and long duration operation of the system.

The testing has documented the success of the $ROVCO_2$ development.

1.0 INTRODUCTION

This report documents work performed by Oceaneering Technologies, a division of Oceaneering International, Inc., (Oceaneering) during phase 2 of its development program, A Remote Operated Vehicle with CO_2 Blasting (ROVCO_2). The ROVCO_2 program was founded and managed by the Morgantown Energy Technology Center (METC) of the US Department of Energy. All criteria for reporting as required by the Department of Energy (DOE) have been satisfied; namely, the report provides

- a statement of the original objectives;
- a concise summary of progress achieved to date;
- a full account of current progress including enhancements, changes, and accomplishments;
- an overview of testing and results;
- a description of problems encountered;
- plans for the next reporting period;
- an economic evaluation; and,
- conclusions.

This report is organized by including the following:

- Chapter 1: A summary of phase 1
- Chapter 2: Details of the work accomplished in phase 2
- Chapter 3: Descriptions of the phase 2 tests performed and their results
- Chapter 4: Evaluation of the economic aspects of the system
- Chapter 5: Phase 2 conclusions

The remainder of this chapter includes the background and objectives of the program and the phase 1 objectives, progress, major decisions, and technical achievements. Chapter 2 includes the two subsystem additions and the four subsystem enhancements accomplished during phase 2. Chapter 3 includes the descriptions of the testing procedures and results for the system's productivity, effectiveness, and reliability. Chapter 4 includes the operational and capital costs of the system. The conclusions of phase 2 including the technical achievements and performance of the system are presented in chapter 5.

Under separate cover, a proposal for work to be performed in the final phase addresses how Oceaneering will complete the development contract's requirements and how the ROVCO_2 system will be used at DOE sites.

1.1 Program Background and Objectives

The ROVCO_2 program was propose DOE requirement for concrete floor decontamination at the Oak Ridge K-25 site. Oceaneering teamed with Waste Minimization and Containment

Services, Inc. (WMC) to respond. The program's objectives are

- reduced decontamination costs,
- reduced waste volume,
- reduced worker exposure to contaminants,
- improved decontamination effectiveness, and
- faster decontamination of floors.

The development program has been contracted in three phases. In phase 1, critical subsystems including carbon dioxide blasting, the vehicle, manipulation, and controls were developed, integrated, and tested. In phase 2, the vacuum, filtration, and containment subsystems were integrated and the system, itself, tested for productivity, reliability, and effectiveness. In phase 3, the entire system will be tested in a contaminated environment. Throughout the development, Oceaneering and WMC have relied on input from the potential end user, the decontaminating and decommissioning site personnel at Morgantown Energy Technology Center.

1.2 Summary of Phase 1

The development of the critical subsystems during phase 1 followed a typical design engineering timetable and sequence of events from the time of system requirements definitions and subsystem development and integration to the system test. The topical report submitted at the end of phase 1, "Phase 1 Report of the Remote Operated Vehicle with CO_2 Blasting ($ROVCO_2$)," dated October 1, 1994, presents the step-by-step design and development of major systems, input to the final decisions, analysis and explanation of each subsystem and its functional allocation, testing analysis, and results and conclusions. A videotape of the concept demonstration, *The Concept Demonstration for the Remote Operated Vehicle with CO_2 Blasting System,* recorded on June 9, 1994, supports and clarifies the testing section of the topical report.

1.2.1 Phase 1 Concept Demonstration

The $ROVCO_2$ program successfully completed its first phase, meeting or exceeding all success criteria, during the concept demonstration. At that demonstration, the integrated $ROVCO_2$ system was navigated by an operator stationed at a remote console who used only cameras mounted on the vehicle to remove coatings from a concrete floor.

During the concept demonstration, six important characteristics were tested against their respective success criteria. The vehicle was tested for its mobility; the workhead, for its maneuverability; the operator control unit, for effective remote control of all functions; the cameras, for adequacy of visual feedback; the blasting nozzle for effective operation; and, the system's ability, to resist contamination. In table 1 the $ROVCO_2$ system's performance during the test is compared to its respective success criteria.

Table 1: The Success of $ROVCO_2$ during Phase 1 Testing

SUCCESS CRITERIA	PERFORMANCE
1. Mobility	
The $ROVCO_2$ vehicle shall be capable of traversing smooth concrete floors to grossly position the CO_2 blasting system.	In both the vehicle positioning test and the maneuvering test, the system easily maneuvered on concrete floors; avoided obstacles; climbed 4-in. curbs; and crossed 6-in. trenches.
The $ROVCO_2$ vehicle shall be capable of indexing forward, under manual control, to sequential blast areas to a tolerance of ± 5 in.	During the vehicle indexing test, an average indexing tolerance of 0.2 in. or 1.1% for the $ROVCO_2$ vehicle was documented. The error is random; it will not accumulate over sequential vehicle indexing.
2. Manipulation	
The $ROVCO_2$ work arm shall be capable of effectively deploying the CO_2 blasting nozzle and vacuum workhead.	During the COYOTEE/workhead positioning test and the concept demonstration, the workhead was effectively deployed by COYOTEE with average position accuracies of 3.4%.
The $ROVCO_2$ work arm shall sweep an area 24 in. x 30 in. (720 sq in.) without holidays in the pattern.	During the work area measurement test, the COYOTEE only reached an area 21.75 in. x 31.5 in., due to an error in specifying the *Y*-tube length. The nozzle's width increases the swept area by 0.8 in. Final swept area was is 22.5 in. x 32.3 in. = 728 sq in., exceeding the specified sweep area. *Y*-tubes of the correct length will be added in phase 2.
The $ROVCO_2$ work arm shall sweep at a controllable rate ranging from 0.6 to 3.45 in. ips in linear motion. [Modified with METC's consent]	During the sweep rate control test, the COYOTEE moved the workhead 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 in. to ≈1 in.
3. Operator Control Unit (OCU)	
The OCU shall provide simple yet effective control of all $ROVCO_2$ remote functions, including vehicle driving, CO_2 blasting, and camera adjustment.	During the control verification tests, the OCU controlled all $ROVCO_2$ functions. During the concept demonstration, a single operator easily controlled the $ROVCO_2$ system.
The OCU shall provide the operator with adequate visual and sensor feedback to perform and monitor vehicle deployment and CO_2 blasting operations.	During the testing and demonstration, the operator evaluated the OCU feedback as very good. Visual and sensor feedback allowed full monitoring of $ROVCO_2$ systems during all operations.
4. Sensing	
$ROVCO_2$ shall be equipped with driving and decontamination monitoring cameras.	This configuration was verified by the operators in the testing and concept demonstration.
5. CO_2 Blasting	

SUCCESS CRITERIA	PERFORMANCE
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]	During the CO_2 blasting tests, coatings were removed from the concrete at removal rates of up to 115 sq ft/hr for concrete sealant and 12.5 sq ft/hr for epoxy paint.
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.	During the verification of blast parameters, ranges from 200 to 370 scfm of blasting gas and from 2.1 to 2.9 lbs/min of dry ice pellets were documented.
6. Decontaminability and Sealing	
The ROVCO$_2$ vehicle/manipulator shall be sealed to prevent dust, dirt, or water infiltration of vehicle interior cavities.	The ROVCO$_2$ system was developed and demonstrated to be sealed against infiltration and to meet the requirements for decontamination of the system.

From the overall results of phase 1, three categories evolved: major decisions affecting scope and cost, technical achievements, and the impact of testing results on future work.

1.2.2 Phase 1 Major Decisions

During the system engineering and performance specification stages of phase 1, important and sometimes significant decisions that would affect future work developing the ROVCO$_2$ occurred. The decisions included the following:

- Carry the vacuum and filtration subsystem on the vehicle
- Carry the carbon dioxide blasting system on the vehicle
- Select a two-axis end effector
- Achieve productivity on continuous open floors at the expense of flexibility and operation in small confined rooms
- Of the five different nozzle designs chosen to test, use the 280 round nozzle
- Replace the pneumatic control with electrical controls
- Use a commercial containment workhead requiring a 2:1 vacuum to blast flow
- Provide Y motion in the COYOTEE to control the positioning accuracy, the level of control, and the programmability of control inherent in the subsystem
- Select the 6 x 6 by Remotec as the vehicle base unit as opposed to the Mark V-A
- Use a bolted channel frame for the support structure

- Locate the material recovery drum aft

- Integrate the control subsystem

- Retain the controls as hardware switches and a joystick, using the vehicle's three spare control circuits for controlling the blasting and vacuum subsystems

- Use a programmable interface for COYOTEE control with optional vehicle control

1.2.3 Phase 1 Technical Achievements

The success of the major decisions during phase 1 was proven by the following technical achievements of phase 1 and the success of the concept demonstration:

- The system requirements were defined and allocated by function to subsystems and their components

- System layout was optimized by mounting the blasting and the vacuum subsystems on the vehicle and by using remote controls

- The carbon dioxide blasting system was adapted from a manually operated, pneumatically controlled system to perform as an automated, remote-controlled system

- The carbon dioxide blasting nozzle was improved by WMC, the manufacturer, to provide extremely aggressive blasting with calculated pellet velocities of up to 1,100 fps

- The preliminary design phase for the vacuum subsystem was completed

- A vacuum workhead was selected, adapted to accept the new Cryogenesis® nozzle, and mounted on the COYOTEE

- A COYOTEE was produced and tested that exceeded success criteria and specifications for manipulation in accuracy and speed

- A vehicle subsystem was selected and integrated into the ROVCO$_2$ system exceeding the success criteria for mobility

- An integrated control system was developed based on a programmable interface that integrates and functionally automates ROVCO$_2$ operation meeting the success criteria

- Sensors were selected and integrated into the control system

- A concept demonstration successfully demonstrated the operation of the ROVCO$_2$ system

How those additions were addressed, when they were addressed, and their present status will be discussed in full in chapter 2.

As phase 1 ended, Oceaneering, WMS, and DOE pursued the next phase, incorporating enhancements and modifications into the schedule, procuring subsystems for integration, and testing the system to prepare for phase 2.

2.0 PHASE 2

2.1 Introduction

This chapter reports on the work accomplished in phase 2. All the fabrication and design work proposed for phase 2 was accomplished including:

- Additions of the vacuum/filtration/containment subsystem
- Addition of the tether management subsystem
- Modifications and enhancements to the $ROVCO_2$ system phase 1

The subsystems added are all non-developmental and, except for the umbilical, were competitively procured from commercial vendors for integration.

The enhancements and modifications identified from phase 1 include the following:

- Expand the blasting work area width closer to the vehicle's sides
- Modify the control system to improve performance
- Decrease the distance between the wall and the blast path
- Extend the COYOTEE's Y-range of motion

The schedule during phase 2 was affected by the additional modifications, lagging vendors' delivery schedules, and underestimated budgetary costs.

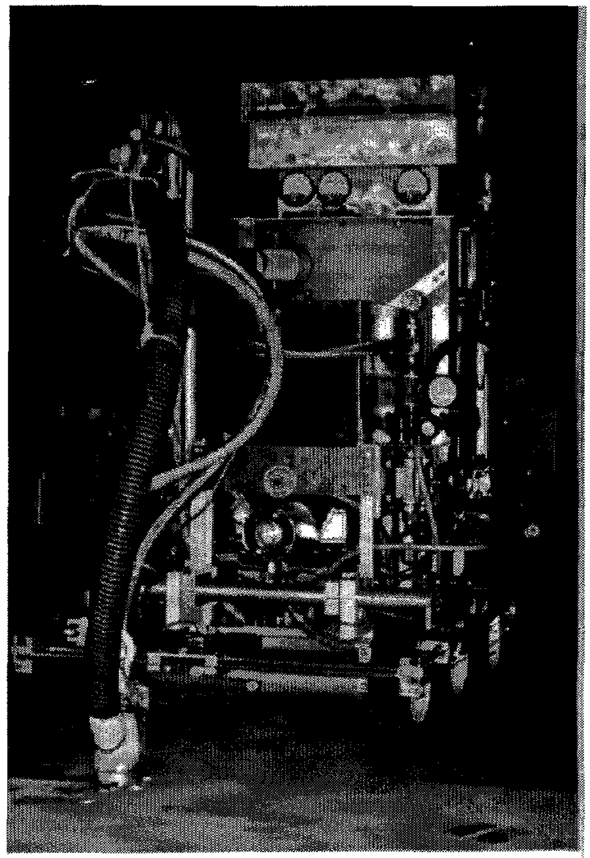

Figure 1: The $ROVCO_2$ vehicle at the end of phase 2

2.2 Success Criteria

Cost tradeoffs affected the program's progress from the start, so much so that contractual success criteria were modified. As reported at the phase 2 design review, quotes received for off-the-shelf items to meet full specification were more than budgeted. As a result, lower cost alternatives had to be explored and requirements had to be reassessed.

The $ROVCO_2$ success criteria, DOE policy factors, and requirements in the statement of work drove the criteria for evaluating the success of phase 2 of the $ROVCO_2$ program. As design and evaluation progressed and cost estimates were received during phase 2, two of the original criteria were modified. Those criteria modifications--approved by the DOE Contracting Officer Representative--affected the TMS and the carbon dioxide blasting unit. The criterion for contingency retrieval of the TMS was relaxed to avoid high costs. The criterion for the carbon dioxide blasting unit was modified when initial design work indicated the power available would not accommodate a substrate heating element. The final success criteria for phase 2 appear below; modifications appear in italics.

2.2.1 Tether Management System

The tether management system (TMS) shall be capable of managing tether pay-out and reel-in as required for effective remote operated vehicle (ROV) motion.

The TMS *may* be capable of ROV recovery in a contingency situation.

Exposed surfaces of the TMS shall be decontaminable by either carbon dioxide blasting or high pressure water washdown techniques.

2.2.2 Vacuum, Filtration, and Containment Subsystem

The vacuum, filtration, and containment subsystem (VFCS) shall employ a HEPA filtration unit to remove separate contaminants for disposal.

The VFCS shall be sealed to provide effective contaminant containment.

Exposed surfaces of the VFCS shall be decontaminable by either carbon dioxide blasting or high pressure water washdown techniques.

2.2.3 Carbon Dioxide Blasting Unit

The carbon dioxide blasting unit shall incorporate *modifications* to enhance contaminant removal.

2.2.4 System Effectiveness

ROVCO_2 shall be capable of removing 75 to 99 percent of smearable contamination from concrete floor surfaces.

ROVCO_2 shall be capable of removing 50 to 99 percent of fixed contamination from the surface pores of the concrete in a single pass.

2.2.5 System Reliability

ROVCO_2 downtime shall not exceed more than 20 percent of expected operation time due to component failure.

2.2.6 System Productivity

ROVCO_2 shall be capable of decontaminating between 30 and 75 sq ft of concrete floor space per hour, dependent upon the level of decontamination required and the contaminated surface relief.

The operator control unit (OCU) shall autonomously control tedious repetitive operations, allowing the operator to focus on overall system operation and monitoring.

2.3 Phase 2 Subsystem Additions

The subsystem additions discuss the goals, design approach, requirements, and the selected equipment. The design approach includes descriptions of how contingencies such as delivery and cost affected design, what decisions were made to address those contingencies, how they affected design, and how Oceaneering achieved a successful outcome. If components required any additional design after its integration on to the system, a redesign section was added to address the problems and their implemented solutions.

The subsystems intended for integration during phase 2 as defined by the contract are depicted in figure 2.

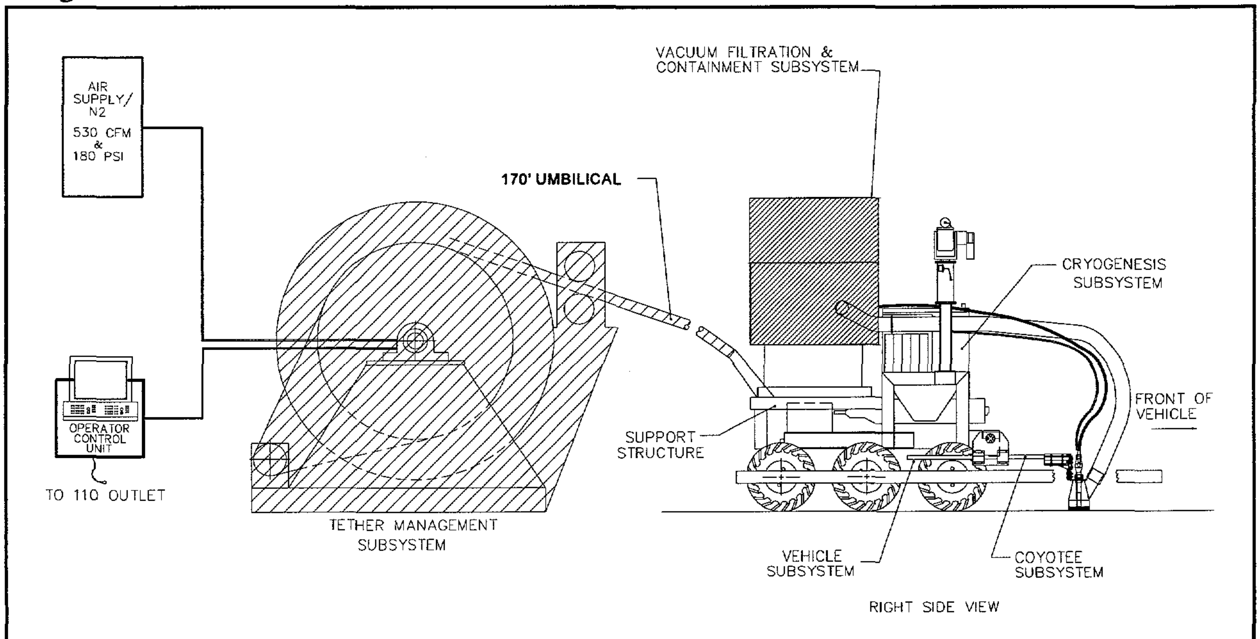

Figure 2: Subsystem integrated into the ROVCO_2 system during phase 2

2.3.1 Tether Management Subsystem Addition

The Tether Management Subsystem (TMS) for the ROVCO_2 is highlighted in figure 3. The TMS enhances the system's remote operation in two ways: it manages umbilical pay-out and reel-in to accommodate vehicular motion and it provides command, data, video, and power transfer between the vehicle and the control system. A third enhancement--ability to recover the vehicle in a contingency situation--was also defined in the original contract and pursued, but was not procured.

2.3.1.1 TMS Goals

The original general requirements for the TMS as directed by the statement of work include the following:

- Developed a tether management subsystem for the ROV system that is adapted for decontamination work
- Design the tether management system for the ROV system
- Accommodate ROV motion and recover the ROV in a contingency situation by reeling-in the tether
- Seal the tether management system against contaminants, making it suitable for decontamination

Oceaneering translated these general requirements into the original set of success criteria for specifying and system engineering for the TMS. The original (unmodified) phase 2 success criteria states the following:

- The TMS shall be capable of managing tether pay-out and reel-in as required for effective ROV motion.
- The TMS shall be capable of ROV recovery in a contingency situation.
- Exposed surfaces of the TMS shall be decontaminable by either CO_2 blasting or high pressure water washdown techniques.

These success criteria served as the basis for system requirements developed during the TMS design.

2.3.1.2 TMS Design Approach

One of Oceaneering's goals in designing and integrating the TMS was to develop the specifications for the TMS and to solicit estimates from vendors of winches, slip rings, and umbilicals.

The development of the TMS specifications concentrated on the following general performance requirements and criteria for each element and its components:

- Lower cost by modifying equipment to meet requirements versus designing custom equipment that already meets requirements

- Size

- Line speed of 24 in./sec vs the minimal 16 in./sec (based on a vehicle speed of 15 in./sec)

- Horsepower required to achieve line speed

- Supply power to support line speed (110 vac or other)

- Levelwind versus alternate, oversized drum size that assumes some operator intervention

- Dead vehicle retrieval requiring approximately 2,000 lb of line pull

Several alternatives were considered while designing the TMS: whether to use a winch or a cable reel assembly; whether to tow it behind the vehicle or station it near the console; whether to use electrical or air power; whether to specify levelwind or an oversized drum that assumed some operator intervention.

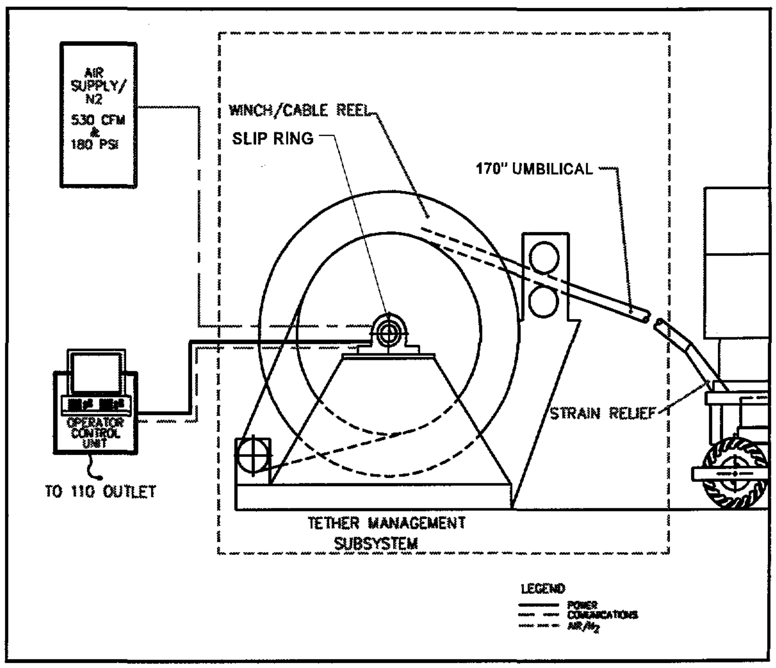

Figure 3: Major Elements of the TMS

One of the first alternatives considered was a winch versus a cable reel assembly. During the definition of the criteria for this alternative, it became apparent that the ability to recover the vehicle with brakes on became a significant cost consideration. To maintain the program budget, Oceaneering scaled back some specifications with allowances for future upgrade.

Oceaneering had originally assumed and proposed that the vehicle would be used in environments where high levels of contamination exist, requiring the operator to remain in a remote, shielded area, away from the vehicle. The definition developed for a *contingency situation* is a failure resulting in the vehicle being unable to move on its own. As the program progressed, direct input from site D&D personnel revealed such retrieval is not functionally required because the OR-K-25 site has low radiation levels and the operator will be in the same room with the ROVCO_2 system.

Design and cost impacts of the contingency retrieval requirement impacted the structural requirements of the winch frame, umbilical stain relief and umbilical breaking strength; as well as the winch motor size and operational safety. The vehicle recovery using the tether represented the most significant impact to design and cost. Without this requirement, the criterion for the winch decreased to 500 lb pull from the original 2,000 lb pull requirement, and a similar decrease in cost occurred. Analyses and trade studies confirmed that the differences required in strain resistance, and therefore cost, were significant enough to validate the decision to reject this requirement. The system's design, however, assures that should the requirement be reinstated the concept remains viable, and the system can be upgraded to allow recovery in a contingency situation. This upgrade will include purchasing both an umbilical and a winch motor capable of withstanding high tension line pull.

Before the winch/cable design assembly could be considered, the umbilical requirements had to be designed. Working from the original criterion that specified contingency retrieval, the umbilical was designed to withstand 2,000 lb of pull while maintaining and protecting the conduits through which compressed gas, power, data, video, and command travelled. An integrated umbilical (150 to 328 foot in length) combining the gas hose with electrical power and control signals was specified.

Bids were requested for cost to procure components that met the full requirements. All quotes received for winches and umbilicals were three to five times those of standard pricing for the size winch and for each foot of umbilical. The cost drivers were (1) the high tension load for contingency recovery and (2) the short (300 ft vs 3,000 ft umbilical). Even the lowest quotes were out of the question for the budget.

After the decision to reject the criterion for vehicle recovery in a contingency situation, the above requirements were modified and final derived requirements were developed. These requirements are summarized in table 1. Specifically, the length of the umbilical, its rated breaking strength and strain relief, minimum rating were modified or deleted.

Table 1: Final requirements for the Tether Management Subsystem

	Winch/Cable Reel	Slip Ring Assembly	Umbilical
Requirements			
General	Capacity 328 ft of 2.44 in. OD umbilical with a weight of 2.25-2.5 lb/ft minimum bend radius of 24 in. (static) Size able to fit through standard double doors (6 ft, 8 in. x 6 ft) Skid mounted for fork lift Compact form preferred Drum must manually lock for transportation and handling	Electrical slip ring assembly and pneumatic rotation joint assembly - multiple electrical and single pneumatic feedthrough (1.5 in. ID; 180-250 psi, air; 530 scfm)	Minimal OD of 2.76-3.2 in. Min. bend radius 22 in. (static) Weight of 2.25-2.5 lb/ft Length: 170 ft Rated breaking strength: NA Collapse strength: should hold shape when not pressurized and wound on drum
Performance	Electrically or air driven Low speed operation: pay-out/take up line speed variable between 0 and 16 in./sec for all normal operating conditions Max. required line pull: 500 lb	Low speed operation - minimal performance degradation between 0 and 10 rpm *Pneumatic Rotating Joint* Operating pressure range: 0 to 350 psi must operate with minimum pressure and flow loss Minimum air flow: 530 scfm Materials compatible with air Low expansion hose to minimize strain on conductors Termination fittings: 1 1/4 in. male JIC swivel, must accommodate a 1 1/4 in female JIC swivel	*Pneumatic Hose* ID: 1 in. gas line/hose Operating pressure: 350 psig Flow: 530 scfm Minimum rating: NA Material compatibility: with air Low expansion hose to minimize strain on conductors Termination fittings: 1 1/4 in. female JIC swivel on both ends

	Winch/Cable Reel	Slip Ring Assembly	Umbilical
Requirements			
Electrical	110 or 220 VAC single phase (110 is preferred) Slip ring to umbilical junction box Drum core access panel External junction box mounting brackets to be provided by winch vendor	*Electrical Slip Rings* 75 Ohm COAX — RG 59 x 2 24 ga. shielded twisted pair (low capacitance) x 3 10 ga. conductors x 4 22 ga. conductors x 6 14 ga. conductors x 8	*Electrical Cables* 75 Ohm COAX — RG 59 x 2 24 ga. Shielded Twisted Pair (low capacitance) x 3 10 ga. conductors: x 3 22 ga. conductors: x 6 14 ga. conductor: x 6 Spares: as allowed by design without increase in OD or major cost impact
Control	Local and remote control of both winch speed and direction		
Reliability	Hours between servicing: 1,000 Average hours between failures: 10,000	Rotations between servicing: 111,000 Minimum rotations between failures: 350,000	
Maintenance	Field maintainable	Capable of retermination in the field Field replaceable	Field maintainable Capable of retermination in the field
Decontaminability	Surface cleaning using carbon dioxide blasting Capable of disassembly to allow thorough cleaning	Surface cleaning using carbon dioxide blasting Capable of disassembly to allow thorough cleaning	Capable of being cleaned by high pressure water wash and typical cleaning solvents
Sealing	Against particles Close out hard to clean areas Seal cracks, crevices, and holes by welding	Against particles Close out hard to clean areas Seal cracks, crevices, and holes by welding	*Outer Jacket* Smooth, sealed, and resistant to oil and lubricants Waterproof Low weight High resistance to abrasion

Oceaneering recommended, and DOE approved, changing the requirement to eliminate the tension requirements for both the winch drive and the umbilical and to reduce the procured umbilical length to contain cost. The winch structure would be made strong enough to allow for future upgrades. The modified criterion now states

The TMS *may* be capable of ROV recovery in a contingency situation.

After revising the specification to reduce the tension requirements, Oceaneering reissued requests for quotes. The winch and slip ring were awarded to the lowest qualifying bidders. A tow winch manufactured by SEA-MAC Marine Products, Inc. satisfied the requirements. SEA-MAC's model 202AMR winch is air-powered with remote control, on a wheeled, lockable base. Instead of a levelwind, Oceaneering relied on a shortened drum core length to provide smooth winding of the umbilical. The winch can hold up to 330 ft of 2.4-in. umbilical.

The slip ring as well as the corresponding rotating and stationary junction boxes was procured from Focal Technologies, Inc. The slip ring is roughly 7.5 in. diameter by 30+ in. long. The slip ring was integrated with the winch by Oceaneering.

All umbilical bids remained too high to accommodate budget constraints. Original estimates had been based on dollars per foot for umbilicals greater than 3,000 ft in length. The manufacturer's setup and plant costs for less than standard quantities--Oceaneering had specified 400 ft--raised the cost significantly. To reduce costs with in the planned budget Oceaneering constructed the umbilical and then integrated it with the winch. The umbilical is 170 ft long and provides the full complement of cables and hoses as well as spares. The quantity of 170 ft was selected after analysis that determined that quantity would be long enough to allow full testing and yet remain within budget constraints. Oceaneering developed a cable winder that spun the 19 wires and 12 filler ropes around the 1-in. high pressure hose (see figure 4). The umbilical was jacketed with a high abrasion-resistant shrink wrap manufactured by Ray Chem to form a smooth continuous jacket. The ends were finished with shrink wrap 'Y' boots and sealed electrical and gas connectors.

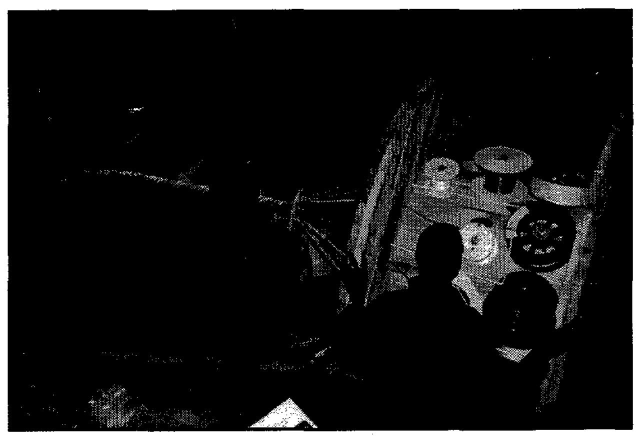

Figure 4: Oceaneering developed a cable winder to remain within budget constraints.

The final result was a fully functional TMS that can be upgraded should contingency vehicle recovery become necessary or desirable. The TMS design incorporated an auxiliary circuit that would power the vehicle's brakes off allowing

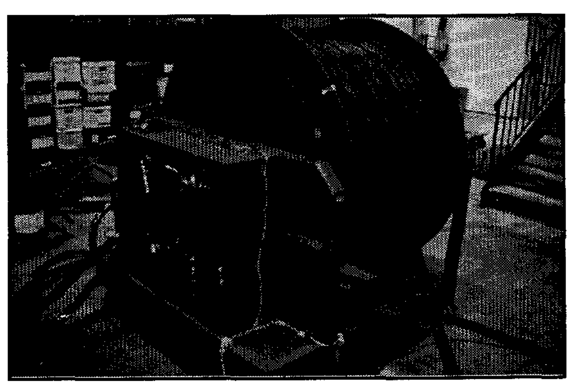

Figure 5: The completed TMS.

easier vehicle recovery. The auxiliary break-off circuit is further discussed in section 2.4.3.4, auxiliary break-off circuit. The completed TMS can be seen in figure 5.

2.3.2 Vacuum, Filtration, and Containment Subsystem (VFCS) Addition

Although contractually required in phase 2, the VFCS was specified during phase 1 so that its proposed volume and weight could be calculated as part of the payload for the vehicle design. In phase 2 WMC and Oceaneering designed and procured a High Efficiency Particulate Air (HEPA) filtration system and vacuum system and integrated it into the $ROVCO_2$ system. This subsystem minimizes cost by using off-the-shelf hardware. The system attaches to the containment workhead and filters out contaminated debris (figure 6). The VFCS design uses a proven radioactive waste handling system. The subsystem resides on the vehicle, providing debris containment.

2.3.2.1 VFCS Goals

One general requirement from the statement of work for the VFCS subsystem directed system engineering: to design and produce a HEPA filtration system and a containment system for nuclear decontamination. Oceaneering translated this general requirement into a set of success criteria for specifying and defining requirements. The phase 2 success criteria includes the following:

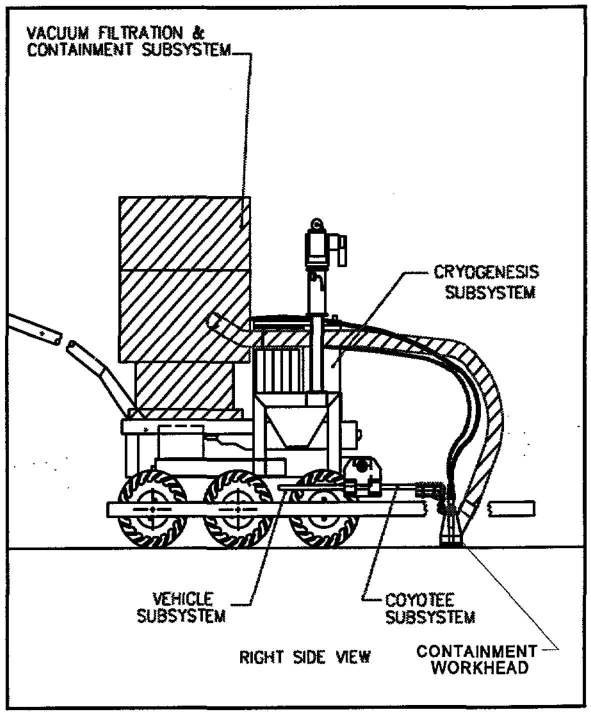

Figure 6: The VFCS used off-the-shelf hardware to minimize cost.

- Vacuum, filtration, and containment subsystem shall employ a HEPA filtration unit to remove separate contaminants for disposal.
- The VFCS shall be sealed to provide effective contaminant containment.
- Exposed surfaces of the VFCS shall be decontaminable by either carbon dioxide blasting or high pressure water washdown techniques.

Subsystem requirements were derived from the statement of work and the original success criteria during the design of the VFCS.

2.3.2.2 VFCS Design Approach

Preliminary design specifications for this system occurred during phase 1. Trade studies evaluated alternatives and justified selection. A typical alternative considered in phase 1 for the VFCS was whether to locate the subsystem on or off the vehicle. The decision considered several factors: the umbilical diameter, the environment where it would be operated, total weight contribution to the vehicle payload, and how the umbilical's length would affect clogging. These combined factors influenced the decision to carry the VFCS on the vehicle. A complete narration of this decision was presented in the topical report, "Phase 1 Report of the Remote Operated Vehicle with CO_2 Blasting (ROVCO_2)".

During phase 1, preliminary design specifications identified the single most important component as the airflow to the vacuum. There was no argument: it had to capture the propellant gas (blasting at a velocity of 250 scfm), the released carbon dioxide, and the waste. One of WMC's vendors experienced in blasting containment workheads recommended a suction volume twice that of the volume from the blasting nozzle. According to the vendor, full containment could be achieved at this ratio in ideal conditions. WMC and Oceaneering decided to use this commercial containment workhead from the vendor.

During phase 2 development, the original phase 1 requirement addressing the drum size was modified. The requirement for a 55-gal drum was dropped and replaced with a requirement for a drum sufficient to hold 8 hrs (1 shift) of blasting, approximately 14 gal. Based on the success criteria and the system requirements, Oceaneering developed the following set of derived requirements for final development:

- HEPA Filtration
  - 0.3 micron particle filtration (99.97 percent efficiency)
  - nuclear-rated system
  - minimized filter replacement
  - 14-gal. drum waste container
- Airflow
  - 500 scfm generated at workhead or better (twice the blasting scfm)
- Power
  - air powered
  - electrically controlled 24 VDC
  - minimum allowed gas consumption: must be less than 400 scfm @ 150 psi
- Command/Data
  - remotely controlled
  - pressure sensors/gauges to provide status of system
  - system shutdown in AutoROV alerts operator to full drum
  - visible clog warning
- Reliability/Maintenance
  - filter replacement weekly intervals or longer
- Safety

- safe drum/bag/container exchange
- minimal loss of waste to atmosphere during filter or container exchange
- operator notification of unsafe operating conditions

- Decontaminability and Sealing
  - sealed against particles, hard to clean areas should be closed out, and cracks/crevices/holes should be sealed

Trade-off analyses based on safety, cost, and performance considered alternatives such as modifying an off-the-shelf system versus custom designing a system. From trade studies and cost comparisons, Oceaneering decided to use an existing system. The VAC-PAC® by Pentek, Inc. was chosen for $ROVCO_2$ (shown in figures 7 and 8).

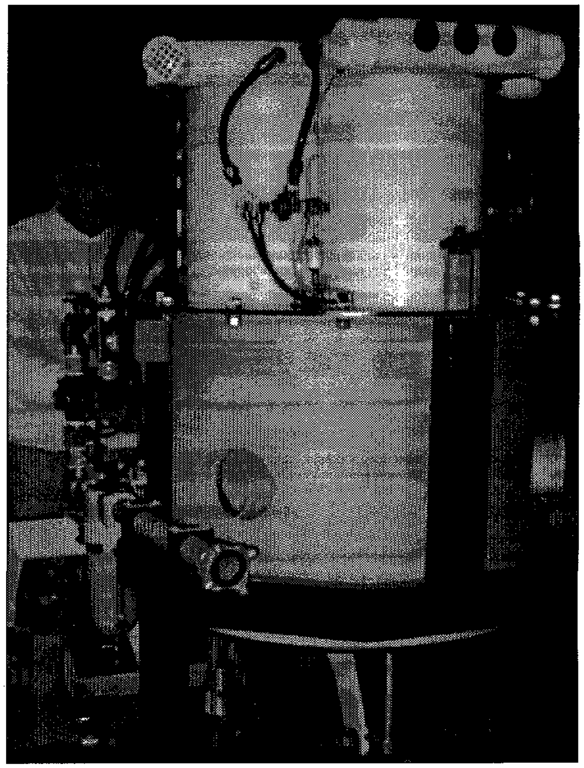

Figure 7: VAC-PAC rear view

When compared to other systems, the VAC-PAC® excelled based on the air supply requirements, containment effectiveness, and safety operator. Other systems need a higher cfm to generate the same vacuum air flow. Higher air consumption also increases compressor maintenance and requires a larger (and harder to manage) ID air hose to manage air hose to minimize pressure loss. The other systems drum exchange procedures increase the probability of airborne contaminants and health hazards. The other systems's records for filter performance are also poor, specifically regarding airborne contaminants, frequent filter exchange, and loss of productivity due to work stoppage. Pentek's model 24D is also a proven commodity at ORNL, INEL, and other DOE sites.

Pentek's VAC-PAC® model 24D satisfies the criteria and requirements for the VFCS. Its components--the vacuum, the filters, the waste drum, the status indicators, and the support frame--required minimal customization.

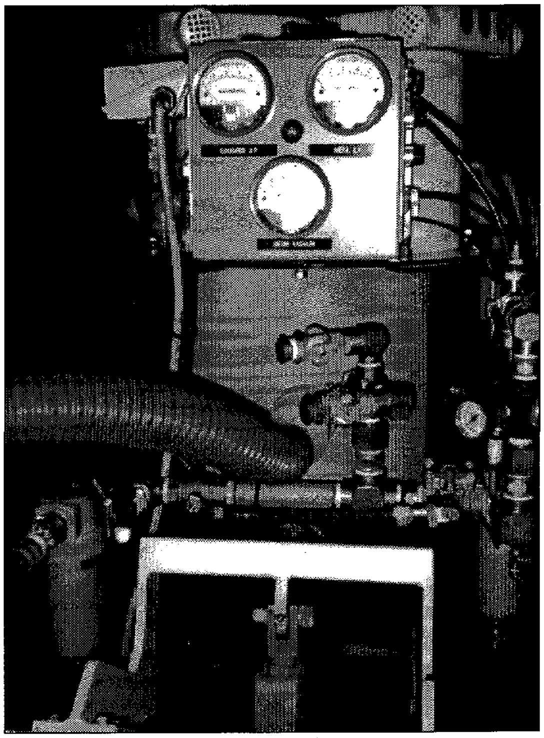

Figure 8: VAC-PAC front view

The VAC-PAC model 24D can be described in more detail by the following:

- Complete HEPA vacuum, filtration, and containment system
- Proven system — used in DOE and nuclear power facilities
- Designed for use on scabbling ROV — very similar requirements
- Off-the-shelf (some modification by vendor required) — will bolt on
- Safe drum exchange
  - always performed with vacuum on to minimize airborne contamination
  - drum-mounted on sliding tray for easier handling
  - 14.9-gallon drums fit in 55-gallon drums for storage and disposal
- Fits within vehicle size constraints, 6 ft x 8 in. x 6 ft, when mounted on ROVCO_2 vehicle
- Air-powered vacuum with 24 VDC controls
- Efficient vacuum production reduces overall air flow requirements from 400 cfm @ 100 psig to 245 cfm @ 85 psig
- Status indicators
  - drum-full alarm, automatic signal sent back to operator
  - pressure gauges, visible from ROVCO_2 pan and tilt camera
- Vacuum
  - air amplifiers — pneumatic eductors
    - induce additional air flow, more than double the cfm of supply air
    - air supply — 245 cfm @ 85 psig provides 530 cfm
  - static lift: 100 in. H_2O
- Filters: two-stage filtration of hazardous particulates, including radioactive particulates, toxic chemicals, and lead-based paint
  - primary roughing filters
    - 3 filters @ 8 in. diameter
    - 95 percent efficient @ 1 micron
    - automatic self-cleaning by reverse-flow pulses
  - secondary HEPA filter
    - 1 filter @ 12 in. x 24 in.
    - 99.97 percent efficient @ 0.3 microns
  - annual filter replacement

2.3.2.3 Workhead Re-design

After phase development was completed and all subsystems were integrated onto the $ROVCO_2$ system, the system was tested and demonstrated. The first of the two sessions of testing determined initial productivity results and concluded improvements were needed to the effectiveness of the containment system.

The containment of the blasted media achieved at the workhead was less than desirable. After additional verification, testing confirmed that the vacuum and filtration system was operating as designed (at a supply pressure of 80 psi and a flow rate of 280 cfm to the vacuum and with a suction of 100 inches of water) the source of the problem was further investigated.

Analysis of the problem revealed that the vendor's rule of thumb, *the suction volume should be twice the blasting volume,* ignored the system's momentum balance. The blasting air stream, driven by 150 psi, discharges at a velocity of 1,200 fps giving it high momentum and energy. The vacuum system is limited to 14.7 psi driving force, limiting the energy to a level 100 times less than the discharge stream. As observed in testing, the discharge stream flows along the surface after impact at velocities calculated as 50 percent of the nozzle velocity. Figure 9 shows the brushes surrounding the original workhead being pulled inward by the vacuum and being pushed outward by the blasting. The suction pressure in the workhead above the stream did not have a significant effect in redirecting the stream.

Figure 9: Blasting operation with original workhead.

The WMC engineers developed a new workhead for use during the second week of testing (figure 10). That workhead design was based on the principle of using the energy in the stream to carry it up to the vacuum hose. Theoretically, by creating smooth flow from just above the surface up into the hose, the workhead prototype would capture the blast and the debris.

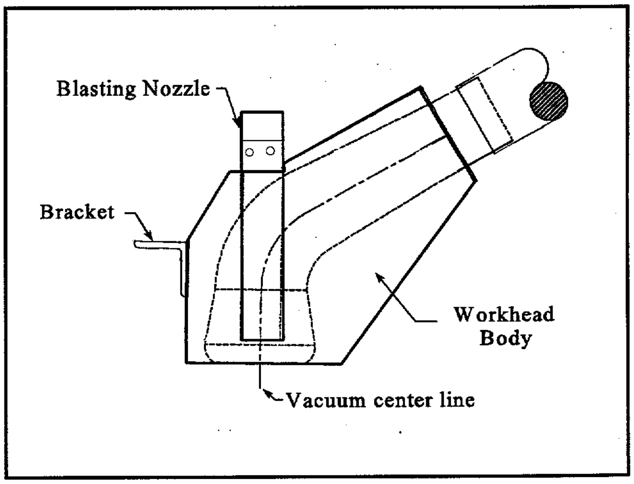

Figure 10: The second $ROVCO_2$ workhead

The second session of testing concluded that the containment of the redesigned workhead was still less than desirable. The workhead improved the effectiveness of the vacuum surrounding the nozzle but was sensitive to the clearance height of the workhead over the floor. When in direct contact with the floor, the workhead increased containment but significantly affected COYOTEE's ability to sweep. To achieve effective sweeping motion, the workhead was raised from direct contact with the floor. A gap between the workhead and the floor to improve sweeping motion degraded the containment performance unacceptably.

After completing phase 2 testing, the team decided to analyze additional configurations of the workhead to evaluate their performance on improving containment. Through this process, valuable concepts were developed. The most promising, *fight fire with fire,* is being proposed for detail design, fabrication, and cold test in phase 3. The details of this work are presented in the phase 3 proposal, volume 2 of this report.

2.4 Subsystem Enhancement

Four enhancements to the ROVCO_2 work vehicle greatly increased system performance and controllability in phase 2. Oceaneering engineered, designed, and procured or fabricated all modifications to assure continued harmonious integration. The enhancements (including both software and hardware) were to the Cryogenesis, the COYOTEE, the control subsystem, and the vehicle subsystem. The following subsystem enhancements discuss the reasons for the enhancements and how they were achieved.

2.4.1 Cryogenesis Subsystem Enhancement

The phase 1 demonstration concluded modifications to the Cryogenesis subsystem were needed. These modification would improve the cleaning rates on tough coatings like epoxy paint to greater than 30 square feet per hour and improve the efficiency of the cleaning operation.

2.4.1.1 Cryogenesis Goals

The original unmodified phase 2 success criteria states that the CO_2 blasting unit shall incorporate a substrate heating unit to enhance contaminant removal.

2.4.1.2 Cryogenesis Subsystem Enhancement Approach

At the beginning of phase 2, WMC planned to enhance the Cryogenesis subsystem (see figure 11) by developing a heating subsystem to increase thermal cracking which, in turn, would improve removal performance on brittle coatings. By adding the heater, WMC believed that blasting productivity would be improved. Analysis of the heating options showed severe limitations with the ROVCO_2 system. There

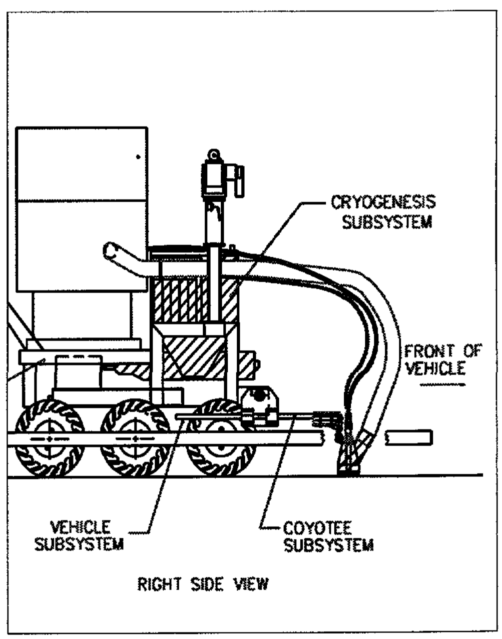

Figure 11: The Cryogenesis Subsystem.

was a requirement to limit $ROVCO_2$'s electrical power requirements to be served by a standard 120 VAC circuit of less than 15 amps. To achieve a hot enough temperature at the blasting rates, more than 5 amps would be required. The vehicle system already used 10 to 12 amps, precluding use of the heating system.

The following alternatives for improving contaminant removal rates were investigated:

- Heat the surface to increase thermal cracking of coatings to improve the removal performance on brittle coatings

- Fabricate a 0.380 nozzle with four carbon dioxide pellet injection ports
  - WMC's analysis indicates a more uniform acceleration pattern for the pellets
  - Not used in manual operation due to unacceptably high nozzle back pressure

- Increase carbon dioxide blasting gas pressure (can be used in addition to the other alternatives)

- Improve the blasting pattern using a flat nozzle

As part of the engineering process, the following series of trade-offs were conducted to investigate these options:

- Surface Heating
  - Using 120 VAC power, only 0.71 Btu can be delivered to the surface
  - To achieve the desired temperature for heating, a 240/480 power circuit will be required complicating deployment and use
  - From hot weather experience over past the two years, WMC no longer predicts significant productivity gain
  - If filter freezing is a problem, which the manufacturer doubts, heating the surface would help control it

- Four-port nozzle
  - The original nozzle design and prototype had 4 ports; the design was changed to 2 ports after the high kickback force caused operator fatigue
  - Improved pellet distribution in blast area raises the "least common denominator" that limits sweep speed
  - The existing COYOTEE can accommodate kickback force

- Increased Blast Pressure
  - Limited only by compressed gas supply availability and costs
  - Cryogenesis system rated for 300 psi

However, after trade analyses and some testing, none of these options was satisfactory. Oceaneering and WMC decided that the design objectives of the modifications could be best met by changing the blasting nozzle from a circular to a rectangular configuration. As shown in figure 12, a rectangular configuration would increase the blasting speed by 30 percent because of a uniform distribution of blasting area covered by the nozzle. The previous

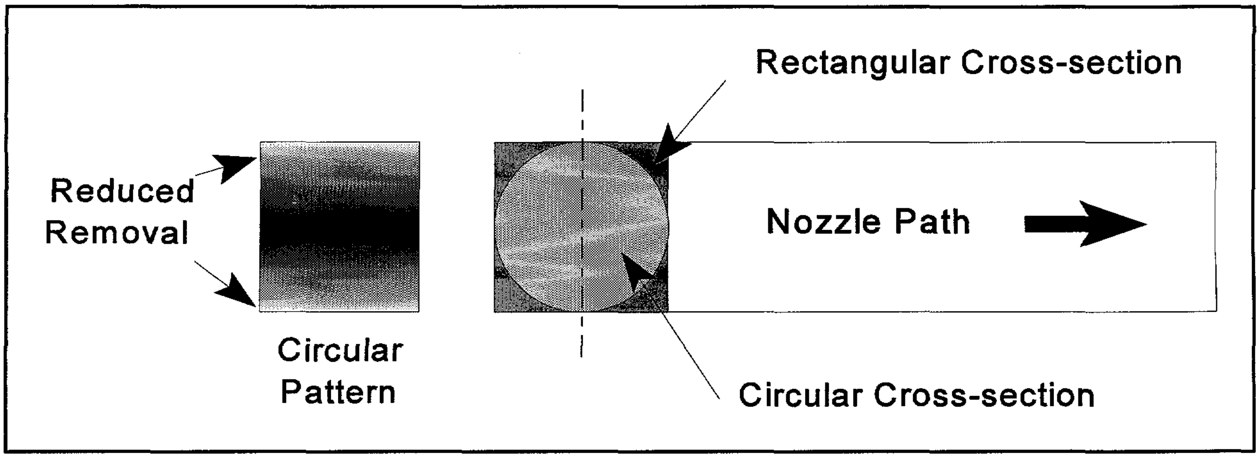

Figure 12: Improved blasting concentration and uniformity of the rectangular nozzle.

blasting speed was slowed by the time required to remove coatings at the top and bottom sections of the circular cross-section. The top and bottom sections of the blasting area covered 30 to 50 percent less area than the center of the nozzle (figure 12). The rectangular design will improve blasting speed at least 30 percent because blasting will be more uniformly concentrated over the area.

2.4.2 COYOTEE Enhancements

Decreasing the minimum distance between the wall and the blast path became a valid COYOTEE enhancement after the concept demonstration in phase 1. As originally designed, the closest distance between the blast path and a wall or a corner was 6 ½ in. DOE asked Oceaneering to shorten this distance. DOE site personnel, however, indicated that the system would not have to provide complete decontamination of a corner if that would require a specially designed work head.

To enhance ROVCO$_2$'s ability to decontaminate floors, Oceaneering extended the blasting work area to both sides of the vehicle, allowing

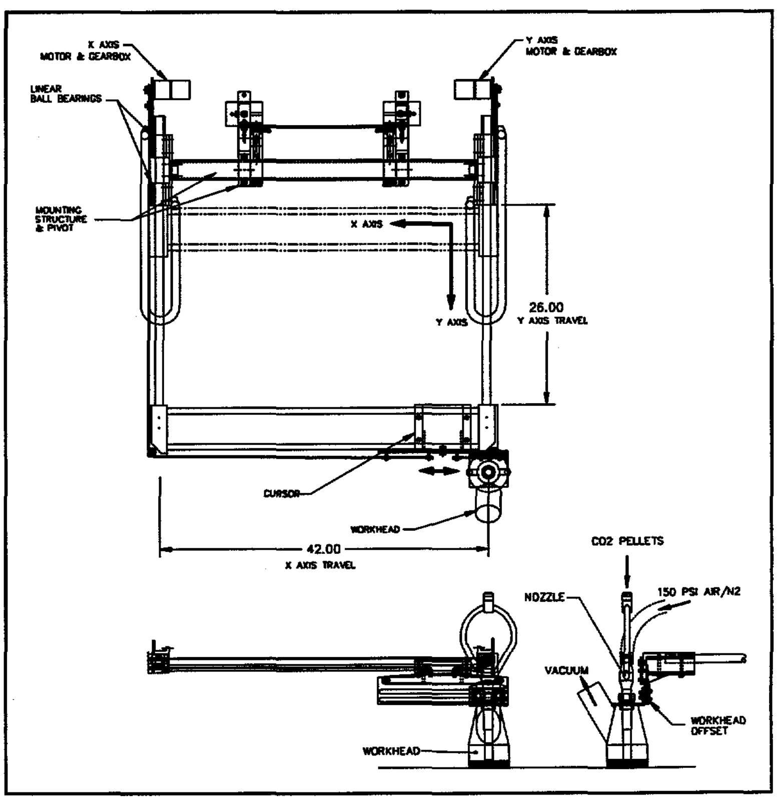

Figure 13: The Extended COYOTEE Path.

decontamination to within a few inches of the wall. To achieve this enhancement, Oceaneering modified the COYOTEE subsystem's cursor to allow the workhead to travel to the side edges of the $ROVCO_2$ envelope (see figure 13). Therefore, the following basic design requirements for COYOTEE design modifications were determined:

- operation as close to walls as possible without work head modification (modification of mounting bracket allowed);
- no operator repositioning of the workhead allowed;
- simple design with minimal impact on existing components.

The initial concepts for closer operations were fixed-offset concepts. The workhead would be mounted on the COYOTEE cursor offset to one side to reach the edge of the $ROVCO_2$. The operating scenario envisioned that the $ROVCO_2$ would keep its near side to the wall to maintain as narrow a gap as possible along walls.

The next group of options were kinematic concepts involving linkages or linear slides, or both, to provide the additional blast capability with the added bonus of an increase in work space and without the need for remounting the work head. The linkage concepts generally provided additional motion by multiplying the X-axis translation of the cursor through the use of a push rod connected to the linkage. The linkage movement was transferred to the workhead which either pivoted or moved linearly via a slotted rail. The linkage concepts had one downfall: they all increased the work head X-axis speed near the end of travel. The resultant speed change would cause variable decontamination effectiveness.

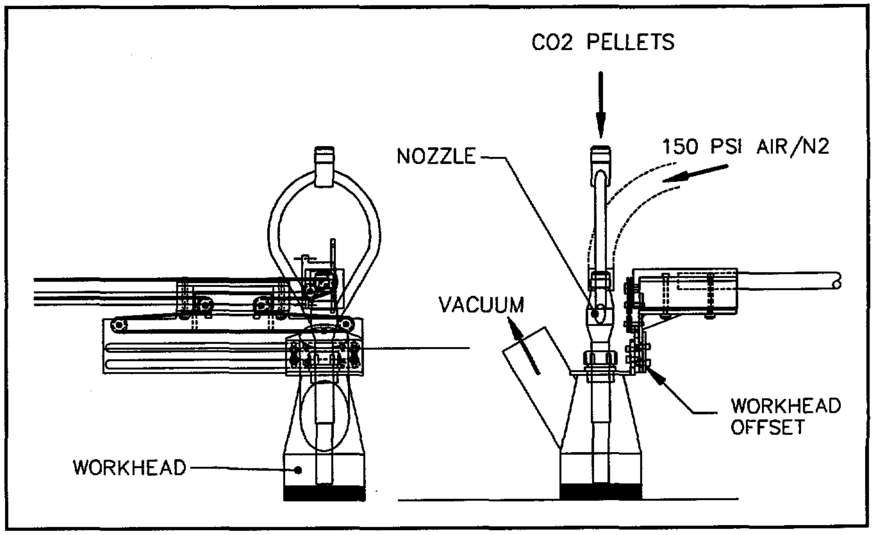

Figure 14: COYOTEE End Effector Offset.

The last--and the implemented--concept (see figure 14) was the offset cable slide. The design rerouted the Synchromesh cable and added a linear slotted rail to provide the additional travel length. The offset slide uses a roller bearing that rides in the double-slotted rail. The Synchromesh cable is terminated on this sliding assembly. The total x-motion generated in this assembly is two part: the workhead assembly sliding in the offset slots and the cursor sliding on its rails. Movement of the X-axis cable causes the workhead assembly to move first due to lower friction, then, at the end of the slots, the motion is transferred to the cursor assembly until the end of the cursor travel is reached. As with the previous design, the X-axis motion is halted when one of the proximity sensors, mounted at the ends of the cursor travel, senses the approaching cursor. With the offset slide, the existing components are used with a minimum of additional components required and only one preexisting item needing modification, the lower cursor plate. Another benefit derived from this modification is an increased workspace measuring about 10 in. along the X-axis. A summary of benefits of the implemented end effect or offset design include the following:

- Uses rerouted Synchromesh cable with only software changes to COYOTEE drive and control
- Simple, lightweight design
- Allows height adjustment of work-head
- Bolt-on design allows disassembly for decontamination
- No modification of existing components required; can easily revert to previous design
- Allows blasting closer to walls on both sides
- Increases X-axis travel distance to 42 inches

The reliability of the Synchromesh cable was also an area of concern after phase 1. The cable sometimes stripped the helically wound wire by the drive pulley when the workhead hit an obstacle. Adjusting the motor controllers to stall before stripping occurred was the solution.

The following specific changes to the system were implemented to the COYOTEE subsystem:

- The end effector was offset to allow blasting closer to walls
- The reliability of sycromesh cable was increased by limiting motor torque
- The Y-axis linear bearings were changed to roller type and the shafts to steel
- The work area was increased from 21 in. x 31.5 in. to 26 in. x 42 in. with the offset and longer Y-axis rails

2.4.3 Control Subsystem Enhancements

For phase 1, the control subsystem met its design goals, including full standard operation with a single operator and automation of repetitive tasks including sweeping areas and on/off sequencing. However, as modifications were made to the ROVCO$_2$ system, the control system needed enhancements to support the new systems and provide for more sophisticated vehicle operations.

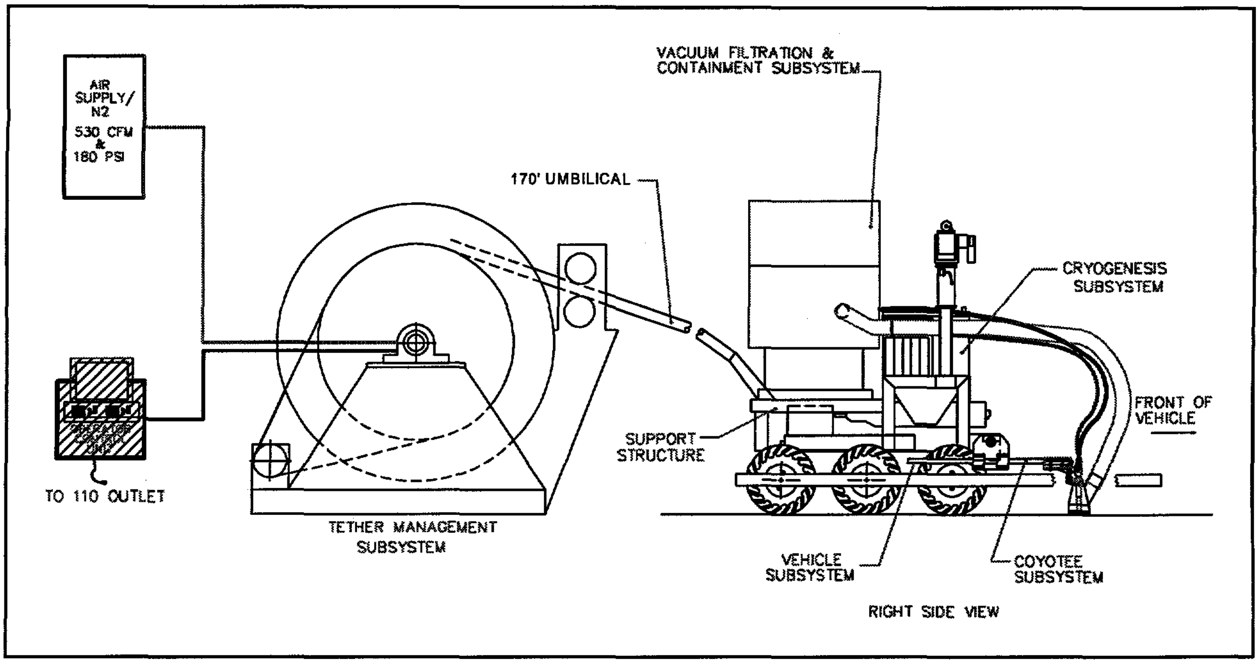

Figure 15: The control subsystems of the $ROVCO_2$ system

The goals of the phase 2 enhancements as they evolved are outlined below.

- Automate $ROVCO_2$ operation, especially blasting operation to perform sequential blasting and ROV moves to blast straight line paths (AutoROV Mode)

- Control the following system changes
    - The enhanced COYOTEE with extended work area
    - The added signals for vacuum/filter electric power and drum-full, provided in phase 1
    - The added TMS in manual and AutoROV modes

The control system was modified to improve overall system functionality and performance.

2.4.3.1 AutoROV Mode

The AutoROV mode automates the $ROVCO_2$ system by allowing the operator to specify sweep range, sweep overlap, and incremental move distance and then, by selecting AUTO on the OCU, letting the system autonomously perform the required actions. The required actions implemented by the $ROVCO_2$, once the AUTO command is sent, are: perform a sweep, retract the blast head, move the vehicle forward to the specified sweep *Y* minus the overlap, perform the next step, repeating the sequence until the total distance specified is achieved.

Oceaneering implemented AutoROV in phase 1, although it was not required by the success criteria, but had problems with vehicle movement accuracy The program provided the proper sequencing and motion except for the incremental vehicle move distance.

In phase 2, the problem was traced to communication timing between three of $ROVCO_2$'s five processors. Oceaneering decided to use the signal line to control the vehicle distance for the AutoROV mode. This change and other minor software changes resulted in surprisingly accurate move distances with errors on the order of 0.25 in.

Oceaneering did not develop automated control of $ROVCO_2$ to decontaminate **nonlinear** areas because of the high overlap of development with other DOE/OST programs with this goal. Should an automated workspace navigation system become available, $ROVCO_2$ can be readily upgraded.

2.4.3.2 Tether Management System

The OCU controls the TMS by analogue circuits. The pay-in/pay-out of the $ROVCO_2$ umbilical is controlled by a 3 way solenoid valve. One analogue circuit controls drum directions and one starts/stops drum motion. Manual switch select Manual or AutoROV operation. During AutoROV operations, the control system synchronizes the winch movements with the vehicle movements. The control system provides only for pay-in and pay-out of the umbilical; it does not sense nor does it respond to umbilical tension.

2.4.3.3 Vacuum Filtration and Containment Subsystem

The OCU controls the VFCS by providing on/off control as part of the blasting sequence. It also monitors the drum-full signal and shuts down blasting and vacuuming when it receives a full signal. During AutoROV operations, it initiates automatic stop of the system.

2.4.3.4 Auxiliary Brake-off Circuit

Oceaneering added the auxiliary vehicle brake-off circuit to permit upgrade should contingency retrieval become necessary. The vehicle brakes are fail safe-on: when power is lost, the brakes are applied. Normal vehicle operation requires the operator depress the vehicle joystick deadman switch to actively release the brakes. However, contingency vehicle retrieval may be required in the event of loss of power or control. Therefore, the vehicle brakes can be released by supplying 24 VDC power separately to the brake circuit from the OCU via a dedicated cable set. This circuit bypasses the OCU power supply, OCU circuit board, and basic vehicle electronics. The umbilical contains additional, separate conductors for this circuit. This combination provides redundancy to release the brakes should a computer or PC board fail, a general electrical failure occur, or should any combination of these scenarios occur.

2.4.4 Vehicle Subsystem

The vehicle subsystem performed well during phase 1. Changes to it were required only to accommodate the other phase 2 additions as well as the planned sealing for decontamination work.

Modifications to the $ROVCO_2$ vehicle were implemented to provide the following enhancements: vehicle emergency stop, sealing for decontamination, and bumper enlargement.

2.4.4.1 Emergency Stop

An emergency stop was integrated into the $ROVCO_2$ to cut off power at the vehicle, providing emergency shutdown of systems and components. The emergency stop is mounted on the forward diaphragm of the $ROVCO_2$ vehicle frame, as shown in figure 16, and halts only those systems mounted on the vehicle. It provides a maximum level of safety for any personnel in the area of the vehicle. When depressed, it halts the vehicle's and the COYOTEE's motion and immediately shuts off the Cryogenesis and the VFCS by shutting off their air supply solenoid valves.

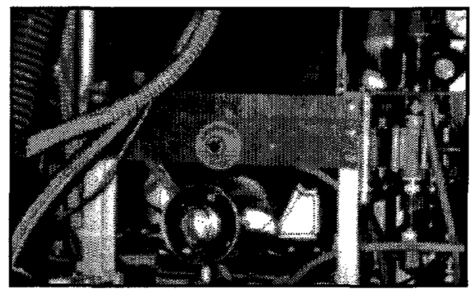

Figure 16: The Emergency Stop on the $ROVCO_2$.

2.4.4.2 Sealing for Decontamination

Oceaneering also upgraded all temporary seals to permanent seals after the prototype's successful demonstration in phase 1. The permanent sealants improve the ease of vehicle decontamination thereby reducing maintenance costs, system downtime for cleaning.

2.4.4.3 Bumper Enlargement

Enhancements to the COYOTEE required expanding the $ROVCO_2$ bumper. The bumper was modified by eliminating the front to accommodate the increased length in the Y-axis rails.

2.4.4.4 Support Structure

Minor modifications were required to the support structure were required during phase 2 to mount the VFCS, creating bolt holes and strain relief for the integrated umbilical. During final selection of the VFCS, Oceaneering revisited the trade-off on positioning the VFCS. During phase 1, the planned procedure deposited the removed debris directly in a 55-gal drum mounted at the rear of the vehicle. This choice was based on height limitations for the overall system and the premise that depositing the waste directly into a 55-gal drum was a benefit. Several disadvantages of a system carrying a filled 55-gal drum were inherent; namely, the system's gross weight increased; the system's center of gravity shifted to a point near the rear axle, greatly increasing chances of tipping over and rendering rapid acceleration dangerous; removing and handling the drum when full became a cumbersome and physically taxing task.

During phase 2, further discussion with DOE site decontamination personnel revealed that little benefit existed in choosing the 55-gal drum over other drum sizes. Accordingly, the size selected (14.9 gallons) was one that would accommodate the quantities estimated for a full shift (8 hr) of blasting waste.

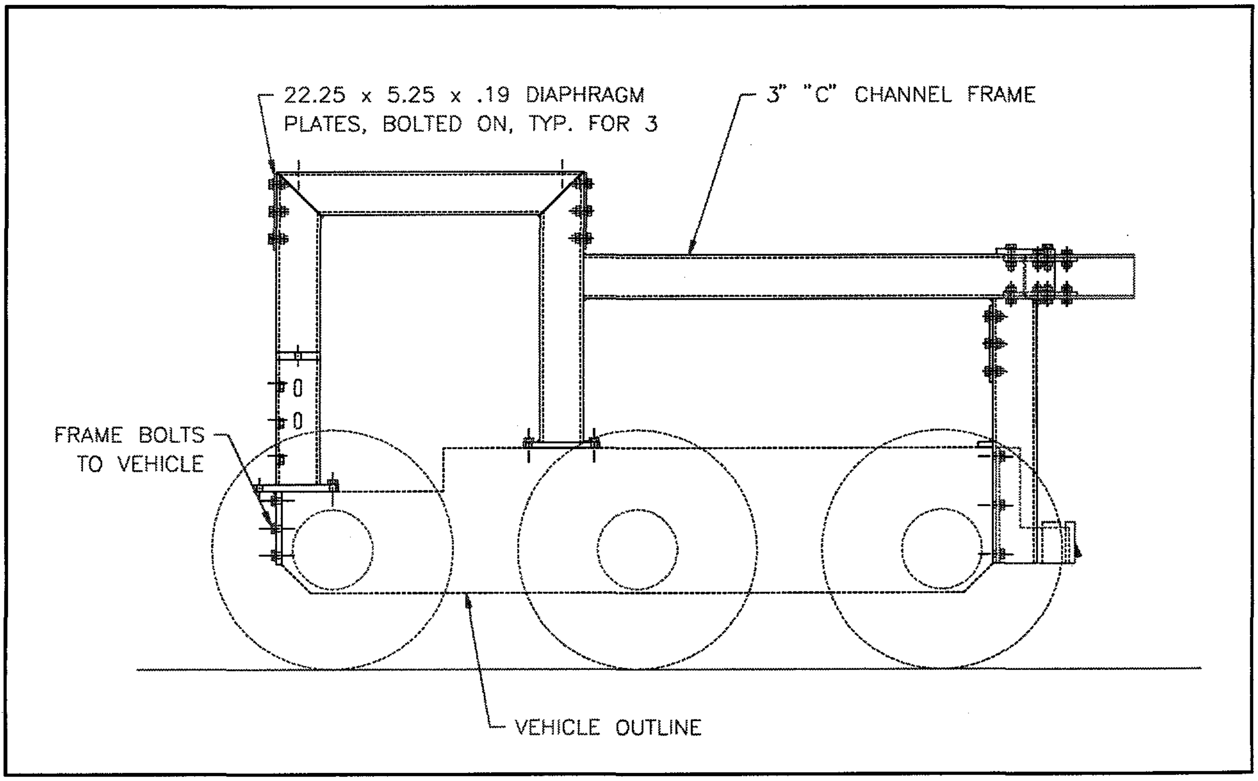

Figure 17: $ROVCO_2$ Support Structure Elevation.

2.5 System Integration

Oceaneering completed the fully outfitted $ROVCO_2$ system by integrating the subsystems procured during phase 2 with those that had been procured and installed during phase 1. The subsystems integrated were the TMS and the vacuum, filtration, and containment system.

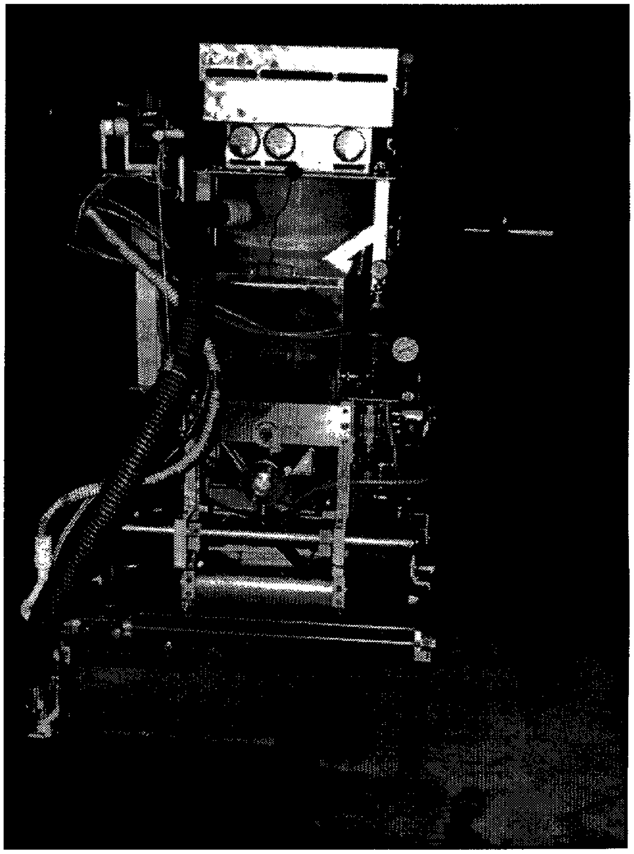

Figure 18: $ROVCO_2$ in phase 2 productivity testing

Oceaneering performed a failure mode effects and criticality analysis (FMECA) to determine the single point failures and expected range of mean time between failure (MTBF). Further discussion of this report and its conclusions will be addressed in chapter 3 where its relevance to the testing is discussed. The report has been included as Appendix A.

The phase 2 system integration process produced a fully functional $ROVCO_2$ system, ready to test. To assess the $ROVCO_2$ system's reliability, productivity, and effectiveness, six tests were designed and performed in August and in October 1995. The results of those tests, their methodology, and details relating to them are presented in chapter 3.

3.0 TESTING

3.1 Background

The testing for the ROVCO_2 program followed the phases of development. In phase 1, the function and performance of the developed subsystems were tested in the phase 1 integrated system demonstration. In phase 2, the function and performance of the complete ROVCO_2 system was tested for productivity, effectiveness, and reliability in decontaminating floors.

During testing conducted at the end of phase 1, the ROVCO_2 system demonstrated that it can provide a productive and effective means of decontaminating concrete floors. The demonstration included tests of the integrated vehicle's motion and control, the COYOTEE's functions, blasting rates, and evaluation of the operator control unit. From the phase 1 testing, the need for modifications and enhancements during phase 2 became apparent. Those modifications--developed and tested in phase 2--were an increase in swept area and the automation of linear path blasting.

3.2 Purpose

The phase 2 testing program was designed to produce reproducible quantitative data for evaluation of ROVCO_2. The data will also be useful for budgeting and planning the hot test and use in a real work environment. The testing provided documentation of the decontamination effectiveness; quantification of system productivity; and, reliability data for availability, mean time between failure, and mean time to repair computation. The cold testing also produced valuable operational experience of the system and increased knowledge of using carbon dioxide blasting for concrete decontamination. The performance of the system and its subsystems during the test were measured against the success criteria and derived requirements. This section describes the basic methodology and results of each test. Refer to the *ROVCO_2 Phase 2 Test Plan,* submitted on April 27, 1995 for detailed information dealing with the test relating to success criteria mapping, test methodology, equipment, data analysis, procedures, and a detailed explanation of how surrogates were chosen and their chemical factors.

3.3 Verification

Meaningful data has been assured throughout the test by analyzing and specifying the test measurement requirements before testing and checking the results for significance versus the errors. Oceaneering performed additional concrete sampling and laboratory testing when a measurement error rendered the results insignificant.

3.4 Testing Objectives

From the statement of work and success criteria for phase 2 testing, five experiments were derived:

- cold test
- decontaminability test
- tether management subsystem test
- system productivity test
- system reliability

Each experiment satisfied one or more success criteria. A map of each criterion and the corresponding test title and measured quantity appears in table 1.

A second objective of the tests was to provide a fully operating demonstration of the integrated system to confirm its function.

3.5 Methodology

From the success criteria, the planned verification tests were mapped. They were:

Table 1: Success Criteria to Test Verification Mapping

SUCCESS CRITERIA	TEST TITLE & MEASURED QUANTITY
2.1 Tether Management System	
2.1.1 The TMS shall be capable of managing tether payout and reel in as required for effective ROV motion.	**Tether Management Subsystem Test** Demonstrates tether payout and reel-in as the vehicle maneuvers around typical obstacles, at angles, forward and reverse Data: Observations and video tape
2.1.2 The TMS shall be capable of ROV recovery in a contingency situation.	**Tether Management Subsystem Test** Demonstrates the ability of the TMS to retrieve the ROV with the brakes released Data: Observations and video tape

SUCCESS CRITERIA		TEST TITLE & MEASURED QUANTITY
2.1.3	Exposed surfaces of the TMS shall be decontaminable by either CO_2 blasting or high pressure water washdown techniques.	**Decontaminability Test** Verifies the effectiveness of decontamination by CO_2 blasting Data: Visual observation from the TMS
2.2	**Vacuum Filtration and Containment Subsystem (VFCS)**	
2.2.1	The VFCS shall employ a HEPA filtration unit to remove separate contaminants for disposal.	**Filtration Subsystem Specifications** Specifications provided by the manufacturer of the filtration system
2.2.2	The VFCS shall be sealed to provide effective contaminant containment.	**Cold Test** Verifies seal effectiveness by placing leak indicators at the seals of the VFCS Data: Visual observation and video tape of leak indicators
2.2.3	Exposed surfaces of the VFCS shall be decontaminable by either CO_2 blasting or high pressure water washdown techniques.	**Decontaminability Test** Verifies the effectiveness of decontaminating by CO_2 blasting Data: Visual observation of VFCS
2.3	**CO_2 Blasting**	**System Productivity Test**
2.3.1	The CO_2 Blasting unit shall incorporate a substrate heating unit to enhance contaminant removal.	Measures the blasting rate at (sq ft/hr) maximum CO_2 pellet rate and blast air/N2 pressure for both epoxy paint and sealant Data: Time, area swept, motor/indexer commands, blast air/N2 pressure, and CO_2 pellet rate.

SUCCESS CRITERIA	TEST TITLE & MEASURED QUANTITY
2.4 System Effectiveness	**Cold Test**
2.4.1 ROVCO_2 shall be capable of removing 75-99% of smearable contamination from concrete floor surfaces.	Determines the effectiveness of removing smearable contamination from concrete floors by laboratory analysis of smearable contamination applied and remaining Data: Smearable contamination applied and remaining
2.4.2 ROVCO_2 shall be capable of removing 50-99% of fixed contamination from surface pores of the concrete in a single pass.	Determines the effectiveness of removing fixed contamination from the surface pores of the concrete in a single pass by laboratory analysis of fixed contamination applied and remaining Data: Fixed contamination applied and remaining
2.5 System Reliability	**System Reliability & System Productivity Tests**
2.5.1 ROVCO_2 downtime shall not exceed more than 20% of expected operation time due to component failure.	Measures down time over 1,000 hours of operation of system except blasting. Blasting reliability is determined from history of manual operation. Data: Run time, component failures, failure effects, time down, repair time, and repetitive failures.
2.6 System Productivity	**System Productivity Test**
2.6.1 ROVCO_2 shall be capable of decontaminating between 30 and 75 square feet of concrete floor space per hour, dependent upon the level of decontamination required and the contaminated surface relief.	Determination of the systems productivity by determining the average time to decontaminate the areas including CO_2 blasting and vehicle movements Data: Time, area swept, motor/indexer commands, blast air/N2 pressure, and CO_2 pellet rate
2.6.2 The OCU shall autonomously control tedious repetitive operations, allowing the operator to focus on overall system operation and monitoring.	Verification of the OCU's ability to control tedious repetitive operations Data: Command given, operation conducted, and visual observations

3.6 Test Safety

At Oceaneering, safety is always first. The safe operation of the $ROVCO_2$ system was laid out in the phase 1 safety memo, included in the phase 1 report, and is included as Appendix B: *Safety for the $ROVCO_2$ System.*

3.7 Concept Demonstration of Phase 2 Additions and Enhancements

Oceaneering completed the fully outfitted $ROVCO_2$ system by integrating the subsystems procured in phase 2 with the phase 1 system. The subsystems integrated were the tether management system and the filtration and vacuum system. Modifications and improvements included the AutoROV function for linear decontamination of operator set distances, and enhancements and changes defined during phase 1 testing. The fully functional system was then tested to demonstrate and verify the integrated operation of the components added during the phase.

The concept demonstration was conducted throughout the phase 2 testing and demonstrated that all subsystems had been successfully integrated into the system as designed with the exception of the workhead containment as elaborated in following sections.

3.8 System Productivity Tests

The system productivity test was designed to evaluate how well the system met the success criteria. Testing objectives were developed to demonstrate the system's capability to perform these actions as well as to obtain reliability data during blasting operations:

- demonstrate the $ROVCO_2$ capability of decontaminating between 30 and 75 square feet of concrete floor space per hour in a realistic duration of operations
- demonstrate the OCU capability to functionally automate tedious, repetitive operations
- determine the blasting rate for epoxy paint and sealant
- obtain reliability data during blasting operations

Phase 2 testing resulted in two blasting sessions. The first round of testing determined initial productivity results and concluded improvements were needed to the effectiveness of the containment system. The remaining tests were postponed until a new workhead to improve containment could be developed by WMC. A new WMC designed blasting nozzle to increase the removal effectiveness on harder coatings like high-grade, two-part epoxy paints was done at the same time.

The second workhead, a prototype, was manufactured by WMC, the maker of the blasting nozzle. As discussed in chapter 2, the design focused on the required geometry to capture the flow lines of the blasting stream. The modification to the blasting nozzle improved the geometry of the blasting pattern as discussed in chapter 2.

The second blasting portion of phase 2 testing:

- tested the second workhead and the new nozzle,
- completed the phase 2 tests requiring blasting operations, and
- demonstrated the need for redesigning the workhead further.

3.8.1 Procedures

The productivity of the ROVCO_2 system was determined by operating the system in conditions similar to the Oak Ridge K-25 site. Two scenarios were developed: The first used sealant as the coating over a large area representing the area between columns in the K-25 building; the second used epoxy paint applied over a smaller area, approximately 75 sq ft. The coatings and the concrete chosen simulated those used by ORNL at the proposed integration demonstration site. The epoxy coating, Pittsburgh Aquapon® Polyamide-Epoxy, is a high-grade, two-part epoxy paint and is the same type as the typical coatings used at Oak Ridge. The sealer, Zeptone Sealer™, manufactured by the Zep Manufacturing Company is the same type and representative of the sealant used at Oak Ridge.

Before testing, the COYOTEE blasting rate for each coating was determined for setting the carbon dioxide pellet and air flow rates as determined by time to clean the surface. These flows were chosen by visually comparing the amount of coating removed at different sweep speeds and step sizes. The blasting speed selected was that which removed more than 85 percent, and preferably 100 percent, of the coating considering the coating and the operator's experience using the system. Small coated areas of epoxy (such as the test) tend to be less uniform and the "lumps" require extraordinary blast duration.

The productivity test was conducted by recording the amount of time required to clean a selected amount of floor area. Both manual and AutoROV operation modes were used in this operation. The operator enabled manual mode to move the vehicle after it had completed cleaning a row and to align it at the next row's start location. The operator then enabled AutoROV to clean each row. Planned manual adjustments were used during AutoROV mode to improve the vehicle's alignment and to reduce gaps between consecutive rows.

The system productivity tests were also used to gather reliability information (including single point failures, time to repair, repeated failures, and failure effects). These data were recorded, combined with, and analyzed as part of the system reliability test.

3.8.2 Results

The productivity test was conducted in two sessions. During the first session (from July 31 through August 4, 1995), the original workhead was used. During the second session (from October 16 through 20, 1995), the new blasting nozzle and workhead discussed in chapter 2 was used.

3.8.2.1 Initial Productivity Testing

The first week of testing showed that the workhead was not containing the desired amount of the contaminants. Although the vacuum was performing to specification, the momentum of the blast was greater than the vacuum and was not significantly affected by the vacuum suction. As discussed in chapter 2, analysis of the result showed that the workhead vendor's rule of

vacuum flow = 2 x blasting flow

was erroneous. Despite the workhead problems, Oceaneering decided to proceed with tests not affected by the workhead problems to take advantage of the compressor equipment being rented at a weekly rate.

The testing selected blasting speeds for sealant and epoxy paint were 7.5 in./sec and 0.4 in./sec, respectively for removing more than 85 percent, and preferably 100 percent, of the coatings. Productivity and reliability data were recorded for the removal of sealant during the initial productivity test and produced more than nine hours of blasting data. The data and results are presented in table 2. The final productivity result for the original nozzle was 49.2 sq ft/hr on sealant.

Table 2: Initial productivity data and results for concrete sealant.

DATE	TIME	Elapsed Time (sec)	Distance Traveled (in)	Area Cleaned (ft^2)	Accum. Area (ft^2)	Area/time (ft^2/hr)	TOTAL Area/Time (ft^2/hr)
Wed, Aug 2 1995	18:34	960	58	12.89	12.89	48.33	48.33
Wed, Aug 2 1995	19:07	2280	202	44.89	57.78	70.88	64.20
Thu, Aug 3 1995	14:00	2100	52	11.56	69.33	19.81	46.74
Thu, Aug 3 1995	14:40	3240	...	...	69.33	...	...
Thu, Aug 3 1995	15:45	3480	...	...	69.33	...	...
Thu, Aug 3 1995	16:50	1320	...	...	69.33	...	...
Thu, Aug 3 1995	17:24	2760	682	151.56	220.89	50.52	49.27

Initial productivity testing indicated that the $ROVCO_2$ system meets the success criterion that between 30 and 75 square feet of concrete floor space be decontaminated per hour.

3.8.2.2 Final Productivity Testing

The final productivity test incorporated the redesigned workhead and the new blasting nozzle. The new nozzle significantly improved blasting productivity and the redesigned workhead was still less successful than desired, as discussed in chapter 2. Cryogenesis Subsystem Enhancement Approach. Productivity testing continued to remove coatings from Oceaneering's warehouse floor, the test site. The new rectangular nozzle clearly improved the removal rates of concrete sealant and epoxy paint. The resulting speed and step size when removing concrete sealant are 10 in./sec and 1.2 in., respectively. The resulting speed and step size when removing epoxy paint are 0.85 in./sec and 0.65 in., respectively. The improvement in speed (from 7.5 to 10 in./sec) consequently improved the productivity of the system from 49.3 sq ft/hr to 93.8 sq ft/hr when removing concrete sealant. The resulting productivity rate when removing epoxy at this blasting speed is 10.9 sq ft/hr. The average removal rate, conservatively assuming a 50/50 division of sealant and epoxy, is 52.4 sq ft/hr.

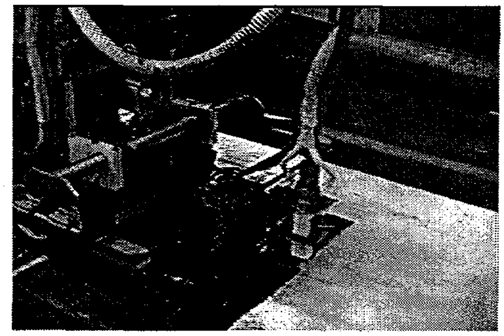

Figure 1: Final productivity testing removing epoxy paint with the new rectangular nozzle

Table 3: Final Productivity data and results for concrete sealant and epoxy paint.

DATE	TIME	Coating	Elapsed Time (sec)	Distance Traveled (in)	Area Cleaned (ft^2)	Accum. Area (ft^2)	Area/time (ft^2/hr)	TOTAL Area/Time (ft^2/hr)
Tue, Oct 17 1995	16:42	Sealant	1440	182	42.97	42.97	107.43	107.43
Tue, Oct 17 1995	17:26	Sealant	240	...	...	42.97	...	...
Tue, Oct 17 1995	17:33	Sealant	480	...	...	42.97	...	...
Tue, Oct 17 1995	17:50	Sealant	960	...	...	42.97	...	...
Tue, Oct 17 1995	18:18	Sealant	480	...	...	42.97	...	...
Tue, Oct 17 1995	18:30	Sealant	1860	...	...	42.97	...	...
Tue, Oct 17 1995	19:05	Sealant	3900	851	200.93	243.90	91.33	93.81

Tue, Oct 17 1995	20:08	Epoxy	4020	...	...	...	...	...
Wed, Oct 18 1995	16:40	Epoxy	8940	...	...	...	...	...
Wed, Oct 18 1995	18:46	Epoxy	1560	...	...	...	...	...
Wed, Oct 18 1995	19:48	Epoxy	10080	...	...	...	...	
Wed, Oct 18 1995	22:47	Epoxy	600	262	76.42	76.42	10.92	10.92

3.8.3 Conclusions

The results of the productivity testing were an average removal rate of 52.4 sq ft/hr vs. success criteria range from 30-75 sq ft.hr (a mean at 52.5 sq ft/hr). The productivity test results include time for manually repositioning the vehicle and routine system support. The average removal rate assumes equal areas of sealant and epoxy coating which is conservative when considering processing sites such as K-29 at ORNL's K-25 site. Estimate of sealant to epoxy in K-29 are 2::1 or 3::1, resulting in average removal rates up to 73.1 sq ft/hr.

Since both manual and AutoROV operation modes were used during the productivity test, improved productivity rates are inevitable as experience is gained operating the system. More operating experience will also assure improved alignment of consecutive blasting rows to achieve maximum coating removal and to eliminate missed areas. Operating experience will also decrease the amount of adjustments required to maintain the vehicle in a straight path. Improved manual alignment of blasting rows can be achieved by further adjusting the camera position to better view the COYOTEE home location.

It is worth noting that the blasting speed for removing 85 to 95 percent of the epoxy from the floor was 0.85 in./sec or 28 sq ft/hr. Improved productivity can be achieved by operating the blast nozzle at faster speeds. The removal effectiveness will be reduced yet remain within the success criterion that calls for 50 to 99 percent of fixed contamination removal.

The test also demonstrated the OCU's capability to autonomously control tedious, repetitive operations. When the AutoROV operation mode is enabled, the operator is free to monitor overall system operation safely, such as alignment, ice hopper level, and vehicle health, and to perform brief, unrelated actions.

3.9 Cold Test

Before describing this test, conventional terminology must be defined.

Contaminant applied: contaminant originally placed on the concrete before blasting.

Contaminant not removed; contaminant remaining: contaminant still physically attached to or within the concrete after blasting.

Contaminant removed: contaminant no longer physically attached to or in contact with the concrete after blasting *(amount applied - amount remaining = materials removed)*

Contaminant contained: contaminant removed from the concrete and stored in the ROVCO_2 system after blasting.

Noncontained contaminant: contaminant detached from the concrete and remain in the containment curtain after blasting.

Smearable contaminant applied: original amount of Smearable contaminant underneath the coating before blasting.

Smearable contaminant remaining: amount of smearable contaminant still physically attached to the concrete and the amount of material fall backs on the surface after blasting.

Contaminant fall backs: contaminants which were detached from the concrete by blasting but were not contained within the containment subsystem and fell back to the concrete.

Fixed contaminant applied: the amount of fixed contaminant underneath the coating before blasting. *(total surrogate applied - smearable surrogate applied = fixed surrogate applied)*

The cold test was designed to evaluate how well the system met the success criteria to verify the vacuum seal's effectiveness, determine the effectiveness of removing smearable contamination, determine the effectiveness of removing fixed contamination, and determine the effectiveness of the ROVCO_2 system by modeling the Oak Ridge site conditions. The cold test determined the effectiveness of:

- the VFCS subsystem's ability to contain contamination around the containment drum,

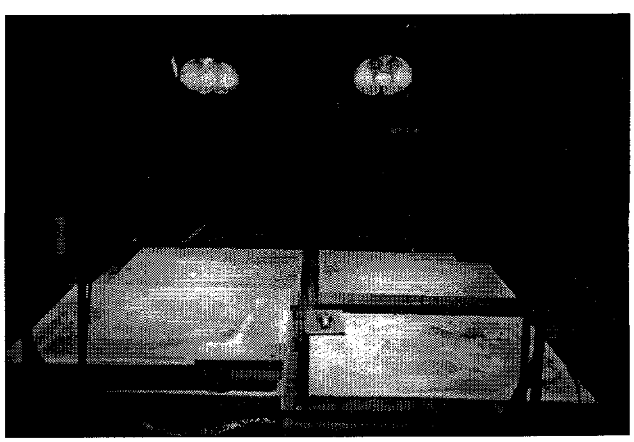

Figure 2: The cold test modeled site conditions as close as possible including building heat and concrete specifications

- the $ROVCO_2$ system's ability to remove smearable contamination,
- the $ROVCO_2$ system's ability to remove fixed contamination.

3.9.1 Procedures

The site was modeled by applying a nonhazardous contaminant surrogate that had been dissolved in an aqueous solution to the concrete surface. After the surrogate had been applied by misting, a coating was applied over the surrogate.

The K-25 site contaminants selected for representation were uranium and polychlorinated biphenyls (PCB) due to their surface behavior and relative abundance at the site. A number of factors were considered in selecting the surrogates including detectability, previous usage, chemical properties, applicable surrogate compound, safety, availability, cost, and reactability. A cerium salt was selected as the surrogate for uranium based on cerium's past performance as a uranium surrogate, its similarity to uranium properties, and documented recommendations as a uranium surrogate. Pennzoil® 409 Gear Lube ™ was selected as the PCB surrogate since PCBs are strongly soluble in oil and are considered as having been carried by the oil used while the site was in operation. The Pennzoil product is considered a straight, heavy-weight mineral oil and is similar to a lubricant used in ventilation equipment. Refer to the $ROVCO_2$ Phase 2 Test Plan (Appendix C) for further information on the modeling of the concrete, coatings, contamination process, and the selection process of the modeled contaminants, surrogates, and detection methods.

Five concrete slabs were cured: four for the below scenarios below and one spare.

- Slab no. 1 sealant over uranium (surrogate: cerium chloride solution)
- Slab no. 2 epoxy over uranium (surrogate: cerium chloride solution)
- Slab no. 3 sealant over PCBs (surrogate: gear lube)
- Slab no. 4 epoxy over PCBs (surrogate: gear lube)

The $ROVCO_2$ blasting system was used to decontaminate the concrete slabs (figure 3). In some cases, when removal appeared questionable, several blasting speeds and step sizes were used to remove the contaminants, contrary to the test plan. The blasting speeds that were determined during the productivity test were initially used to remove the coatings and contaminants. Poor results when using those blasting speeds led to the conclusion that slower speeds and possibly smaller step sizes would remove the contaminants beneath the applied coatings. The remaining cerium was visible by the yellow tint it lent to the concrete.

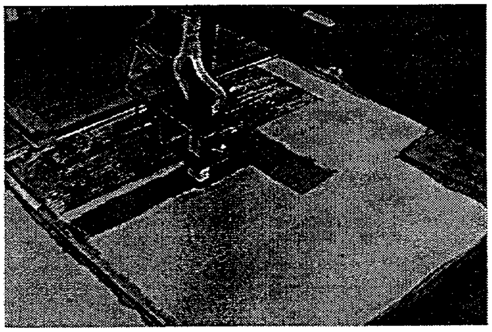

Figure 3: The $ROVCO_2$ System decontaminating slab no.2

After collecting the test samples according to the test plan, the effectiveness of the $ROVCO_2$ system was determined by laboratory analysis. Samples of the concrete and the smear cloth, taken before and after blasting, were submitted to XRAL Laboratories, Canada. The laboratory analyses used and their respective sample contents evaluated appear in table 4.

Table 4: Laboratory analysis performed on samples.

Sample Contents	Laboratory Analysis
Fixed or Smearable Cerium Chloride	Inductively Coupled Plasma/Mass Spectrometry (ICP/MS)
Fixed or Smearable Gear Oil	Gravimetric Determination by Methylene Chloride Extraction (GD/MCE)
Epoxy Paint	X-Ray Fluorescence (XRF)

Concrete samples were taken using a hand-held scarifier. To prepare the area that was to be sampled, a shield surrounded and sealed the scarified area to collect any concrete dust removed by the scarifier. The shield was a simple cardboard box with a seal that was pliant enough to maintain contact where it met the floor. After the amount of concrete defined in the test plan had been removed, the concrete dust was carefully swept into a dust pan, transferred to a sample container, and weighed to verify enough sample material had been taken for each analysis. Between each sampling, the items used to collect the concrete samples were cleaned by blasting them with compressed air. The concrete samples determined the amount of contaminants and coating applied and remaining after blasting. The samples were taken at three different depths to indicate the system's ability to penetrate. Clean, uncoated concrete samples were taken for control.

To obtain smearable contaminant samples, the slabs were wiped with Masslinn® Dust Cloths. This is the brand used at the Oak Ridge site to conduct smear tests. During this test, the procedure to determine the amount of applied smears on the slabs was done incorrectly. Initially the applied smear test included wiping the entire slab with the cloths. This resulted in removing the smears from the entire slab therefore the difference between before and after would not have been realistic. When this error was discovered, additional smear tests were performed on the spare concrete slab, number 5 to recreate the test. The two contaminants were applied to the fifth slab (one per half) in the same manner as the previous slabs. Two smear tests were conducted on each half of the spare slab:

1. The first smear was conducted identically to the previous smear test on the other slabs by covering the whole area of the slab.

2. The second smear was conducted over an area equal to a scarified area and indicates the amount of smearables remaining under the applied coatings.

3.9.2 Results

3.9.2.1 Accuracy

The following accuracies were achieved by the laboratory analysis:

- During the inductively couples plasma and mass spectrometry analysis of fixed or smearable cerium chloride, the laboratory achieved a 0.1 ppm detection limit for the cerium with an accuracy of ± 0.3 ppm.

- During the X-ray fluorescence analysis for epoxy paint, the laboratory achieved a 0.01 percent detection limit for SiO_2, Al_2O_3, CaO, MgO, Na_2O, K_2O Fe_2O_3, MnO, C_2r_3, $_2P_5O$, T2iO with an accuracy of ± 0.5 percent.

- During the gravimetric determination by methylene chloride extration analysis, the laboratory achieved approximately 0.001 percent detection limit for a 10 gram sample of oil with an accuracy of $\pm$ 0.0015 percent.

As illustrated in figure 4, the scarifier may have removed surrounding surface material from previously detached layers. Any of that material collected with and analyzed as part of the tested layer contributes to a number of errors. Therefore, error analysis involving the above accuracies was not computed. Additional possible sources of errors are discussed in the following results.

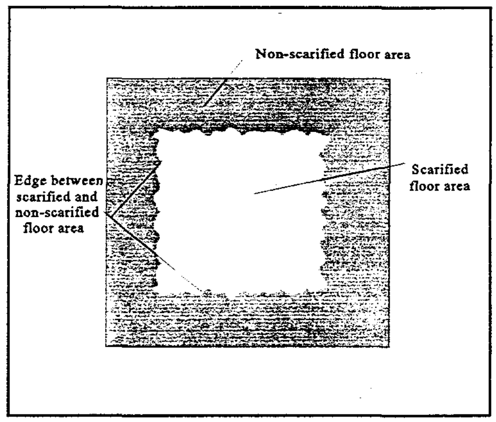

Figure 4: A possible source for error in the second and third removed layers is from the scarifier removing surrounding surface material

3.9.2.2 Removal Effectiveness

Fixed Contaminants

From the laboratory analyses, quantitative results have been obtained to verify the $ROVCO_2$ system's effectiveness in removing coatings. The results from the concrete samples are presented in tables 5 and 6.

Before evaluating the results, the significance of the results obtained from testing the second and third layers must be understood. The depth of a layer that the scarifier reached in one sampled area varies from corresponding layers taken in other sampled area locations. The significance of defining the layers as one, two, or three is limited only to the sequence that layer one is above two, and layer two is above layer three for each individual sample area. The errors involved in taking the layered samples should also be noted. After removing the first layer of concrete, several locations indicated that epoxy or cerium was still present by the color of the remaining concrete. The remaining contaminants are more likely to be from the difficulty in removing an evenly distributed layer of concrete by the scarifier. Other errors can be introduced into the second and third layer samples if the scarifier hit the edges of the removal area adding material from the top surface of the concrete (see figure 4). The samples taken at deeper depths should give a basic understanding of the end results of the blasting system provided the numbers are large enough to provide a confident conclusion.

Results from testing slab no. 2 (table 5) illustrate that the ROVCO$_2$ is quite successful in removing the epoxy coating well within the requirements outlined in the success criteria. At the speed used to achieve the productivity test results, 79 percent of the coating was removed, and 50 percent of the fixed contaminants was removed (based on one sample of the concrete). The percent removed significantly increases as the blasting speed decreases. Operating at half the speed increases the percent removal to 95 percent for epoxy coating and 75 percent for the fixed contaminants. Comparing the results from the blank sample and the second and third layer indicates that minimal traces of epoxy coating were found.

To apply the cerium to the concrete slabs, the cerium was mixed into a water-based solution and sprayed on to the slabs. It was observed that the amount of water used to dissolve the cerium was more than desirable after it was applied to the concrete. The water may have given the surrogate a penetrating ability unlike the characteristics of the uranium simulated. The concrete slabs may have absorbed the cerium solution explaining the amount of cerium found in the second and third layers.

Table 5: Slab # 2 removal effectiveness results for fixed contaminants and epoxy

Slab # 2						
Blank Content	Depth	Applied	Remaining		Percent Removed	Percent Removed
			0.425 in/sec 0.65 in step	0.85 in/sec 0.65 in step		
Epoxy 0.137 pph	1	5.220 pph	0.375 pph	1.190 pph	95.31 %	79.28 %
	2	0.173 pph	0.131 pph	0.149 pph	--	--
	3	0.144 pph	0.167 pph	0.108 pph	--	--
Cerium 134 ppm	1	95400 ppm	24200 ppm	48200 ppm	74.74 %	49.55 %
	2	21100 ppm	13200 ppm	25500 ppm	37.68 %	-20.99 %
	3	10900 ppm	7910 ppm	13700 ppm	27.77 %	-26.01 %

Results from testing slab no. 4 further illustrate ROVCO$_2$'s ability to successfully remove the epoxy coating well within the requirements outlined in the success criteria. At the speed used to achieve the productivity test results, 97 percent of the coating was removed, and 46 percent of the fixed contaminants was removed. Analysis of the amounts of applied and removed gear lube samples indicates that the gear lube migrated into the concrete.

Table 6: Slab # 4 removal effectiveness results for fixed contaminant and coating

Slab # 4				
Blank Content	Depth	Applied	Remaining	Percent Removed
			0.85 in/sec 0.65 in step	
Epoxy 0.137 pph	1	9.16 pph	0.428 pph	96.77 %
	2	0.738 pph	NSS	--
	3	0.417 pph	0.099 pph	--
Gear Lube 0.07 pph	1	0.48 pph	0.29 pph	46.34 %
	2	0.45 pph	0.20 pph	65.79 %
	3	0.49 pph	0.24 pph	59.52 %

Unlike the other test slabs, two samples were taken from slab no. 3. The first results appeared corrupted and did not correlate with other results or contribute to invalid conclusions. The second set of results are presented in table 7. These results demonstrate that ROVCO$_2$ can remove more than 50 percent of the fixed contaminants as specified in the success criteria.

Table 7: Slab # 3 removal effectiveness results for fixed contaminates

Slab # 3						
Blank Content	Depth	Applied	Remaining		Percent Removed	Percent Removed
			2 in/sec 1.2 in step	10 in/sec 1.2 in step		
Gear Lube 0.07 pph	1	1.65 pph	0.79 pph	0.91 pph	54.43 %	46.84 %
	2	0.92 pph	0.51 pph	0.46 pph	48.24 %	54.12 %
	3	0.69 pph	0.07 pph	0.17 pph	100.00 %	83.87 %

Slab no. 1 (concrete sealant over cerium) results indicate that the percent removed is less than the amount listed in the success criteria. The test was conducted at three different blasting speeds. The blasting speeds for removing concrete sealants were initially used and slowed to remove the visible cerium. Visual observation of the results achieved at speed "A" (2 in./sec and 0.65 in. step) indicated that approximately 80 to 90 percent of the cerium was being removed. Comparing slab no. 1 results with slab no. 2 results shows that at the slower speed used on the epoxy (slab no. 2) also removed more cerium. This may be a result from more cerium being applied (more than double) to the surface of the epoxy slab in the area that the samples were taken. The remaining cerium on slab no. 1 is very close to the amount remaining on slab no. 2 which had a higher percent removal of 75 percent.

Table 8: Slab # 1 removal effectiveness results for fixed contaminants

Slab #1							
Depth	Cerium Applied	Cerium Remaining			A Percent Removed	B Percent Removed	C Percent Removed
		A	B	C			
		2 in/sec 0.65 in step	10 in/sec 1.2 in step	10 in/sec 0.65 in step			
1	40600 ppm	24800 ppm	26300 ppm	29900 ppm	39.05 %	35.34 %	26.44 %
2	24200 ppm	17000 ppm	15000 ppm	18100 ppm	29.92 %	38.23 %	25.35 %
3	22800 ppm	13600 ppm	13100 ppm	13800 ppm	40.59 %	42.80 %	39.71 %

3.9.2.3 Smearable Contaminants

Results for the smearable contaminants were received for the two cerium slabs, no. 1 and 2, only. The smear cloth type does not have favorable reactability to the methods planned and used to detect oil; therefore, results for the gear lube smear samples were not achieved.

After the cerium smear results had been received, it was discovered that an error had resulted. Two different engineers had taken the smearables applied and remaining samples. The applied samples were taken by lightly wiping over the area, and the remaining samples were taken by vigorously wiping the area as if a spill were being cleaned. This process resulted in a quantity remaining that was more than what had been applied. To correct the error, cerium contaminants were re-applied to the other side remaining, (the clean surface) of slab no. 5. The same procedures were followed for taking the first set of applied smearables, except the wipe was performed rigorously (in the same manner as the remaining smears were conducted). The results from the smearable analysis are presented in table 9.

Table 9: Removable effectiveness for smearable contaminates

Sample	Slab	Speed and Step Size	Cerium ppm	Percent Removal
Blank Cloth	--	--	<10	--
Applied	Slab #5	--	12800	--
		--	5170	--
Average Applied			11570	--
Remaining	Slab #2	0.425 in/sec 0.65 in step	133	98.85 %
		0.85 in/sec 0.65 in step	181	98.44 %
Remaining	Slab #1	2 in/sec 0.65 in step	46	99.60 %
		10 in/sec 1.2 in step	30	99.70 %
		10 in/sec 0.65 in step	38	99.67 %

The results indicate that the $ROVCO_2$ system successfully meets the success criteria requiring the removal of 75-99 % of smearable contamination from concrete floor surfaces.

3.9.2.4 Containment Effectiveness

The effectiveness of the containment subsystem focused on two components of the $ROVCO_2$ system: the workhead and the containment drum seal.

3.9.2.4.1 Workhead

The effectiveness of the containment at the workhead was examined during both sessions of phase 2 testing. The initial blasting tests showed that the subsystem's containment performance was less than desirable. Additional verification testing concluded that the system was operating as designed (at a drum pressure of -90 to -100 inches of water). The concept of vacuuming at twice the cfm of the blasting (given by the commercial workhead vendor) was concluded to be inadequate to capture the blasted particles. The concept design had not considered the implications of the rate of velocity of the blasting stream, 1,200 fps.

The second session concluded that the containment of the re-designed workhead was still less than desirable. The workhead improved the effectiveness of the vacuum surrounding the nozzle but was unacceptably sensitive to the clearance height of the workhead over the floor. The vacuum achieved at distances from the floor of less than 0.005 in. increased containment but significantly impacted COYOTEE's ability to move across the floor. As the distance between the workhead and the floor was increased in small increments, the ability to contain decreased markedly. Further testing of the containment with the containment curtain as planned was regarded as unnecessary until further improvements could be implemented to the workhead.

During the second week of testing, after completing phase 2 test requirements, additional configurations of the workhead were quickly constructed to evaluate their performance on improving containment. Throughout this process, a number of valuable concepts were developed. The most beneficial aspect of phase 2 testing was the experience gained during blasting operations of the ROVCO_2 vehicle. The experience has increased the knowledge of cleaning floors by carbon dioxide blasting. This experience has been used as a basis to find a solution to the workhead problem in phase 3 (see volume II of this report).

3.9.2.4.2 Containment Drum Seal

The integrity of the seal on the containment drum was verified by visual observation. After the leak indicator (a 4-mil plastic sheet) was wrapped around the drum seal, the vehicle was powered up and maximum blasting air rates reached. During normal operation, that is, sweeping the test area, the leak indicator was observed. The seal was impressive. The vacuum's effectiveness was demonstrated in two ways: The plastic adhered to and contoured the shape of the drum flawlessly, and the bottom of the containment drum assumed a permanent concave depression.

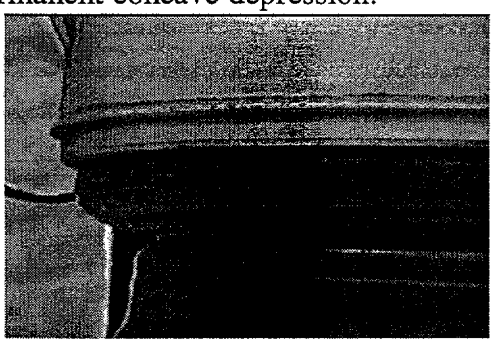

Figure 5: The vacuum filtration's drum seal inflated against the storage drum.

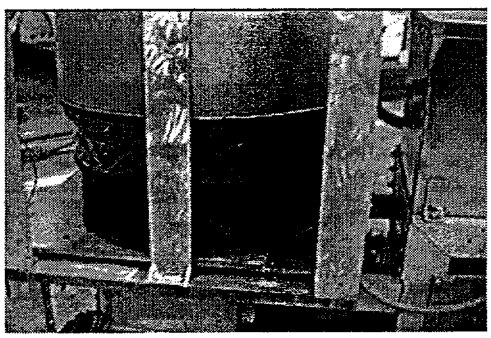

Figure 6: The seal leak indicator attached over the drum seal.

3.10 Decontaminability Test

The decontaminability test was designed to verify that the exposed surfaces of the vacuum filtration and containment system (VFCS) and the tether management system (TMS) can be decontaminated by carbon dioxide blasting.

3.10.1 Procedures

The test was conducted by applying a brightly colored powdered chalk to the entire vehicle and Tether Management System (TMS). In addition to the applied chalk, the vehicle and TMS had acquired a thick layer of dust and dirt while prior tests were being conducted in the Oceaneering warehouse. Based on observations, the powdered chalk exhibits stronger cohesive characteristics than those expected in decontamination residue. The powdered chalk was distributed over the vehicle's flat surfaces and in its multiple crevices. The chalk was removed by blasting the vehicle and the TMS first with air and then with carbon dioxide.

3.10.2 Results

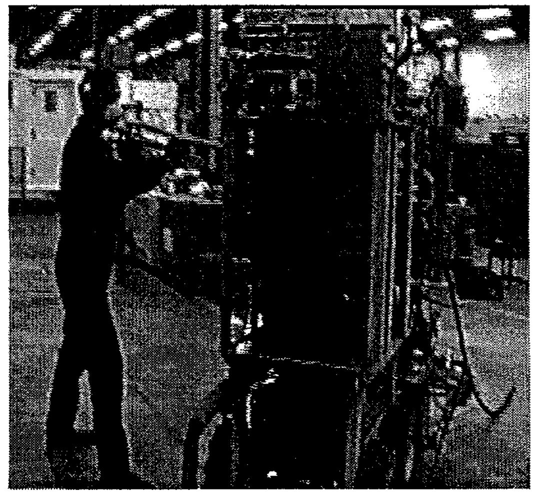

Figure 7: The vehicle was successfully decontaminated by manually operating the blasting nozzle

Decontamination was conducted by manually operating the carbon dioxide blasting subsystem. Initial attempts to remove the chalk were conducted by using the blasting nozzle with only air at approximately 150 psi. Initial tests showed that air pressure removed most of the dust and chalk, but a few hard spots remained (approximately 10 percent of the chalk applied). The test continued by blasting the vehicle and the TMS with carbon dioxide at the same pressure. Using carbon dioxide blasting clearly removed the remaining residue and further cleaned the other surfaces. The difference between the effectiveness of air and carbon dioxide was clearly visible. Recorded videotape of the vehicle before and after decontamination illustrates the effectiveness of the carbon dioxide blasting subsystem for cleaning the vehicle. A white whipping cloth was also used to verify the cleaning effectiveness. Since decontaminating the vehicle was so successful, less time was focussed on cleaning the TMS. The tape also shows the results of wiping down the vehicle using the white cloth.

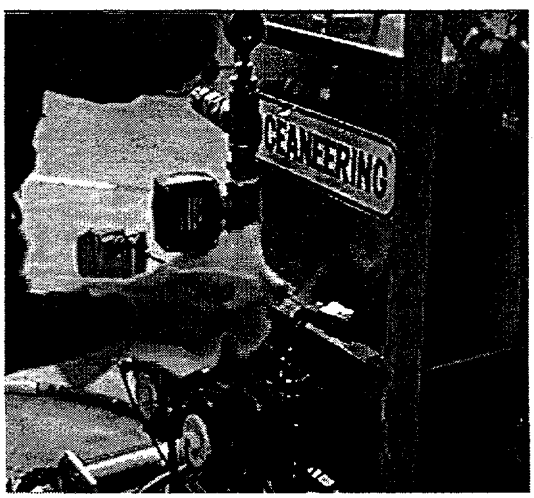

Figure 8: The vehicle was wiped down with a white cloth after cleaning to assure successful decontamination

3.10.3 Conclusions

The carbon dioxide system can be used to decontaminate the vehicle. For continued operation of the system, safety procedures should be implemented to eliminate the danger of manually operating the nozzle at high pressures. Example safety procedures include:

- The front of the vehicle should be positioned close to the item being cleaned to maintain mobility in the hoses around the object.

- The number of blasting cycles required to clean the item should be sufficient to allow reorientation of the nozzle. Before beginning this cleaning cycle, both operators must agree on the length of the cycle to allow the operator at the system to adjust blasting orientation to the vehicle between cycles.

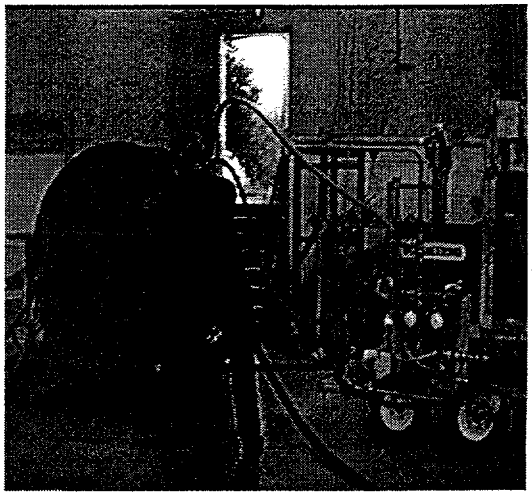
Figure 9: Locating the vehicle close to the TMS gives the operators maneuverability while decontaminating the TMS

3.11 Tether Management Subsystem Test

The tether management subsystem (TMS) test was designed to verify the tether's ability to pay out and reel in as the vehicle moved and to recover the vehicle in a contingency situation. This latter requirement was rejected during the subsystem's development and was not included in the actual testing.

- Verify the ROVCO_2's capability of managing tether payout and reel-in as required for effective ROV motion

- Demonstrate the TMS's capability of recovering the vehicle in a contingency situation

3.11.1 TMS Test

Testing of this system occurred throughout the testing, including the 900 hours of operation on the test stand. As the COYOTEE completed a cycle, the vehicle, connected to the TMS, moved forward forcing the tether to pay out and reel in the umbilical while the vehicle was on the stand.

During the productivity test vehicle movement and the required support by the TMS occurred constantly, visual observations concluded success by operating the vehicle in expected conditions during the productivity test and cold test. The vehicle was regularly relocated and maneuvered during both rounds of blast tests.

Although the test plan included an extensive section on maneuverability, actual operating experience proved more realistic and more valuable. Almost from the beginning of the testing, the decision was made to abandon this part of the test plan. The operations evaluated the vehicle's maneuverability around typical obstacles, at angles, and when traveling in forward and reverse in straight lines. The maneuvers required to execute the blast tests were adequate to prove maneuverability and produced valuable results viewed more beneficial than could be achieved from the planned tests. As can be observed, the test videotape documents this success.

3.11.2 Vehicle Recovery Test

As discussed in chapter 2, ability to recover the vehicle in a contingency situation was eliminated for cost reasons. Therefore, this phase of the test was deleted.

3.11.3 Results

The TMS is easily operated from the operator control unit as the vehicle is maneuvered. Coincidentally, the TMS pays out and reels in cable at about the same speed as the vehicle travels when in slow speed (sharing the same air supply pressure). The winch can be operated without manual intervention. Lagging loops may form in the cable around the drum as it is reeled out. The loops are removable by remotely reeling the cable back until the loop is removed. Manual intervention at the winch is an optional method in assisting the level wind of the cable.

3.12 System Reliability Test

The system reliability test was designed to verify that the ROVCO_2's downtime due to component failures does not exceed more than 20 percent of the expected operation time. Reliability data was collected throughout portions of phase 2 testing of the ROVCO_2 system.

3.12.1 Procedures

Data for this test were recorded during two different phases of testing: during the blasting operation test and during the system reliability test, itself. During this latter phase, the system was mounted on a test stand. The vehicle ran continuously on the test stand after inputting a command to the AutoROV to over ride the controls that determine the linear distance the system must travel to clean the area usually defined by the operator. AutoROV then continuously repeated cycles defined as the vehicle completing a sweep of the COYOTEE and its advancement (wheel rotation and winch pay-out) to the next sweep area.

The system was monitored by sensors attached to components that had been identified as integral. These sensors recorded data from six proximity sensors (one to each wheel); four proximity sensors (one at each corner of COYOTEE); one proximity sensor on the winch; four pressure switches on each valve on the vehicle.

The system identified the time when any single point failure occurred, logged the current sensor status, and shut off the system. All single point failures were monitored by wheel and winch rotations, COYOTEE movements, and valve actuation. From the electronic log of the current status of the monitoring signals, the failed component was identified. The monitoring system also logged the time when each successful cycle completed allowing an accurate count of operation time.

The test stand modeled the forces that act on the vehicle when it is operating on concrete. Flywheels attached to each wheel of the vehicle modeled the inertial forces each time the vehicle started or stopped motion. Flooring was fabricated and placed to simulate the frictional forces that act on the brushes around the workhead. The upward thrust that results from the blasting operation was modeled by applying a weight pulling upward on the workhead via a pulley mounted on the 30 foot tall ceiling.

Several trade-offs exist between conducting the reliability test manually and monitoring the system on a test stand. Conducting the test on a stand with a monitoring system increased the testing time period by adding time for fabricating the stand and fine tuning the configuration of the monitoring system. The monitoring system required time-consuming adjustments to increase its reliability. After the monitoring system reliably recorded failures, the system ran continuously until the ROVCO_2 system failed. During the test, inspection every eight hours assured that the systems were operating properly and double checked for undetected failures.

The time to repair the failure was calculated by considering only the amount of elapsed time between one of the test supervisor's discovering the failure and the time the test was restarted. This modeled the test operation as if it had been conducted manually and provided the same repair time results. Although conducting the test manually would have prevented time delays caused by set up and failure discovery, the test produced more accurate data than would have resulted from manual recordings. The monitoring system logged the time after each cycle was completed during the entire test. Only a few, approximately 9 hours, were completed without the monitoring system logging mode activated. These hours were noted and added into the data on the spreadsheet.

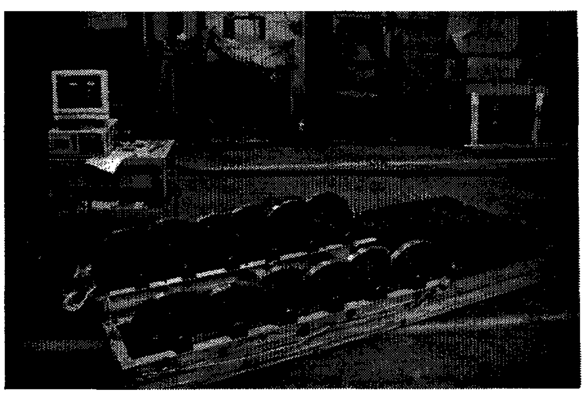

Figure 10: Reliability test stand and monitoring system

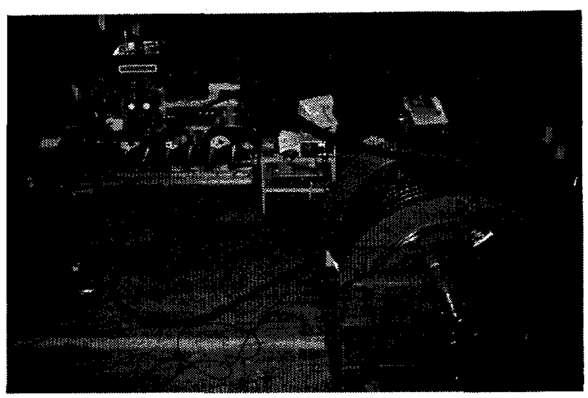

Figure 11: ROVCO_2 vehicle mounted on stand and winch setup

Since the reliability test conducted on the test stand did not actually conduct carbon dioxide blasting, blasting data was recorded during productivity and effectiveness testing. The CO_2 pellet supply subsystem has an established MTBF > 1000 hrs.

3.12.2 Results

The reliability testing has been categorized according to how it was generated:

- Data from the test stand are categorized as reliability growth testing (RGT).
- Data from blasting operations during the productivity test are categorized as design tryout (DTO).

Reliability growth testing is a value-added test, sometimes called test, analyze, and fix. The RGT provides a measured reliability figure of merit (availability) and, more importantly, identifies failure causes and corrective actions to eliminate the causes from the failure distribution. The test improves reliability as opposed to simply measuring it.

3.12.2.1 Availability

The RGT completed 371 hours on the test stand and demonstrated an achieved availability well in excess of the required 80 percent defined in the success criteria. During those 371 hours, the $ROVCO_2$ system experienced six maintenance actions, a statistically significant demonstration. The maintenance actions required a total of 2.39 hours corrective repair time. The corrective repair time also includes the logistics time for each repair. The 371 hours completed represents the total amount of time that the test was running (uptime). The results conclude that the $ROVCO_2$ system achieved an availability of 99 percent. From the equation to calculate availability

$$A_A = \frac{Uptime}{Total\ Time} \qquad (2)$$

and substituting the data from the tests

$$= \frac{371}{371 + 2.39} = 0.99 \qquad (3)$$

3.12.2.2 Mean Time Between Failures

The final data from the RGT is summarized in the following table.

Table 10: RGT Data Summary

Fail #	Time to Fail (Hours)	Time to Repair (Hours)	Fail Mechan #	Fail Mechan.	Maint. Type	Life Cycle Period
1	6.54	0.67	1	X-motor	Correct	Latent
2	65.89	0.67	2	X-Coy cable	Correct	Wearout
3	110.33	0.20	2	X-Coy cable	Correct	Wearout
4	60.45	0.20	2	X-Coy cable	Correct	Wearout
5	41.00	0.23	2	X-Coy cable	Prevent	Wearout
6	33.75	0.42	3	Limit Switch cable	Correct	Wearout
N/A	54.00	N/A	N/A	Failure Free	N/A	N/A

Five corrective and one preventative maintenance actions were conducted during the test. The preventative maintenance action replaced the X-COYOTEE cable before it failed at 41 hours. The other cables, numbers 2, 3, and 4, were replaced when the COYOTEE began to spin in the location of the worn cable. Wear on a cable can result from normal wear and from operational errors. The results in the above table include both influences on the cable.

The point estimate of the MTBF for the $ROVCO_2$ system is calculated using the formula

$$MTBF = \frac{Operational\ Time}{No.\ Failures} \qquad (4)$$

and substituting the data

$$\frac{371}{5} = 74.2\ hrs \qquad (5)$$

The point estimate is the resulting MTBF of the system over the operated time. The results are statistically significant because they allow boundaries to be assigned to the computed MTBF of the system. Standard assumptions for calculating the MTBF range assume an exponential distribution of failures. The resulting MTBF range from the demonstration, at the 90 percent confidence level, lies between 40.1 and 188.6 hours. The result also assumes no reliability growth has occurred. Reliability growth improves system operations by eliminating failure causes throughout system operations.

3.12.2.3 Increasing ROVCO$_2$ Reliability

The reliability of the system can and will be improved by incorporating changes into the design of the system and adding a preventative maintenance schedule. The failures are comparable to typical system/component life cycle characteristics. The following figure summarizes the life characteristics of most systems and/or components.

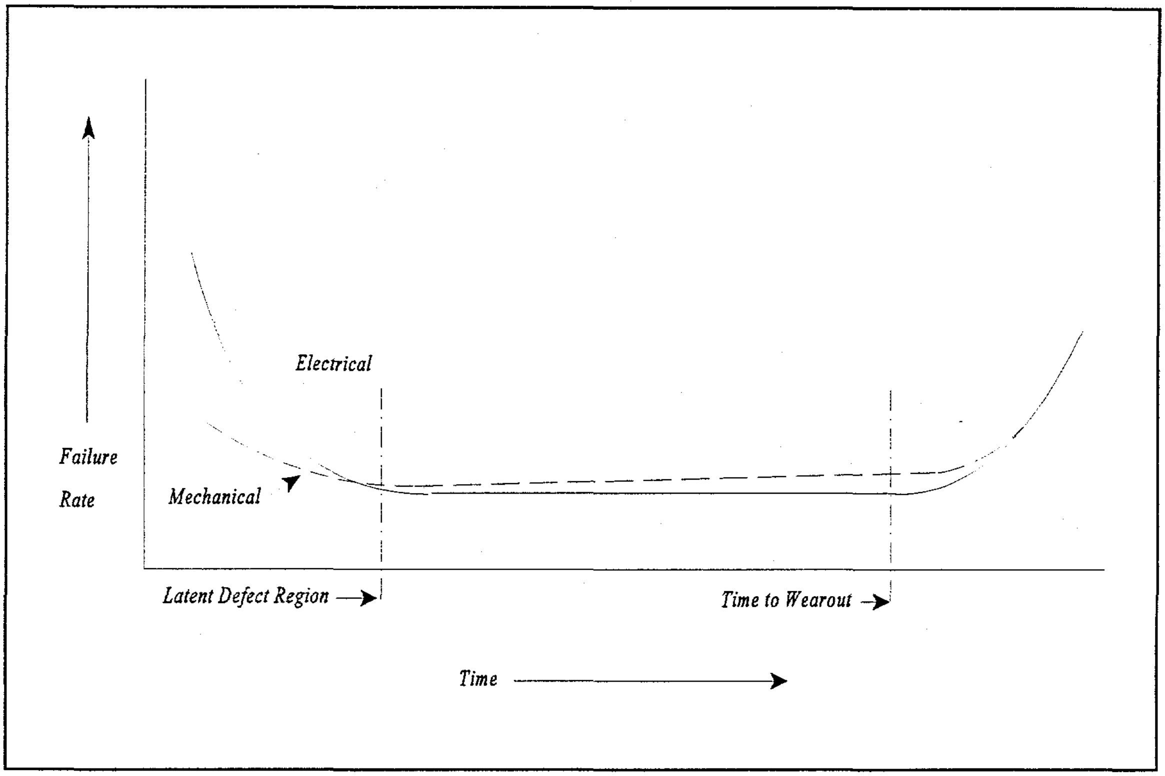

Figure 12: System/Component Life Cycle Characteristics

Three discrete time periods make up the life cycle:

- Early life: Initially, any hardware item exhibits a high failure rate due primarily to latent defects such as weak bonds, poor soldering, or cracked structures, introduced through manufacturing errors. These items are called weak units, and they usually fail at an initially high, but rapidly decreasing, rate and stabilize at a value-caused constant hazard rate. This aging can be achieved in the factory through a burn in period.

- Useful life: After the early life period, the item reaches its lowest failure rate level, characterized by a relatively constant failure rate. Often called the constant hazard rate region, this period extends until effects of wearout become noticeable by an increase in failure rate. This period is normally quite long, often lasting more than two decades. The reliability during this constant hazard region can be represented by a MIL-STD-756 reliability prediction.

- Wearout: The onset of the wearout period is characterized by a rapidly increasing failure rate due to the degenerative effects of fatigue and accumulated wear.

Note that the electrical and mechanical portions of the system are represented by different distributions but are, for the purposes of this discussion, similar.

Comparing the failures that $ROVCO_2$ experienced (shown in table 10) indicates that only two different failure modes were experienced. The first failure was a latent defect and the other failures were due to wearout.

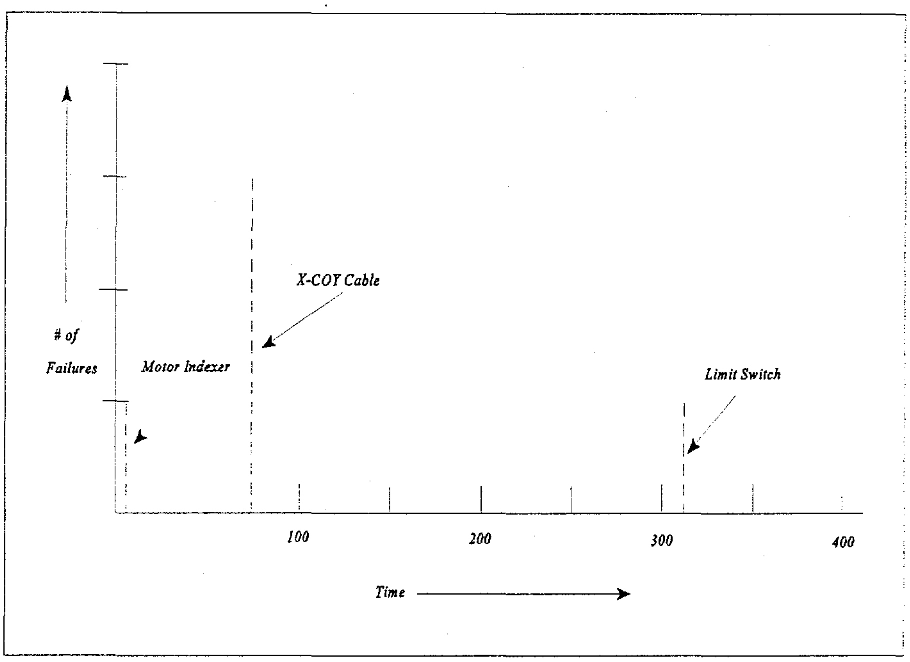

Figure 13: Distribution of Time to Failure

Figure 13 indicates that the motor indexer failed early in the demonstration. The indexer did not fail at any time during the remainder of the test. The manufacturer replaced the failed component (RS-232 chip) in the indexer, noting that the replaced chip was a common problem and advising that since having changed vendors they have not experienced the same failure again. This is clearly a latent defect and could be prevented in future systems by assuring that the installed indexer has the appropriate installed RS-232 chip. To prevent latent defects on new systems, a burn-in program of 12 to 24 hours per unit is recommended.

The three X-COYOTEE cable failures (statistically combined in figure 13) have a mean time to wearout of 78.89 hours (σ = 22.34). By physically examining the cable, the failure mechanism was classified as wearout. It can be prevented by incorporating a preventative maintenance operation performed weekly and requiring less than 15 minutes of labor and approximately $15 of material. Corrective action was implemented near the end of the testing by limiting the motor torque. Further exploration of elimination of this wear mechanism can be investigated in phase 3. One possible improvement is increasing the size of the drive pulley.

The last failure was caused by electrical wire fatigue at a limit switch on COYOTEE's cursor. The fatigue is a combination of repeated operation of the system and operator handling during assembly. The failure occurred at 318 hours. This failure mechanism can be eliminated by the addition of strain reliefs during phase 3.

In summary, if the two wearout failure mechanisms are eliminated by the proposed preventative maintenance program and the design change of added strain reliefs, the number of failures anticipated in an equivalent future demonstration of 371 hours would decrease in frequency to one. The point estimate of MTBF would grow from 74.3 hours to 371 hours.

3.12.2.4 Design Tryout

The design tryout (DTO) included 23.4 hours of total system operation including blasting. No statistical conclusions can be drawn from this series of DTOs. Measuring a reliability figure of merit availability in DTO testing is not appropriate due the nature of the test and its short operational period. Seven system failures occurred representing three different failure mechanisms. A failure history summary follows.

3.12.2.4.1 Ice Jams

Operating in a high humidity environment can lead to a water-based ice buildup along the walls of the auger. The ice can break off from the wall creating large particles restricting the flow of carbon dioxide pellets in the feed hose, resulting in ice jams. The problem is easily fixed by moving the air inlet away from the auger and locating it at the hose fitting below the auger. The system also experienced a few ice jams due to poor quality of drice containing water ice. This can also be eliminated by assuring quality by manufacturing the ice directly on site.

3.12.2.4.2 COYOTEE Cable Failures

Two cable failures were experienced on the same day while experimenting with a new and subsequently abandoned workhead design. These failures are not applicable to the current design concept.

3.12.2.4.3 Drive Motor Connector Failure

One drive motor cable connector failure occurred during the DTO. A single pin was found to have high impedance caused by overheating. Following the DTO testing, a visual examination discovered that the same pin was overheating, again, but had not yet failed. The primary source of this failure mechanism has not been identified and is deferred for phase 3. At that time, appropriate corrective action will be identified and documented.

3.13 Success Criteria Performance

All subsystems were demonstrated to be integrated successfully into the system as designed. The concept demonstration was conducted throughout the phase 2 testing.

Testing also produced valuable operational experience of the system and increased knowledge of using carbon dioxide blasting for concrete decontamination. The performance of the system and its subsystems during the test were measured against the success criteria and derived requirements. This section describes the basic methodology and results of each test. Refer to the *ROVCO$_2$ Phase 2 Test Plan,* submitted on April 27, 1995 for detailed information dealing with the test relating to success criteria mapping, test methodology, and procedures (Appendix C).

The performance of the developed ROVCO$_2$ system to each of the phase 2 success criteria is presented in table 11.

Table 11: Success Criteria Performance

SUCCESS CRITERIA	PERFORMANCE
Tether Management System	
The TMS shall be capable of managing tether payout and reel in as required for effective ROV motion.	In the productivity test and the cold test, the TMS was successfully demonstrated as capable of managing cable payout and reel in for effective ROV motion.
The TMS shall be capable of ROV recovery in a contingency situation.	The requirement for the TMS to comply with this criterion was eliminated due to cost.
Exposed surfaces of the TMS shall be decontaminable by either carbon dioxide blasting or high pressure water washdown techniques.	The decontaminability test successfully demonstrated that the carbon dioxide blasting system is capable of cleaning the TMS.
Vacuum, Filtration, and Containment Subsystem	

SUCCESS CRITERIA	PERFORMANCE
The VFCS shall employ a HEPA filtration unit to remove separate contaminants for disposal.	As demonstrated in the concept demonstration, the HEPA filtration unit performs effectively in separating contaminants provided that the contaminants are contained at the workhead. Improvements in the $ROVCO_2$ workhead are planned to increase containment of removed contaminants at the workhead.
The VFCS shall be sealed to provide effective contaminant containment.	The seal leak indicators during the cold test demonstrated that the seal around the containment drum was more than adequate to provide effective contaminant containment.
Exposed surfaces of the VFCS shall be decontaminable by either carbon dioxide blasting or high pressure water washdown techniques.	The VFCS was successfully decontaminated by carbon dioxide blasting.
Carbon Dioxide Blasting	
The carbon dioxide blasting unit shall incorporate *improvements* to enhance contaminant removal.	The contaminant removal was enhanced by incorporating a new blasting nozzle that increased sealant blasting speeds from 7.5 in./sec to 10 in./sec and more than doubled epoxy speeds from 0.4 in./sec to 0.85 in./sec.
System Effectiveness	
$ROVCO_2$ shall be capable of removing 75-99% of smearable contamination from concrete floor surfaces.	The $ROVCO_2$ system was successful in removing 98% to 99% of the smearable contamination. Smearable removal results were achieved for both concrete slabs containing the cerium (surrogate for uranium). Smearable results for slabs containing gear lube were not achievable due to the reaction of the smear cloths with the chemicals used in the laboratory analysis.

SUCCESS CRITERIA	PERFORMANCE
$ROVCO_2$ shall be capable of removing 50-99% of fixed contamination from surface pores of the concrete in a single pass.	The phase 2 testing demonstrated that the system's ability to remove fixed contamination depends on the blasting speeds selected by the operator. The two slabs containing the cerium surrogate were decontaminated at different blasting speed due to different coatings applied over the contaminants. Slab no.2 (coated with epoxy) was blasted at a slower rate (.425 in/sec) and achieved 95% removal of the coating and 74.7% removal of the cerium. Slab no. 4 (coated with concrete sealant) was blasted at a 4.7 times faster speed of 2 in/sec. This slower speed achieved 39.05% removal of the cerium. Although the speed used during productivity testing did not achieve greater than 50% removal of the fixed contamination for this slab, removal effectiveness is achievable as demonstrated by the results (74.7%) achieved with slab no. 2.
System Reliability	
$ROVCO_2$ downtime shall not exceed more than 20% of expected operation time due to component failure.	During the reliability test the system operated a total of 371.4 hours on the test stand and only 2.4 hours were spent making repairs (0.64% downtime over the duration of the test). During blasting operations the system operated 23.4 hours and spent a total of 3.32 hours making adjustments and a few repairs resulting in 14.22% downtime. Downtime will be significantly reduced in the future as the number of adjustments required decreases from operational experience and system optimization.
System Productivity	

SUCCESS CRITERIA	PERFORMANCE
ROVCO_2 shall be capable of decontaminating between 30 and 75 sq ft of concrete floor space per hour, depending on the level of decontamination required and the contaminated surface's relief.	The average productivity of the ROVCO_2 system is 52.4 sq ft/hr. The productivity removing approximately 98% of sealant is 93.8 sq ft/hr. The productivity for removing 85-95% of epoxy paint is 10.9 sq ft/hr.
The OCU shall autonomously control tedious repetitive operations, allowing the operator to focus on overall system operation and monitoring.	The OCU successfully controlled tedious operations of the vehicle and allowed the operator to monitor path alignment, ice hopper level, and cable condition on the winch and still have time for other activities.

4.0 ECONOMIC EVALUATION

4.1 Introduction

The unit cost evaluation of the $ROVCO_2$ system depends on:

- The productivity rate of the system which also depends on:
  - The type of coating and thickness
  - The level of decontamination required
- The labor rate

4.2 Productivity

The productivity of the $ROVCO_2$ system significantly depends on the required level of decontamination and the type of coating covering the contamination. The productivity decreases as the level of contamination increases and the grade of coating increases. The system achieves a productivity rate of 94 sq ft (for 98 percent removal) on concrete sealant coatings during testing and a rate of 11 sq ft (for 85 to 100 percent removal) on epoxy. As the productivity rate increases, the cost per square foot quickly decreases (see figure 1).

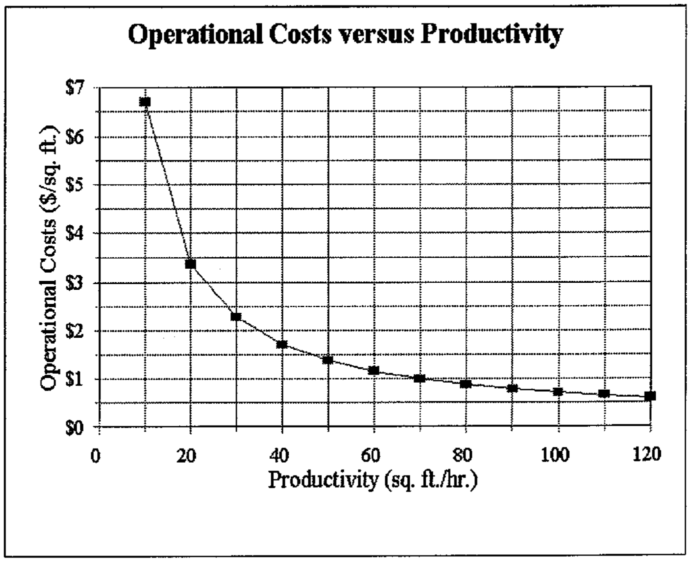

Figure 1: The $ROVCO_2$ operational costs decrease as the productivity of the system increases

4.2.1 Costs

4.2.1.1 Labor

The $ROVCO_2$ system controls repetitive tedious tasks, eliminating the need for constant interaction from the operator and decreasing labor costs. This feature enables a single operator to tend to other operational system tasks.

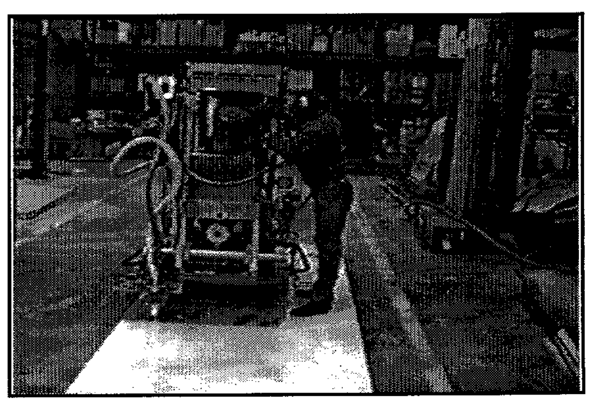

Figure 2: $ROVCO_2$ system operator filling the dry ice hopper during system operation

The responsibilities of the operator are:

- keep the dry ice hopper filled with ice (requires filling about every 60 minutes)
- maintain vehicle alignment with previous rows
- drive the vehicle to the next start position after each completed row

- observe overall vehicle performance and condition
- perform drum change out procedures and scheduled maintenance

4.2.1.2 Consumables

The consumables for the ROVCO_2 system are dry ice, support air compressor's diesel fuel, and parts for preventative maintenance. The system uses pelletized dry ice at an adjustable rate of approximately 150-190 lb/hr. Dry ice may be made directly on site or may be shipped from a distributor. The economic evaluation is based on the purchase of a pelletizer to make the ice as needed directly at the decontamination site verses shipping costs.. Making the ice on site decreases costs and eliminates difficulties due to poor ice quality, therefore increasing the reliability and effectiveness of the system. Poor quality in ice may lead to decreased productivity due to potential ice jams from clogged clumps of ice.

Items requiring preventative maintenance of the system were identified during the reliability test conducted in phase 2. The system performed exceptionally well requiring preventative maintenance for only one item on the system. The helical wire on the Synchromesh cable used for the horizontal (x-direction) motion of COYOTEE wears down producing inadequate sweep patterns. The condition of the cable should be monitored by the operator and may require replacing every 40-70 hours. The variability of the operating life of the cable depends on operator errors. Cable replacement requires approximately 10 to 15 minutes to replace at a cost of approximately $15 each repair.

4.2.1.3 Support Equipment

The ROVCO_2 system requires dry, cooled compressed air at the vehicle and pelletizer. The system requires 530 cfm at 150 psi at the vehicle. The size of the compressor may vary depending on the distance between the vehicle and compressor (pressure drop along the line). The system uses cooled, dry air to assure the production of quality dry ice and to maintain the quality at the nozzle. The economic evaluation categorizes the support equipment costs as capital costs.

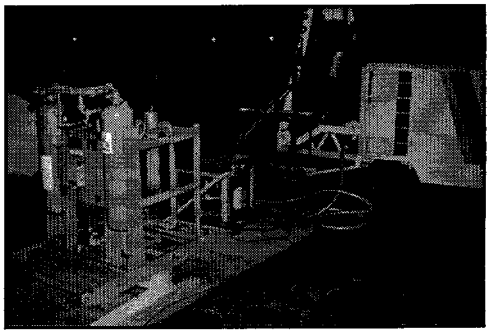

Figure 3: System support equipment: air dryer, cooler, and compressor (left to right)

4.2.1.4 Waste Handling and Disposal

When compared with other concrete decontamination systems, ROVCO_2 minimizes waste generation. Since the system uses carbon dioxide to remove contaminants, the system does not add secondary waste. The system stores the removed contaminants in 14.9 gallon waste drums. Four of the drums can also be overpacked into a 55-gallon drum if needed. The economic evaluation is based on a 1.20 packing factor for the storage drum. A drum capacity is estimated at storing over 1,420 sq ft of contaminated floor area. The evaluation is also based on disposal costs of $12 per cubic foot and a shipping fee of $5 per cubic foot.

The ROVCO$_2$ system meets all ALARA (as low as reasonably achievable) standards. The system reduces worker dose and risk of contamination. Due to the difficulty and the expected low expenses associated with exposure and contamination, the economic evaluation does not take consider dose or contamination levels.

4.3 ROVCO$_2$ System Costs Summary

The system costs were categorized as operational or capital costs.

4.3.1 Operational Costs

In table 1, the total operational costs of the system are summarized. The final unit operational cost for the defined conditions is $0.72 per square foot.

Table 1: ROVCO$_2$ System Operation Costs

Operating Cost	Unit	Cost/unit	Cost
Labor	1 ROV Operator	$35.00/hour	$175,000
Consumables			
Dry Ice		$21.95/hour	$109,750
Cable	0.17 ft/hour	$0.83/ft	$706
Drums	351.41 drums	$39.46/drum	$13,867
Diesel Fuel	10 gal/hour	$0.94/gallon	$47,000
Waste Disposal			
Primary Disposal	0.0168 in/ft^2	$12.00/ft^3	$8,400
Shipping	351.41 drums	$5.00/ft^3	$3,496
Total $358,219			
$/square foot			$0.72

Table 1 is based on the following conditions:

- The air support equipment and dry ice production is considered a part of the capital costs.

- The productivity rate is based on removing 100 percent of concrete sealant.
- The primary waste includes a 0.014 in. depth of removal based on removing 3 mils of epoxy paint and >1 mil of concrete with a 1.20 packing factor (conservative estimate).
- The surface area to be decontaminated is based on the number, 50,000 sq ft.

4.3.2 Capital Costs

Table 2: ROVCO$_2$ System Capital Costs

Component	Estimated Capital Cost
ROVCO$_2$ system	$304,000
Support Equipment	
900 cfm Air Compressor	$75,700
900 cfm Desiccant Air Dryer	$27,700
Air Cooler	$9,700
250 lb Carbon dioxide Pelletizer	$39,500
Total	$456,600

The ROVCO$_2$ system capital costs are included in table 2.

The ROVCO$_2$ system capital cost is based on building a new complete system. The ROVCO$_2$ system and the dry ice pelletizer use the same air compressor, cooler, and desiccant dryer. The ROVCO$_2$ system requires 530 cfm and the pelletizer requires between 200-300 cfm, requiring a maximum of 830 cfm. The estimates are also based on purchasing used support equipment.

4.4 ROVCO$_2$ Versus Other Technologies

The ROVCO$_2$ system compares quite favorably when compared to other methods used to decontaminate concrete. It is a difficult task to compare each technology due to the number of factors involved with each system. Table 3 was created by altering the ROVCO$_2$ evaluation to meet the others, resulting in an attempt to standardize the comparison of the technologies. The end notes describe the conditions and assumptions used. Sources for the information included O'Brien & Gere Engineers, Inc., and LTC, manufacturers of the soda blasting and vacuum blasting technologies, respectively.

Table 3: Economic comparison of $ROVCO_2$ vs. Similar Technologies

Technology	$ROVCO_2$	7" Shot Blasting	Soda Blaster
Production Rate	10 to 120 sf/hr [1]	NA	120 to 240 sf/hr[2]
Depth of Penetration	0.014" [2]	0.03125"	< 0.03125"
Solid Waste Generation [3]	0.0012 cf/sf	0.0026 cf/sf	0.007 cf/sf
Liquid Waste Generation	None	None	1.9 gal/sf
Disposal Unit Cost [4]	$.16/sf	$.35/sf	$1.14/sf
Removal Unit Costs	$0.68/sf [5]	$2.18/sf	$5.62/sf [6]
Total Unit Costs for Removal and Disposal	$0.84/sf	$2.53/sf	$6.76/sf
Estimated Capital Costs	$457K	$4M	$30-35K

Notes

1. Production rate depends on level of contamination and coating type.
2. Based on removing epoxy at 3 mil thick, and >1 mil concrete removal.
3. Included concrete volume (based on maximum depth of removal indicated) plus a 20 percent volume expansion factor.
4. Disposal costs estimated to be $1000/drum which is equivalent to $136/cf.
5. Based on a productivity rate of 100 sf/hour (achievable rate for 98 percent removal of sealant) and a labor rate including a one person team at $37/person/hour.
6. Based on a productivity rate of 120 sf/hour (achievable rate for removing light non-epoxy paints) and a labor rate including a two person team at $37/person/hour.

5.0 CONCLUSIONS AND DISCUSSION

Phase 2 of the $ROVCO_2$ system has resulted in the development of a system that has been tested and demonstrated to effectively remove coatings and contaminants from concrete floors.

With one exception, the $ROVCO_2$ system exceeds its contractual Success Criteria and works as proposed (see the Success Criteria Results table below).

In Phase 2 of the $ROVCO_2$ program, the following was achieved:

- Technical Achievements:
    - The Vacuum, Filtration, and Containment Subsystem (VFCS) was integrated on to the $ROVCO_2$ vehicle.
    - The COYOTEE sweep area was increased from 21" X 31.5" to 26" X 42".
    - The COYOTEE was improved by incorporating an end effector offset bracket allowing closer access to walls on either side.
    - AutoROV was integrated and successfully demonstrated and tested to provide automated operation of tedious repetitive tasks.
    - A 170 foot umbilical and Tether Management System (TMS) capable of 300 feet was manufactured and integrated into the system.
    - All latent defects common to all developmental vehicles were worked out of the system, further increasing the reliability and availability of the system.
    - Air control valves were equipped with an added safety feature eliminating possible pressure hammer affects.
- Removal effectiveness results were achieved for contamination characteristics of the K-25 Site.
- Productivity results were achieved for removing epoxy and sealant from floors.
- The blasting system's capability of decontaminating the vehicle and TMS was demonstrated.

Success Criteria Performance

The performance of the developed $ROVCO_2$ system to each of the phase 2 success criteria is tabulated below.

Table 1: Success Criteria Performance

SUCCESS CRITERIA	PERFORMANCE
2.1 Tether Management System	
2.1.1 The TMS shall be capable of managing tether payout and reel in as required for effective ROV motion.	In the Productivity Test and Cold Test, the TMS was successfully demonstrated to be capable of managing cable payout and reel in for effective ROV motion. Manual intervention may be required to prevent lagging loops and to assist in the proper winding of the cable.
2.1.2 The TMS shall be capable of ROV recovery in a contingency situation.	The ability of the TMS to recover the vehicle in a contingency situation was eliminated due to cost of equipment to comply with this criterion and was not tested.
2.1.3 Exposed surfaces of the TMS shall be decontaminable by either carbon dioxide blasting or high pressure water washdown techniques.	The decontaminability test successfully demonstrated that the carbon dioxide blasting system is capable of cleaning the TMS.

SUCCESS CRITERIA	PERFORMANCE
2.2 Vacuum Filtration and Containment Subsystem (VFCS)	
2.2.1 The VFCS shall employ a HEPA filtration unit to remove separate contaminants for disposal.	As demonstrated in the concept demonstration, the HEPA filtration unit performs effectively in separating contaminants provided that the contaminants are contained at the workhead. Improvements in the ROVCO$_2$ system are needed to increase containment of removed contaminants at the workhead (as discussed in volume 2).
2.2.2 The VFCS shall be sealed to provide effective contaminant containment.	The seal leak indicators in the Cold Test demonstrated that the seal around the containment drum was more than adequate to provide effective contaminant containment.
2.2.3 Exposed surfaces of the VFCS shall be decontaminable by either carbon dioxide blasting or high pressure water washdown techniques.	The VFCS was successfully decontaminated by carbon dioxide blasting. It is recommended that the manual operation of the blasting nozzle should be modified to increase safety and ease of operation.
2.3 Carbon Dioxide Blasting	
2.3.1 The carbon dioxide blasting unit shall incorporate a substrate heating unit to enhance contaminant removal.	The contaminant removal was enhanced by incorporating a new blasting nozzle which increased sealant blasting speeds from 7.5 in./sec to 10 in./sec and more than doubled epoxy speeds from 0.4 in./sec to 0.85 in./sec.

SUCCESS CRITERIA	PERFORMANCE
2.4 System Effectiveness	
2.4.1 ROVCO_2 shall be capable of removing 75-99% of smearable contamination from concrete floor surfaces.	The ROVCO_2 system was successful in removing 98% to 99% of the smearable contamination. Smearable removal results were achieved for both concrete slabs containing the cerium (surrogate for uranium). Smearable results for slabs containing gear lube were not achievable due to the reaction of the smear cloths with the chemicals used in the laboratory analysis.
2.4.2 ROVCO_2 shall be capable of removing 50-99% of fixed contamination from surface pores of the concrete in a single pass.	The phase 2 testing demonstrated that the system's ability to remove fixed contamination depends on the blasting speeds selected by the operator. The two slabs containing the cerium surrogate were decontaminated at different blasting speed due to different coatings applied over the contaminants. Slab no.2 (coated with epoxy) was blasted at a slower rate (.425 in/sec) and achieved 95% removal of the coating and 74.7% removal of the cerium. Slab no. 4 (coated with concrete sealant) was blasted at a 4.7 times faster speed of 2 in/sec. This slower speed achieved 39.05% removal of the cerium. Although the speed used during productivity testing did not achieve greater than 50% removal of the fixed contamination for this slab, removal effectiveness is achievable as demonstrated by the results (74.7%) achieved with slab no. 2.

SUCCESS CRITERIA	PERFORMANCE
2.5 System Reliability	
2.5.1 $ROVCO_2$ downtime shall not exceed more than 20% of expected operation time due to component failure.	During the reliability test the system operated a total of 371.4 hours on the test stand and only 2.4 hours were spent making repairs (0.64% downtime over the duration of the test). During blasting operations the system operated 23.4 hours and spent a total of 3.32 hours making adjustments and a few repairs resulting in 14.22% downtime. Downtime will be significantly reduced in the future as the number of adjustments required decreases from operational experience and system optimization.
2.6 System Productivity	
2.6.1 $ROVCO_2$ shall be capable of decontaminating between 30 and 75 square feet of concrete floor space per hour, dependent upon the level of decontamination required and the contaminated surface relief.	The productivity of the $ROVCO_2$ system for removing approximately 98% of sealant is 93.8 square feet per hour. The productivity for removing 85-95% of epoxy paint is 10.9 sq ft/hr. The productivity of the system removing the toughest coating can increase by reducing the effectiveness of the system still within the define requirements.
2.6.2 The OCU shall autonomously control tedious repetitive operations, allowing the operator to focus on overall system operation and monitoring.	The OCU successfully controlled tedious operations of the vehicle and allowed the operator plenty of time to observe the overall system operation. Items the operator may monitor are path alignment, ice hopper level, and cable condition on the winch.

Phases 1 and 2 have successfully developed the ROVCO_2 system with the exception of the commercial workhead. In phase 3 Oceaneering and WMC will develop a containment workhead specifically for the very high velocity blasting stream. The complete system will then be transitioned to Oceaneering Hanford for demonstration as part of the C-105 demonstration. The Oceaneering Hanford office will then support the deployment of ROVCO_2 at Hanford and throughout the DOE complex.

APPENDIX A

AVAILABILITY PREDICTION FOR THE REMOTE OPERATED VEHICLE WITH CO_2 BLASTING ($ROVCO_2$)

AVAILABILITY PREDICTION

for the

REMOTE OPERATED VEHICLE

WITH

CO_2 BLASTING (ROVCO_2)

April 30, 1995

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US Department of Energy

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1.0 INTRODUCTION

1.1 Scope

This report provides a detailed availability prediction of the Remote Operated Vehicle with CO_2 Blasting (ROVCO_2). It verifies that the system will be available for operation well in excess of the required 80% of the time, when considering failures and the associated down time required for corrective maintenance.

The analysis approach taken is a bottom's up process that derives the failure rate of the lowest contributing level and combines them, via a proabilistic availability model based on the system's and subsystem's success path, to determine the probability that the system will be available for operation when required. Success path modeling is performed for the lowest practical assembly level; determining the failure rates of the lowest assembly levels (components); and combining them via the model to represent the assembly and subsequently the system's availability. Failure rates for mechanical components and some electronic assemblies were obtained from NPRD-95. Where detailed schematics were available, the stress method reliability prediction techniques of MIL-HDBK-217F, with generalized application assumptions, were used for this analysis.

The prediction summary may be found in paragraph 1.2 and the detailed prediction in Appendix B. Section 2 describes the availability modeling in detail.

Several sensitivity analyses are also included to evaluate the impact of failure rate growth, mission lengths, and sparing philosophy on system availability and probability of success..

The analysis demonstrates that a high degree of availability is incorporated in the design of the ROVCO_2.

1.2 Prediction Results

Table 1.2-1 summarizes the ROVCO_2 availability prediction and the associated sensitivity analyses. This table is identical to Appendix A.

Table 1.2-1
Prediction Summary

Subsystem	Element	Element Serial FR	Tot Elmt Prob of Success (180 Hrs)	Tot Elmt Prob of Success (2000 Hrs.)	Subs Avail	Tot Elmt Prob of Success (180 Hrs.)	Subs Avail	Subs Avail
		Fail/ 10^6 Hrs	*110% FR*	*110% FR*	*110% FR*	*150% FR*	*150% FR*	*150% FR + MDT*
Cryogenesis		129.2088	0.971174	0.722527	0.999809	0.960899	0.99974	0.998619
Delivery		74.83064	0.985227	0.847581	0.999894	0.979909	0.999854	0.998785
Tether Management		78.7341	0.977451	0.776148	0.999864	0.969378	0.999814	0.997885
Vacuum Filtration		154.6918	0.970678	0.711541	0.999931	0.96023	0.999906	0.999906
Vehicle		74.70877	0.989207	0.835894	0.999999	0.985312	0.999998	0.999998
Video								
	B&W Camera	60.6119	0.988071	0.875162	0.999934	0.983768	0.99991	0.997836
	Color Camera	76.7073	0.984927	0.844715	0.999916	0.984927	0.999886	0.997267
	Misc.	106.052	0.979221	0.791905	0.999905	0.971772	0.99987	0.998555
Vehicle Boards	Decoder	2.724673	0.999461	1	0.999996	0.999265	0.999994	0.999902
	Interface	60.53102	0.988086	0.875318	0.999901	0.983789	0.999865	0.997839
	Main Relay	151.2445	0.970498	0.716958	0.999795	0.963258	0.999745	0.995101
	Light Xstr	3.04	0.999398	0.993334	0.999997	0.99918	0.999995	0.999994
Electric Air Compressor		10.3061	0.997961	0.999802	0.999983	0.997221	0.999977	0.999629
Operator Console								
	Controls	34.6741	0.993158	0.926554	0.999847	0.990682	0.999792	0.996813
	Color Monitor	90.361	0.982268	0.819719	0.999926	0.975898	0.9999	0.997858
	Ground Fault Interrupt	0.6384	0.999874	0.998597	0.999982	0.999828	0.999976	0.999934
	220 VAC Pack	16.00283	0.996836	0.965406	0.999999	0.995689	0.999999	0.999999
	CPU Board	17.5586	0.996529	0.962108	0.999971	0.99527	0.999961	0.999369
	Relay Brd	1.21095	0.99976	0.997339	0.999999	0.999673	0.999999	0.999999
SYSTEM		**1143.838**	**0.792454**	**0.072473**	**0.998648**	**0.734705**	**0.998182**	**0.975558**

The structure of Table 1.2-1 is as follows:

The first and second columns identify $ROVCO_2$ functional subsystems and next lower assembly levels, as defined for prediction purposes. The prediction was performed at the lowest assembly level where detailed information was available. In some cases, this was at the subsystem level and in others at the lower component level identified as " Element."

The third column, element serial failure rate reflects the relative failure rates of major system elements.

The detailed failure element contributions, found in Appendix B can be utilized, if adjusted for preventive maintenance requirements to establish a sparing philosophy. Columns 4 through 6 summarize the element probability of success for two different operating periods, i.e., 180 hours (one month, one shift), and 2000 hours (one year, one shift), and the system availability. The latter is not sensitive to mission time. This prediction allows for a 10% growth in failure rate and assumes that all elements are spared.

Several sensitivity analyses were also run to determine the impact of additional failure rate growth and a limited local sparing philosophy. Column 7 permits the failure rate growth to reach 50% above the baseline as opposed to 10% growth. This is a worst case condition. Finally, the 9th column assumes both a 50% growth in failure rate and a selective several day sparing lead times for the more expensive but " off-the-shelf" system. The results are as follows:

1) The serial failure rate $\lambda = 1144$ failures/10^6 hours is equivalent to a serial MTBF of 874 hours (MTBF = $1/\lambda$). This means, on the average, a component failure can be expected every 874 hours. This is not system failure since the ROVCO_2 system contains some fault tolerance.

2) Reliability, which is defined as probability of success, is predicted to be 0.79 for a month mission, i.e. 180 hours (one month, one shift) and 0.073 for a one year mission, i.e., 2000 hours (1 year, one shift). This prediction assumes that a competent preventive maintenance cycle is accomplished. These mission definitions allow adequate time for either corrective or preventive maintenance downtime. This means that the probability of success is reasonable for one month's operation but low for a continious mission time of a year. In other words, planning for corrective maintenance several times a year is required. This is an expected result for a system constructed with moving parts (wear items such as motors) and commercial quality components. Note that availability is insensitive to of mission time.

3) A comparison of the results of predictions based on two failure rate assumptions were also made. That is the failure rates for the baseline generated in column 5 of Appendices B through D, based on the best available information, were used to calculate probability of success and availability assuming that the failure rates "grow" 10% (typical) in one case and 50% (worst case) in the other. Potential causes of failure rate growth include down stream better insight into purchased item components, design modifications for functional or reliability purposes, and prediction refinements. A noticeable impact on probability of success was predicted, as expected, but no significant impact on system availability surfaced. This is a direct function of the relatively high element Mean-Time-To Failure to Mean-Time-To-Repair ratio. This ratio reflects the simplicity of the design and the modular and functional packaging permitting corrective action, in the event of failure, to be quickly accomplished.

4) The two predictions discussed above assume a high degree of on-site sparing. That is all necessary spares are kept on site and can be obtained in 30 minutes or less. This includes complete motors, circuit cards, and the video monitor. The final column of Table 1.2-1 reflects a different sparing philosophy. That is, in this case, it is assumed that only the inexpensive components are spared on site and all other failed assemblies or components will either be disassembled and repaired or shipped to the site on demand. For such cases a period of several calendar days was allocated. This approach to sparing provides a noticeable impact on availability, but it is still predicted to be much greater than the required 80%. This is due to the high component MTBF to MTTR ratio and to a lessor extent, the impact of one shift per day operation assumption permitting repair and spares shipments to occur during standby hours.

2.0 METHODOLOGY

The analysis approach taken is a bottom's up process that derives the failure rate of the lowest contributing level and combines them via a probabilistic availability model based on the system's success path to determine the probability that the system will be available for operation when required.

2.1 Availability

Availability (A) is the ratio of the time a system is available for use to the time it is unavailable. It is a probability and is usually defined mathematically as equal to 1 - Unavailability. That is:

$$A = 1 - \frac{Time\,Unavailable}{Total\,Applicable\,Time}$$

Availability can be defined in several ways based upon the type of downtime considered.

The three options are:

1) Inherent availability, A_i, which considers only corrective maintenance time.

$$A_i = \frac{MTBF}{MTBF + MTTR}$$

2) Achieved availability, A_a, which considers both corrective and preventive maintenance times.

3) Operational Availability, A_o, which considers corrective, preventative, and logistics time.

$$A_a, A_o = \frac{Uptime}{Uptime + Downtime} = \frac{MTBF}{MTBF + MDT}$$

where:

MTBF = Mean Time Between Failures
MTTR = Mean Time to Repair (for corrective maintenance)
MDT = Mean Down Time

The ROVCO_2 availability requirement is based on an MDT composed of two elements MTTR and Logistics Time to obtain spares. Examination of these fundamental availability equations shows that the larger the ratio between the MTBF and the MDT are, the less significant are maintenance times. This effect provides flexibility in the sparing approach for ROVCO_2 failures, assuming preventive maintenance is accomplished.

The definitions found in these equations are suitable for simple series availability models. They are presented here as fundamental availability definitions. Since the ROVCO_2 contains some fault tolerance (redundancy), availability must be calculated using probability. The methodology used is defined in paragraph 2.4.

2.2 Reliability Modeling

Probability models were generated at the subsystem and "element" levels showing the associated critical or success paths for the $ROVCO_2$. All subsystems are considered failure independent and necessary for system operation. In other words, if one subsystem fails (such as the video), it is assumed that the entire $ROVCO_2$ has failed. Therefore, each subsystem level reliability (probability of success) model is as follows:

$$R_{ROVCO}=\prod_{i}^{k} R_i$$

where,

n = number of subsystems
R_i = Reliability of subsystems

The model for most $ROVCO_2$ Subsystems is serial. Operational experience, however, has demonstrated that only 4 of 6 wheels (and associated drive systems) are required to perform the $ROVCO_2$ mission. This subsystem is not serial and must be modeled as a redundant unit. Each $ROVCO_2$ subsystem was examined for potential redundancy and "fail soft" alternatives other than than the rough vacuum filters, no others found. An argument can be made for video camera redundancy but this was not considered in the model. It is used for illustrative purposes in the next paragraph.

Figure 2.2-1 provides examples of serial and redundant reliability models (block diagrams). The three serial elements represent a simple top level system reliability model that contains three major subsystems (or components) that are all necessary to complete a mission. That is if one fails, the system fails and the mission can not be completed. A $ROVCO_2$ vehicle model might show propulsion, steering, and video subsystems to perform its task. The two parallel elements shown in the center of the figure, reflect a redundant system such as that suggested for the video subsystem. In this fault tolerant example, the video requirements could be accomplished if either camera unit functioned. The two block diagrams could be combined as in the third group showing a system reliability model containing one fault tolerant subsystem.

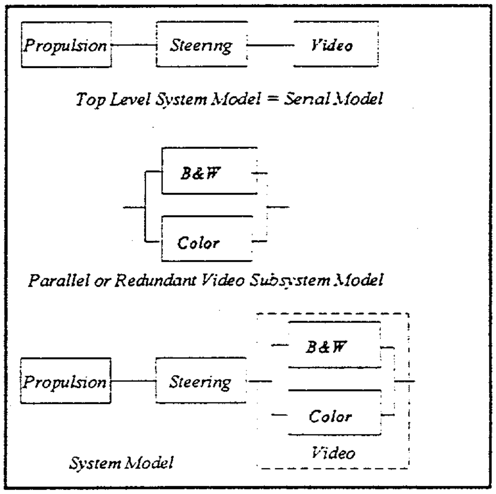

Figure 2.2-1
Reliability Model Examples

2.3 Reliability Predictions

Component and subsystem reliability failure rates are a necessary input to the availability model. Historical data, vendor data, parametric projections, and experiential judgment was used. The Reliability Analysis Center's NPRD-95 handbook for NonElectronic Parts Reliability and Mil-HDBK-217F (for electronic components) were the primary failure sources.

NPRD-95 is a historical list of components and assemblies, operating times, application environments, and numbers of failures. This source is used by making the best match between historical data and $ROVCO_2$ characteristics. The Mil-HDBK-217F, (Military Handbook, Reliability Prediction of Electronic Equipment) failure rates of the component parts are a function of the electrical and thermal stress applied, the quality of these components (based upon part testing and an associated learning curve), and the complexity and technology used in the component's construction. This information is then input into a general application component specific failure rate prediction model.

The prediction model assumes that the hardware has been aged beyond the "latent defect" region of its life and has not entered the wearout period. Assuming no latent defects or wearout, the constant hazard rate failure rate can be utilized to estimate reliability. During the useful life period, reliability of electronics is generally predicted by means of the single parameter exponential distribution. This is given by the relationship:

$$R(t) = e^{-\lambda t}$$

where:

R(t) is the probability that the device will operate for a time period t under stated operating *conditions*

λ_p is the device failure rate

Calculating component part reliability involved estimating their failure rates from mathematical models that describe the relationship between stress and failure. The failure rates consider specific part quality, application characteristics and assumed stress levels.

The reliability prediction performed using the stress methodology of MIL-HDBK-217F required identifying many parameters, based on the component construction and known failure modes for each component part in its specific application. Examples of the requirements of this methodology include the identification of the following parameters:

(1) Electrical stress level for all electronics and, for components dissipating measurable power, thermal derating.

(2) Quality level of each component e.g. Mil-Spec or commercial with refinements for hermeticity, inherent maximum operating temperatures, and component screening levels.

(3) For microcircuits, factors for design maturity, complexity of chip design, package design, and form factor of the package.

(4) The appropriate environment category from those listed in MIL-HDBK-217F and a suitable temperature.

The general assumptions used for this prediction are as follows:

(1) Assembly and/or board failure is a reflection of part failure; i.e., reliability of the assembly is dependent upon each of its parts.

(2) The exponential failure distribution for electronic parts was assumed valid.

(3) The analysis was based on the stress part failure rate models of MIL-HDBK-217F.

- o The prediction was performed assuming a 30°C ambient condition.

- o MIL-HDBK-217F provides a list of standardized environmental definitions from which "k" factors are selected for each component type. The most appropriate environmental factors for the $ROVCO_2$ application were ground benign, ground mobile, and inhabited airborne fighter. The ground fixed (GF) environmental factor was used for the tethered management system, air compressor, and cart assembly mounted components. Alternative environmental factors were considered for vehicle mounted components. It was concluded that the Airborne Inhabited Fighter (AIF) environment was most suitable for these components. The logic is that the temperature variation and shock exposure expected in a ground mobile (GM) application, the first intuitive choice, would not imposed on the $ROVCO_2$ vehicle. Components on the vehicle, however, would be exposed to considerable broadband acoustic energy stimulus on a continuous basis and is closest to the AIF environmental factor. This AIF environmental factor is conservative and the correct factor is probably somewhere in between the GF and AIF factors. The failure rates used for each element are provided in the Appendices.

- o The stresses used were assumed, based upon normal design conservative practices.

- o The quality level of the parts was assumed commercial grade. Mil-HDBK-217 provides a substantial penalty for this quality level.

- o The number of solder joints and active connector pins were estimated from schematic drawings.

(4) The failure rates of some purchased assemblies and all mechanical parts such as valves and bearings were obtained from NPRD-95.

A "Parts List" was assembled from circuit schematics and is provided in Appendices B, C and D. Appendix A is a series of tables containing the prediction in a "family tree" sequence. Assigned failure rates and MTTRs are shown.

2.4 Availability Modeling

Paragraph 2.2 describes how the reliability models are generated by defining success paths. Availability is calculated using the probability of success equation but substitutes availability (probability that system is available) for individual subsystem or component reliability (probability of success). The system level availability equation is therefore:

$$A_{ROVCO}=\prod_{i=1}^{n} A_i$$

where:

n = number of subsystems

A_i = Availability of "I" subsystems

The availability model is based upon the following assumptions:

1) The system is in either an operating state or a failed state.

2) The state of the system changes as time progresses.

3) The transition of the system from one state to the other takes place instantaneously.

4) Failure and repair rates are constant.

The transition states are illustrated in Figure 2.4-1.

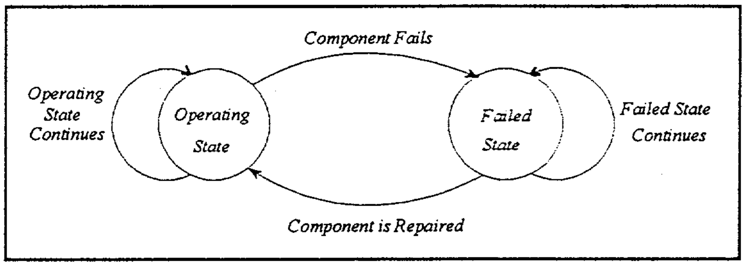

Figure 2.4-1
Transition Diagram

Availability of the lowest subsystem/ component is conventionally defined as:

$$\frac{MTBF}{MTBF+MDT}$$ where:

MTBF = Mean Time to Failure = 1/Failure Rate
MDT = Mean Down Time = Mean Time to Repair (MTTR) for corrective maintenance plus logistics times. Preventive maintenance times is excluded from the system requirements.

This is the ratio of uptime to total time. The MDT predictions were based on engineering judgment or experience.

The Availability definitions above may be restated (approximated), as :

$$A = 1 - \frac{MDT}{ROVCO_2 MissionTime} = 1 - \frac{\Sigma(P_F \times (LOG + MTTR))}{MissionTime(Hrs.)}$$

where:

LOG = Logistics Downtime which is the sum of the predicted downtime due to logistics issues such as remotely repairing a Printed Circuit Board or obtaining a spare and shipping it.

P_F = Probability of Failure of a single component/assembly or redundant components/assemblies over the mission time.

This is the sum of uptime of each uptime of each component to total mission time. Availability , as defined by this equation, is insensitive to reasonable mission times. It appears in the probability of success in the numerator and as the denominator, essentially self cancelling.

The availability prediction does not include any time for performing preventive maintenance. It was excluded from the requirement as they can be scheduled for non-mission times. At present, the only required preventive maintenance identified are those required for lubrication, filter renewing, and potentially motor brush or bearing replacement.

The Appendices are the availability prediction. It is composed of a series of linked spreadsheets. The element probability of success and all the availability equations are embedded in the spreadsheet cells.

Availability Calculations

System availability was calculated using the equation defined above:

$$A_{oElement} = 1 - \frac{MDT}{ROVCO_2 MissionTime} = 1 - \frac{\Sigma(P_F \times LOG + MTTR)}{MT}$$

where:

LOG = Logistics Down Time
MT = Mission Time
P_F = Probability of Failure = $1-P_S$
P_S = Probability of Success = $e^{-\lambda t}$
λ = Failures per hour

Once the element availabilities were calculated, each subsystem's availability was calculated using probability equations determined by the configuration model elements. There are three basic types of configurations within the models. The first of these is "k of m" redundancy. That is k of m units must function for the system to work. An example is the drive motors, i.e. the $ROVCO_2$ vehicle will function if 4 of the 6 motors work. The binomial equation used to calculate the availability of such a configuration is:

$$A_{oSubsy} = \sum_{i=m}^{k} \binom{k}{i} A^{i}_{oElement} (1 - A_{oElement})^{k-1}$$

The second type of configuration is parallel redundancy where only one of two or more of the same or different elements in a reliability parallel configuration are required for the system to function. None examples of simple redundancy were identified. In the case of a two element parallel path with identical elements, Availability = $2A-A^2$; for 3 identical elements in parallel: $= 1-(1-A)^3$. When the elements are different, the equations are: $A_1 + A_2 - A_1A_2$ and $1-(1-A_1)(1-A_2)(1-A_3)$ respectively. The third configuration is the serial path. In this case, the availability equation is: A^n, where n is the number of identical units in a path, or $A_1A_2....A_n$ when there are different elements in series. The system model is of this configuration.

The availability of each subsystem, and/or element was calculated and then combined through a serial availability equation. Each subsystem availability table in Appendix A provides traceability back to the mission model. The reviewer can follow, to a large extent, the availability calculation process described above through the table entries.

3.0 REFERENCES

The following two documents were used for component failure rate generation:

MIL-HDBK-217F, Notice 1, Military Handbook, Reliability Prediction of Electronic Equipment, Department of Defense

NPRD-95, NonElectronic Parts Reliability Data-95, Reliability Analysis Center

4.0 SUMMARY

The $ROVCO_2$ is predicted to have an operational availability in excess of 0.98 when incorporating the downtime caused by failures. This prediction provides a substantial safety margin relative to the requirement of 0.80. This prediction included a sensitivity analysis that verified that an error in the basic prediction assumptions did not lead to an overstatement of the system's availability. It also showed that a cost effective approach to sparing can be adopted while meeting the availability requirement. The prediction is based on the primary industry standard failure rate sources maintained by DoD and standard definitions of availability and assumes that an effective preventive maintenace program is accomplished.

ROVCO$_2$
Availability Prediction

Subsystem	Element	Element Serial FR	Tot Elmt Prob of Success (180 Hrs)	Tot Elmt Prob of Success (2000 Hrs.)	Subs Avail	Tot Elmt Prob of Success (180 Hrs.)	Subs Avail	Subs Avail
		Fail/ 10^6 Hrs	*110% FR*	*110% FR*	*110% FR*	*150% FR*	*150% FR*	*150% FR + MDT*
Cryogenesis		129.2088	0.97117	0.7225273	0.99981	0.960899	0.99974	0.998619
Delivery		74.83064	0.98523	0.8475811	0.99989	0.979909	0.999854	0.998785
Tether Management		78.7341	0.97745	0.776148	0.99986	0.969378	0.999814	0.997885
Vacuum Filtration		154.6918	0.97068	0.7115412	0.99993	0.96023	0.999906	0.999906
Vehicle		74.70877	0.98921	0.8358936	1	0.985312	0.999998	0.999998
Video								
	B&W Camera	60.6119	0.98807	0.8751621	0.99993	0.983768	0.99991	0.997836
	Color Camera	76.7073	0.98493	0.8447149	0.99992	0.984927	0.999886	0.997267
	Misc.	106.052	0.97922	0.7919046	0.9999	0.971772	0.99987	0.998555
Vehicle Boards	Decoder	2.724673	0.99946	1	1	0.999265	0.999994	0.999902
	Interface	60.53102	0.98809	0.8753178	0.9999	0.983789	0.999865	0.997839
	Main Relay	151.2445	0.9705	0.716958	0.9998	0.963258	0.999745	0.995101
	Light Xstr	3.04	0.9994	0.9933343	1	0.99918	0.999995	0.999994
Electric Air Compressor		10.3061	0.99796	0.9998024	0.99998	0.997221	0.999977	0.999629
Operator Console								
	Controls	34.6741	0.99316	0.9265539	0.99985	0.990682	0.999792	0.996813
	Color	90.361	0.98227	0.8197186	0.99993	0.975898	0.9999	0.997858
	Ground Fault	0.6384	0.99987	0.9985965	0.99998	0.999828	0.999976	0.999934
	220 VAC Pack	16.00283	0.99684	0.9654063	1	0.995689	0.999999	0.999999
	CPU Board	17.5586	0.99653	0.9621077	0.99997	0.99527	0.999961	0.999369
	Relay Brd	1.21095	0.99976	0.9973395	1	0.999673	0.999999	0.999999
SYSTEM		1143.838	**0.79245**	**0.0724726**	**0.99865**	**0.734705**	**0.998182**	**0.975558**

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
Cryogenesis					0.9711736	0.7225273		0.99980929
	Pneumatic Solen Valve		4	18.5185	0.9854404	0.8496228	1.25	0.99989889
	Air Valve		2	16.5368	0.9934728	0.9298222	1.25	0.99995467
	Manual Valve		1	7.186	0.9985782	0.9843151	1.25	0.99999013
	DC Motor		1	3.3	0.9993468	0.9927663	1.25	0.99999546
	Air Hose (150 PSI)		1	11.5752	0.9977107	0.9748561	0.75	0.99999046
	Pulser		1	18.5185	0.9963401	0.960078	1	0.99997967
Delivery			1		0.985227	0.8475811		0.99989394
	DC Motor		2	3.3	0.9986941	0.9855849	1	0.99999274
	Gear Box		2	11.726	0.9953673	0.949714	1	0.99997426
	Linear Ball Bearings		4	10.9297	0.991381	0.9082993	1.5	0.99992818
	Synchromesh cable		1		1	1	1	1
	Limit Switches		2	0.52992	0.9997902	0.9976711	0.75	0.99999913
	Nylon Gears		2	0.1685	0.9999333	0.9992589	1	0.99999963
Tether Managment					0.977451	0.776148		0.99986354
	Bearings		2	1.446	0.9994275	0.9936578	1.5	0.99999523
	Pneumatic Motor		1	3.15	0.9993765	0.993094	1	0.99999654
	Chain Drive		1	2.8	0.9994458	0.9938589	1	0.99999692
	Slip Ring (Air & Elect)		1	27.4758	0.9945746	0.9413439	1.5	0.99995479
	Air/elect Umbilical		1	12.49	0.99753	0.9728961	1.25	0.99998285
	Local Controls (Speed)		1	29.9263	0.9940921	0.9362827	1	0.99996718
	Local Controls (On/Off)		1	36.4532	0.9928083	0.9229345	0.75	0.99997003
Vacuum Filtration					0.9706779	0.7115412		0.99993097
	HEPA Filter							0.99993691
		Roughing Filters (2 of 3 Reqd)	3	2.193	0.9995659	0.9856304	1	1
		HEPA Filter	1	2.193	0.9995659	0.995187	1	0.99999759
		Pressure Indicator	5	2.6114	0.9974181	0.9716833	0.75	0.99998924

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		Air Valve	1	16.5368	0.9967311	0.9642729	1.25	0.9999773
		Solenoid Valve	1	18.5185	0.9963401	0.960078	1.25	0.99997458
		Primary Air Filter	1	2.193	0.9995659	0.995187	0.75	0.99999819
	Hose		1	11.5277	0.9977201	0.9749579	0.75	0.9999905
	Air Valve		1	16.5368	0.9967311	0.9642729	1.25	0.9999773
	Pressure Reduction Valve		1	20	0.9960478	0.956954	1.25	0.99997255
	Pressure Gauges		2	11	0.9956535	0.9527526	0.75	0.99998189
	Drum Full Alarm		1	7	0.998615	0.984718	0.75	0.99999423
	Solid State Sensor		1	13.15	0.9973997	0.9714845	1.5	0.99997833
	Press. Energ. Seal		1	5.4	0.9989314	0.9881903	1	0.99999406
Vehicle					0.9892074	0.8358936		0.9999987
	Veh Drive Motors		4 of 6	3.3	1	0.9653713	1.5	1
	Brake		2	4.2735	0.9983091	0.9813723	1.5	0.99998591
	Brake Release		2	2.6082	0.9989677	0.9885895	1.5	0.9999914
	On/Off Control Switch		1	16.1568	0.9968061	0.9650793	0.75	0.99998669
	Dc Circuit Brakers		5	4.788	0.9952711	0.9486949	0.75	0.9999803
	Connectors, Drive		4 of 6	0.017442	1	0.9768303	1.25	1
	Connectors, Other		4	0.23598	0.9998131	0.9979255	1.25	0.9999987
Video								
	B&W Camera (Fixed Focus, Auto Iris)		1	60.6119	0.9880706	0.8751621	1	0.99993373
		CCD/ Intensifier	1	32.3888				
		HV Supply	1	11.6609				
		Syn Brd	1	1.9758				
		Video Brd	1	10.3				
		Automatics	1	4.2584				

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		BNC Connector	1	0.028				
	Color Camera		1	76.7073	0.9849267	0.8447149	1	0.99991626
		CCD/ Intensifier	1	40				
		HV Supply	1	11.6609				
		Syn Brd	1	1.9758				
		Video Brd	1	15.3				
		Automatics	1	7.7426				
		BNC Connector	1	0.028				
					0.9792206	0.7919046		0.99990475
	24VDC Light		2	38	0.9850647	0.8460304	0.75	0.99993777
	Pan DC Motor		1	3.3	0.9993468	0.9927663	1	0.99999637
	Pan Gear Box		1	11.726	0.9976809	0.9745327	1	0.99998712
	Tilt DC Motor		1	3.3	0.9993468	0.9927663	1	0.99999637
	Tilt Gear Box		1	11.726	0.9976809	0.9745327	1	0.99998712
	Decoder Board		1		0.9994607	1	1.5	0.99999551
		HOTL-2000	2	0.27175	0.9998924	0.998805		
		LM5550N	1	0.15675	0.999969	0.9996552		
		74LS374	1	0.2035	0.9999597	0.9995524		
		.1ufd Cap	4	0.288	0.9997719	0.9974688		
		10 ufd Cap	1	0.10296	0.9999796	0.9997735		
		220pfd Cap	1	0.15048	0.9999702	0.999669		
		Resistors	4	0.08844	0.99993	0.999222		
		Board Connector	1	0.008448	0.9999983	0.9999814		
		Connections	65	0.000069	0.9999991	0.9999901		
		PCB	1	0.04879	0.9999903	0.9998927		
	Interface Board		1		0.9880864	0.8753178	1.5	0.99990072
		NEC uPD6450	1	0.3375	0.9999332	0.9992578		
		LM1851	1	0.11925	0.9999764	0.9997377		
		Fixed Resistors	10	0.08844	0.9998249	0.9980562		
		100 ufd Cap	1	0.14256	0.9999718	0.9996864		
		33 pfd Cap	1	0.0441	0.9999913	0.999903		
		Var Cap	1	5.72	0.9988681	0.9874948		
		RF Choke	1	0.1272	0.9999748	0.9997202		

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		XTAL	1	4.62	0.9990857	0.9898875		
		.1 ufd Cap	6	0.288	0.9996579	0.9962056		
		220 ufd Cap	1	0.15048	0.9999702	0.999669		
		Potentimeter	4	2.2176	0.9982452	0.9806743		
		SK3054	1	0.040205	0.999992	0.9999116		
		1N4001	1	0.43776	0.9999133	0.9990374		
		DPDT Relay	1	17.7606	0.9964896	0.9616802		
		800562	1	1.442	0.9997145	0.9968326		
		PSD311	1	0.7705	0.9998475	0.9983063		
		Max693	1	0.14125	0.999972	0.9996893		
		Max232	1	0.17725	0.9999649	0.9996101		
		IRFD9120	2	0.31752	0.9998743	0.9986039		
		Voltage Reference	2	0.05625	0.9999777	0.9997525		
		UCN5801A	4	0.4505	0.9996433	0.9960434		
		7404	1	0.29325	0.9999419	0.9993551		
		LM1456	1	0.14875	0.9999705	0.9996728		
		AD7225	1	0.4505	0.9999108	0.9990094		
		Resistors	56	0.08844	0.9990199	0.9891633		
		LEDs	27	0.023552	0.9998741	0.998602		
		10 ufd Cap	3	0.10296	0.9999388	0.9993207		
		.1 ufd Cap	8	0.288	0.9995439	0.994944		
		33 pfd Cap	2	0.0441	0.9999825	0.999806		
		100 ufd	1	0.14256	0.9999718	0.9996864		
		Xtal	1	4.62	0.9990857	0.9898875		
		Zener	1	0.2304	0.9999544	0.9994932		
		P1 Brd Connector-44 Pins used	1	0.021504	0.9999957	0.9999527		
		P2, P3 Brd Connector 6 Pins used	2	0.00512	0.999998	0.9999775		
		Connections	250	0.000069	0.9999966	0.9999621		
		PCB	1	0.24395	0.9999517	0.9994635		
	Main Relay Brd		1		0.9704975	0.716958	1.25	0.99979512
		DPST Relay	16	4.0365	0.9872938	0.8675477		
		RF Choke	16	0.1272	0.9995971	0.9955326		
		Thermistor	7	11.25	0.9845284	0.8409274		
		1N4004	6	0.43776	0.9994801	0.9942382		
		Resistor	19	0.08844	0.9996673	0.99631		
		.1 ufd Cap	3	0.288	0.9998289	0.998101		
		.22ufd Cap	1	0.312	0.9999382	0.9993138		
		7810 Volt Ref	1	0.05625	0.9999889	0.9998763		
		LED	10	0.023552	0.9999534	0.999482		

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		Connector-23 Pins used	1	0.011264	0.9999978	0.9999752		
		Connector-5 Pins used	1	0.004864	0.999999	0.9999893		
		Connector-9 Pins used	1	0.006144	0.9999988	0.9999865		
		Connections	75	0.000069	0.999999	0.9999886		
		PCB	1	0.073185	0.9999855	0.999839		
	Light Xstr Ckt	Darlington	2	1.52	0.9993983	0.9933343	1	0.99999666
Electric Air Compressor			1	10.3061	0.9979615	0.9998024	1.5	0.99998301
Operator Console					0.993158	0.9265539		0.99984693
	Controls		1		0.993158	0.9265539		0.99996901
		Membrane keyboard	1	8.8789	0.9982435	0.980656	1	0.99999024
		Toggle Switches	9	2.6928	0.9952129	0.948079	0.75	0.99998005
		Potentiometer	1	0.312	0.9999382	0.9993138	0.75	0.99999974
		Joy Sticks	2	0.624	0.9997529	0.9972582	0.75	0.99999897
	1 NTSC Color Monitor (TV)		1		0.9822676	0.8197186	0.75	0.99992612
		CRT	1	76.8	0.9849086	0.8445427		
		HV Supply	1	2.6	0.9994853	0.9942963		
		Video & Sync	1	6.86	0.9986426	0.9850213		
		Potentiometer	6	0.312	0.9996294	0.9958901		
		Switch	1	2.229	0.9995588	0.9951082		
	Ground Fault Interup		1	0.6384	0.9998736	0.9985965	1	0.9999993
	220 VAC Pack		1		0.9968365	0.9654063		0.99998242
		220:30V Xfmr	1	0.846	0.9998325	0.9981405	1	0.99999907
		220/110 Xfmr	1	0.576	0.999886	0.9987336	1	0.99999937
		Rect. Diodes	2	0.010022	0.999996	0.9999559	1	0.99999998
		0.1 Fd Caps	2	7.28	0.9971213	0.9684756	1	0.99998401
		AC Outlet	1	0.000392	0.9999999	0.9999991	0.75	1
		2 Active Pin Conn	1	0.000392	0.9999999	0.9999991	0.9	1

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
	CPU Board		1	17.5586	0.9965294	0.9621077	1.5	0.99997108
	DPST Relay		3	0.40365	0.9997603	0.9973395	0.75	0.999999

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
Cryogenesis				57.1165	0.9608986	0.6419904		0.99974042
	Pneumatic Solen Valve		4	18.5185	0.9801987	0.8007376	1.25	0.99986249
	Air Valve		2	16.5368	0.9911099	0.9055427	1.25	0.99993826
	Manual Valve		1	7.186	0.9980617	0.9786727	1.25	0.99998654
	DC Motor		1	3.3	0.9991094	0.9901488	1.25	0.99999382
	Air Hose (150 PSI)		1	11.5752	0.9968796	0.9658704	0.75	0.999987
	Pulser		1	18.5185	0.9950125	0.9459595	1	0.99997229
Delivery			1	26.48562	0.9799093	0.7981147		0.99985433
	DC Motor		2	3.3	0.9982196	0.9803947	1	0.99999011
	Gear Box		2	11.726	0.993688	0.9320619	1.5	0.9999474
	Linear Ball Bearings		4	10.9297	0.9882653	0.8770806	1.25	0.99991851
	Synchromesh cable		1		1	1	1	1
	Limit Switches		2	0.52992	0.9997139	0.9968255	0.75	0.99999881
	Nylon Gears		2	0.1685	0.999909	0.9989895	1	0.99999949
Tether Managment				77.2881	0.9693781	0.7078225		0.9998141
	Bearings		2	1.446	0.9992195	0.9913615	1.5	0.9999935
	Pneumatic Motor		1	3.15	0.9991499	0.9905945	1	0.99999528
	Chain Drive		1	2.8	0.9992443	0.9916352	1	0.9999958
	Slip Ring (Air & Elect)		1	27.4758	0.992609	0.9208783	1.5	0.99993841
	Air/elect Umbilical		1	12.49	0.9966334	0.9632233	1.25	0.99997662
	Local Controls (Speed)		1	29.9263	0.9919525	0.9141333	1	0.99995529
	Local Controls (On/Off)		1	36.4532	0.9902059	0.896408	0.75	0.99995919
Vacuum Filtration					0.9602299	0.6287161		0.99990592
	HEPA Filter							0.99991401
		Roughing Filters (2 of 3 Reqd)	3	2.193	0.9994081	0.9804565	1	1
		HEPA Filter	1	2.193	0.9994081	0.9934426	1	0.99999671
		Pressure Indicator	5	2.6114	0.9964808	0.9615863	0.75	0.99998534

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		Air Valve	1	16.5368	0.995545	0.9516001	1.25	0.99996906
		Solenoid Valve	1	18.5185	0.9950125	0.9459595	1.25	0.99996536
		Primary Air Filter	1	2.193	0.9994081	0.9934426	0.75	0.99999753
	Hose		1	11.5277	0.9968924	0.9660081	0.75	0.99998705
	Air Valve		1	16.5368	0.995545	0.9516001	1.25	0.99996906
	Pressure Reduction Valve		1	20	0.9946146	0.9417645	1.25	0.9999626
	Pressure Gauges		2	11	0.9940776	0.9361309	0.75	0.99997532
	Drum Full Alarm		1	7	0.9981118	0.979219	0.75	0.99999213
	Solid State Sensor		1	13.15	0.9964558	0.961318	1.5	0.99997046
	Press. Energ. Seal		1	5.4	0.9985431	0.9839305	1	0.99999191
Vehicle					0.9853118	0.7836706		0.99999823
	Veh Drive Motors		4 of 6	3.3	1	0.9535801	1.5	1
	Brake		2	4.2735	0.997695	0.9746849	1.5	0.99998079
	Brake Release		2	2.6082	0.9985926	0.9844726	1.5	0.99998827
	On/Off Control Switch		1	16.1568	0.9956472	0.9526855	0.75	0.99998186
	Dc Circuit Brakers		5	4.788	0.993557	0.9306984	0.75	0.99997315
	Connectors, Drive		4 of 6	0.017442	1	0.9686787	1.25	1
	Connectors, Other		4	0.23598	0.9997452	0.9971722	1.25	0.99999823
Video								
	B&W Camera (Fixed Focus, Auto Iris)			60.6119	0.983768	0.8337383	1	0.99990982
		CCD/ Intensifier	1	32.3888				
		HV Supply	1	11.6609				
		Syn Brd	1	1.9758				
		Video Brd	1	10.3				
		Automatics	1	4.2584				

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		BNC Connector	1	0.028				
	Color Camera			76.7073	0.979502	0.7944368	1	0.99988612
		CCD/ Intensifier	1	40				
		HV Supply	1	11.6609				
		Syn Brd	1	1.9758				
		Video Brd	1	15.3				
		Automatics	1	7.7426				
		BNC Connector	1	0.028				
					0.971772	0.7274893		0.99987036
	24VDC Light		2	38	0.9796891	0.7961243	0.75	0.99991537
	Pan DC Motor		1	3.3	0.9991094	0.9901488	1	0.99999505
	Pan Gear Box		1	11.726	0.996839	0.9654336	1	0.99998244
	Tilt DC Motor		1	3.3	0.9991094	0.9901488	1	0.99999505
	Tilt Gear Box		1	11.726	0.996839	0.9654336	1	0.99998244
	Decoder Board		1		0.9992646	1	1.5	0.99999387
		HOTL-2000	2	0.27175	0.9998533	0.9983708		
		LM5550N	1	0.15675	0.9999577	0.9995299		
		74LS374	1	0.2035	0.9999451	0.9993897		
		.1ufd Cap	4	0.288	0.999689	0.99655		
		10 ufd Cap	1	0.10296	0.9999722	0.9996912		
		220pfd Cap	1	0.15048	0.9999594	0.9995487		
		Resistors	4	0.08844	0.9999045	0.9989393		
		Board Connector	1	0.008448	0.9999977	0.9999747		
		Connections	65	0.000069	0.9999988	0.9999865		
		PCB	1	0.04879	0.9999868	0.9998536		
	Interface Board		1		0.9837895	0.8339406	1.5	0.99986491
		NEC uPD6450	1	0.3375	0.9999089	0.998988		
		LM1851	1	0.11925	0.9999678	0.9996423		
		Fixed Resistors	10	0.08844	0.9997612	0.9973503		
		100 ufd Cap	1	0.14256	0.9999615	0.9995724		
		33 pfd Cap	1	0.0441	0.9999881	0.9998677		
		Var Cap	1	5.72	0.9984568	0.9829864		
		RF Choke	1	0.1272	0.9999657	0.9996185		

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		XTAL	1	4.62	0.9987534	0.9862356		
		.1 ufd Cap	6	0.288	0.9995335	0.9948294		
		220 ufd Cap	1	0.15048	0.9999594	0.9995487		
		Potentimeter	4	2.2176	0.9976079	0.9737398		
		SK3054	1	0.040205	0.9999891	0.9998794		
		1N4001	1	0.43776	0.9998818	0.9986876		
		DPDT Relay	1	17.7606	0.9952161	0.9481128		
		800562	1	1.442	0.9996107	0.9956833		
		PSD311	1	0.7705	0.999792	0.9976912		
		Max693	1	0.14125	0.9999619	0.9995763		
		Max232	1	0.17725	0.9999521	0.9994684		
		IRFD9120	2	0.31752	0.9998286	0.9980967		
		Voltage Reference	2	0.05625	0.9999696	0.9996626		
		UCN5801A	4	0.4505	0.9995136	0.9946086		
		7404	1	0.29325	0.9999208	0.9991206		
		LM1456	1	0.14875	0.9999598	0.9995538		
		AD7225	1	0.4505	0.9998784	0.9986494		
		Resistors	56	0.08844	0.9986637	0.9852519		
		LEDs	27	0.023552	0.9998283	0.9980941		
		10 ufd Cap	3	0.10296	0.9999166	0.9990738		
		.1 ufd Cap	8	0.288	0.9993781	0.9931118		
		33 pfd Cap	2	0.0441	0.9999762	0.9997354		
		100 ufd	1	0.14256	0.9999615	0.9995724		
		Xtal	1	4.62	0.9987534	0.9862356		
		Zener	1	0.2304	0.9999378	0.999309		
		P1 Brd Connector-44 Pins used	1	0.021504	0.9999942	0.9999355		
		P2, P3 Brd Connector 6 Pins used	2	0.00512	0.9999972	0.9999693		
		Connections	250	0.000069	0.9999953	0.9999483		
		PCB	1	0.24395	0.9999341	0.9992684		
	Main Relay Brd		1		0.963258	0.6597241	1.25	0.99974485
		DPST Relay	16	4.0365	0.9827135	0.8238622		
		RF Choke	16	0.1272	0.9994506	0.993913		
		Thermistor	7	9.45	0.9822981	0.8200008		
		1N4004	6	0.43776	0.9992911	0.9921513		
		Resistor	19	0.08844	0.9995464	0.9949716		
		.1 ufd Cap	3	0.288	0.9997667	0.9974114		
		.22ufd Cap	1	0.312	0.9999158	0.9990644		
		7810 Volt Ref	1	0.05625	0.9999848	0.9998313		
		LED	10	0.023552	0.9999364	0.9992937		

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		Connector-23 Pins used	1	0.011264	0.999997	0.9999662		
		Connector-5 Pins used	1	0.004864	0.9999987	0.9999854		
		Connector-9 Pins used	1	0.006144	0.9999983	0.9999816		
		Connections	75	0.000069	0.9999986	0.9999845		
		PCB	1	0.073185	0.9999802	0.9997805		
	Light Xstr Ckt	Darlington	2	1.52	0.9991795	0.9909215	1	0.99999544
Electric Air Compressor			1	10.3061	0.9972212	0.9997308	1.5	0.99997684
	-							
Operator Console					0.9906817	0.9012052		0.99979166
	Controls				0.9906817	0.9012052		0.99995777
		Membrane keyboard	1	8.8789	0.9976056	0.9737149	1	0.9999867
		Toggle Switches	9	2.6928	0.9934779	0.9298745	0.75	0.99997282
		Potentiometer	1	0.312	0.9999158	0.9990644	0.75	0.99999965
		Joy Sticks	2	0.624	0.9996631	0.996263	0.75	0.9999986
	1 NTSC Color Monitor (TV)		1	88.801	0.9758977	0.7625532	0.75	0.99989957
		CRT	1	76.8	0.9794775	0.7942159		
		HV Supply	1	2.6	0.9992982	0.9922303		
		Video & Sync	1	6.86	0.9981495	0.9796303		
		Potentiometer	6	0.312	0.9994947	0.9943997		
		Switch	1	2.229	0.9993984	0.9933353		
	GFI		1	0.6384	0.9998276	0.9980866	1	0.99999904
	220 VAC Pack		1		0.9956886	0.9531257		0.99997604
		220:30V Xfmr	1	0.846	0.9997716	0.9974652	1	0.99999873
		220/110 Xfmr	1	0.576	0.9998445	0.9982735	1	0.99999914
		Rect. Diodes	2	0.010022	0.9999946	0.9999399	1	0.99999997
		0.1 Fd Caps	2	7.28	0.9960765	0.9572602	1	0.9999782
		AC Outlet	1	0.000392	0.9999999	0.9999988	0.75	1
		2 Active Pin Conn	1	0.000392	0.9999999	0.9999988	0.9	1
	CPU Board		1	17.5586	0.9952704	0.9486875	1.5	0.99996059

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
	DPST Relay		3	0.40365	0.9996731	0.9963737	0.75	0.99999864

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
Cryogenesis				57.1165	0.9608986	0.6419904		0.99861889
	Pneumatic Solen Valve		4	18.5185	0.9801987	0.8007376	1.25	0.99986249
	Air Valve		2	16.5368	0.9911099	0.9055427	1.25	0.99993826
	Manual Valve		1	7.186	0.9980617	0.9786727	1.25	0.99998654
	DC Motor		1	3.3	0.9991094	0.9901488	32	0.99984167
	Air Hose (150 PSI)		1	11.5752	0.9968796	0.9658704	0.75	0.999987
	Pulser		1	18.5185	0.9950125	0.9459595	36	0.9990025
Delivery			1	26.48562	0.9799093	0.7981147		0.99878489
	DC Motor		2	3.3	0.9982196	0.9803947	1	0.99999011
	Gear Box		2	11.726	0.993688	0.9320619	32	0.99887786
	Linear Ball Bearings		4	10.9297	0.9882653	0.8770806	1.25	0.99991851
	Synchromesh cable		1		1	1	1	1
	Limit Switches		2	0.52992	0.9997139	0.9968255	0.75	0.99999881
	Nylon Gears		2	0.1685	0.999909	0.9989895	1	0.99999949
Tether Managment				77.2881	0.9693781	0.7078225		0.99788514
	Bearings		2	1.446	0.9992195	0.9913615	24	0.99989593
	Pneumatic Motor		1	3.15	0.9991499	0.9905945	40	0.99981108
	Chain Drive		1	2.8	0.9992443	0.9916352	1	0.9999958
	Slip Ring (Air & Elect)		1	27.4758	0.992609	0.9208783	24	0.99901453
	Air/elect Umbilical		1	12.49	0.9966334	0.9632233	40	0.99925186
	Local Controls (Speed)		1	29.9263	0.9919525	0.9141333	1	0.99995529
	Local Controls (On/Off)		1	36.4532	0.9902059	0.896408	0.75	0.99995919
Vacuum Filtration					0.9602299	0.6287161		0.99990592
	HEPA Filter							0.99991401
		Roughing Filters (2 of 3 Reqd)	3	2.193	0.9994081	0.9804565	1	1
		HEPA Filter	1	2.193	0.9994081	0.9934426	1	0.99999671
		Pressure Indicator	5	2.6114	0.9964808	0.9615863	0.75	0.99998534

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		Air Valve	1	16.5368	0.995545	0.9516001	1.25	0.99996906
		Solenoid Valve	1	18.5185	0.9950125	0.9459595	1.25	0.99996536
		Primary Air Filter	1	2.193	0.9994081	0.9934426	0.75	0.99999753
	Hose		1	11.5277	0.9968924	0.9660081	0.75	0.99998705
	Air Valve		1	16.5368	0.995545	0.9516001	1.25	0.99996906
	Pressure Reduction Valve		1	20	0.9946146	0.9417645	24	0.99928194
	Pressure Gauges		2	11	0.9940776	0.9361309	0.75	0.99997532
	Drum Full Alarm		1	7	0.9981118	0.979219	0.75	0.99999213
	Solid State Sensor		1	13.15	0.9964558	0.961318	24	0.99952744
	Press. Energ. Seal		1	5.4	0.9985431	0.9839305	1	0.99999191
Vehicle					0.9853118	0.7836706		0.99999823
	Veh Drive Motors		4 of 6	3.3	1	0.9535801	1.5	1
	Brake		2	4.2735	0.997695	0.9746849	1.5	0.99998079
	Brake Release		2	2.6082	0.9985926	0.9844726	1.5	0.99998827
	On/Off Control Switch		1	16.1568	0.9956472	0.9526855	0.75	0.99998186
	Dc Circuit Brakers		5	4.788	0.993557	0.9306984	0.75	0.99997315
	Connectors, Drive		4 of 6	0.017442	1	0.9686787	1.25	1
	Connectors, Other		4	0.23598	0.9997452	0.9971722	1.25	0.99999823
Video								
	B&W Camera (Fixed Focus, Auto Iris)			60.6119	0.983768	0.8337383	24	0.99783573
		CCD/ Intensifier	1	32.3888				
		HV Supply	1	11.6609				
		Syn Brd	1	1.9758				
		Video Brd	1	10.3				
		Automatics	1	4.2584				

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		BNC Connector	1	0.028				
	Color Camera			76.7073	0.979502	0.7944368	24	0.99726694
		CCD/ Intensifier	1	40				
		HV Supply	1	11.6609				
		Syn Brd	1	1.9758				
		Video Brd	1	15.3				
		Automatics	1	7.7426				
		BNC Connector	1	0.028				
					0.971772	0.7274893		0.99855467
	24VDC Light		2	38	0.9796891	0.7961243	0.75	0.99991537
	Pan DC Motor		1	3.3	0.9991094	0.9901488	24	0.99988125
	Pan Gear Box		1	11.726	0.996839	0.9654336	32	0.99943804
	Tilt DC Motor		1	3.3	0.9991094	0.9901488	24	0.99988125
	Tilt Gear Box		1	11.726	0.996839	0.9654336	32	0.99943804
	Decoder Board		1		0.9992646	1	24	0.99990195
		HOTL-2000	2	0.27175	0.9998533	0.9983708		
		LM5550N	1	0.15675	0.9999577	0.9995299		
		74LS374	1	0.2035	0.9999451	0.9993897		
		.1ufd Cap	4	0.288	0.999689	0.99655		
		10 ufd Cap	1	0.10296	0.9999722	0.9996912		
		220pfd Cap	1	0.15048	0.9999594	0.9995487		
		Resistors	4	0.08844	0.9999045	0.9989393		
		Board Connector	1	0.008448	0.9999977	0.9999747		
		Connections	65	0.000069	0.9999988	0.9999865		
		PCB	1	0.04879	0.9999868	0.9998536		
	Interface Board		1		0.9837895	0.8339406	24	0.99783859
		NEC uPD6450	1	0.3375	0.9999089	0.998988		
		LM1851	1	0.11925	0.9999678	0.9996423		
		Fixed Resistors	10	0.08844	0.9997612	0.9973503		
		100 ufd Cap	1	0.14256	0.9999615	0.9995724		
		33 pfd Cap	1	0.0441	0.9999881	0.9998677		
		Var Cap	1	5.72	0.9984568	0.9829864		
		RF Choke	1	0.1272	0.9999657	0.9996185		

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		XTAL	1	4.62	0.9987534	0.9862356		
		.1 ufd Cap	6	0.288	0.9995335	0.9948294		
		220 ufd Cap	1	0.15048	0.9999594	0.9995487		
		Potentimeter	4	2.2176	0.9976079	0.9737398		
		SK3054	1	0.040205	0.9999891	0.9998794		
		1N4001	1	0.43776	0.9998818	0.9986876		
		DPDT Relay	1	17.7606	0.9952161	0.9481128		
		800562	1	1.442	0.9996107	0.9956833		
		PSD311	1	0.7705	0.999792	0.9976912		
		Max693	1	0.14125	0.9999619	0.9995763		
		Max232	1	0.17725	0.9999521	0.9994684		
		IRFD9120	2	0.31752	0.9998286	0.9980967		
		Voltage Reference	2	0.05625	0.9999696	0.9996626		
		UCN5801A	4	0.4505	0.9995136	0.9946086		
		7404	1	0.29325	0.9999208	0.9991206		
		LM1456	1	0.14875	0.9999598	0.9995538		
		AD7225	1	0.4505	0.9998784	0.9986494		
		Resistors	56	0.08844	0.9986637	0.9852519		
		LEDs	27	0.023552	0.9998283	0.9980941		
		10 ufd Cap	3	0.10296	0.9999166	0.9990738		
		.1 ufd Cap	8	0.288	0.9993781	0.9931118		
		33 pfd Cap	2	0.0441	0.9999762	0.9997354		
		100 ufd	1	0.14256	0.9999615	0.9995724		
		Xtal	1	4.62	0.9987534	0.9862356		
		Zener	1	0.2304	0.9999378	0.999309		
		P1 Brd Connector-44 Pins used	1	0.021504	0.9999942	0.9999355		
		P2, P3 Brd Connector 6 Pins used	2	0.00512	0.9999972	0.9999693		
		Connections	250	0.000069	0.9999953	0.9999483		
		PCB	1	0.24395	0.9999341	0.9992684		
	Main Relay Brd		1		0.963258	0.6597241	24	0.99510106
		DPST Relay	16	4.0365	0.9827135	0.8238622		
		RF Choke	16	0.1272	0.9994506	0.993913		
		Thermistor	7	9.45	0.9822981	0.8200008		
		1N4004	6	0.43776	0.9992911	0.9921513		
		Resistor	19	0.08844	0.9995464	0.9949716		
		.1 ufd Cap	3	0.288	0.9997667	0.9974114		
		.22ufd Cap	1	0.312	0.9999158	0.9990644		
		7810 Volt Ref	1	0.05625	0.9999848	0.9998313		
		LED	10	0.023552	0.9999364	0.9992937		

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
		Connector-23 Pins used	1	0.011264	0.999997	0.9999662		
		Connector-5 Pins used	1	0.004864	0.9999987	0.9999854		
		Connector-9 Pins used	1	0.006144	0.9999983	0.9999816		
		Connections	75	0.000069	0.9999986	0.9999845		
		PCB	1	0.073185	0.9999802	0.9997805		
	Light Xstr Ckt	Darlington	2	1.52	0.9991795	0.9909215	1.25	0.9999943
Electric Air Compressor			1	10.3061	0.9972212	0.9997308	24	0.9996295
Operator Console					0.9906817	0.9012052		0.99681289
	Controls				0.9906817	0.9012052		0.99965182
		Membrane keyboard	1	8.8789	0.9976056	0.9737149	24	0.99968074
		Toggle Switches	9	2.6928	0.9934779	0.9298745	0.75	0.99997282
		Potentiometer	1	0.312	0.9999158	0.9990644	0.75	0.99999965
		Joy Sticks	2	0.624	0.9996631	0.996263	0.75	0.9999986
	1 NTSC Color Monitor (TV)		1	88.801	0.9758977	0.7625532	16	0.99785758
		CRT	1	76.8	0.9794775	0.7942159		
		HV Supply	1	2.6	0.9992982	0.9922303		
		Video & Sync	1	6.86	0.9981495	0.9796303		
		Potentiometer	6	0.312	0.9994947	0.9943997		
		Switch	1	2.229	0.9993984	0.9933353		
	GFI		1	0.6384	0.9998276	0.9980866	1	0.99999904
	220 VAC Pack		1		0.9956886	0.9531257		0.9999339
		220:30V Xfmr	1	0.846	0.9997716	0.9974652	24	0.99996955
		220/110 Xfmr	1	0.576	0.9998445	0.9982735	16	0.99998618
		Rect. Diodes	2	0.010022	0.9999946	0.9999399	1	0.99999997
		0.1 Fd Caps	2	7.28	0.9960765	0.9572602	1	0.9999782
		AC Outlet	1	0.000392	0.9999999	0.9999988	0.75	1
		2 Active Pin Conn	1	0.000392	0.9999999	0.9999988	0.9	1
	CPU Board		1	17.5586	0.9952704	0.9486875	24	0.99936939

Subsystem	Element	Next Lower Ass'y	Qty	Element FR	Tot Elmt Prob of Success (180)	Tot Elmt Prob of Success (2000)	MDT	Subs Avail
	DPST Relay		3	0.40365	0.9996731	0.9963737	0.75	0.99999864

APPENDIX B

SAFETY FOR THE ROVCO$_2$ SYSTEM

B. SAFETY FOR THE ROVCO_2 SYSTEM

Hazards

Collision:

The ROVCO_2 vehicle will weigh up to 1 ton and is powered by 6 motors with high gear reductions. Collisions with personnel or property will cause damage!

Asphyxiation:

The ROVCO_2 blasting system uses CO_2 pellets and may use N_2 blasting gas. Personnel confined in an area with the operating blasting system could be asphyxiated.

Abrasion:

The ROVCO_2 blasting system shoots a very high velocity jet of CO_2 pellets and compressed gas to remove surface material. Personnel or property hit by the jet may be hurt.

Noise:

The ROVCO_2 blasting system uses high volumes of high pressure gas creating noise above acceptable levels. Personnel near the blasting could suffer hearing loss.

Dust:

The ROVCO_2 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 ROVCO_2 system is electrically powered and in a mishap has the potential to shock personnel in contact with the vehicle or console.

Precautions

Operators:

The ROVCO_2 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 ROVCO_2 system will only be operated from properly grounded power sources. Power will be shut off, locked or disconnected, and drained before performing any servicing.

Vehicle Movement:

The vehicle will only be driven either with a 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 O_2 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

ROVCO_2 PHASE 2 TEST PLAN

PHASE 2 TEST PLAN

for

REMOTE OPERATED VEHICLE WITH CO_2 BLASTING ($ROVCO_2$)

AN R&D PROGRAM FOR

THE MORGANTOWN ENERGY TECHNOLOGY CENTER

of the

U.S. DEPARTMENT OF ENERGY

27 April 1995

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1.0 BACKGROUND

Phase 1 demonstrated that the ROVCO$_2$ system can provide a productive and effective means of decontaminating concrete floors. The system in Phase 1 included the development and integration of a remotely operated vehicle, CO_2 blasting system, and end effector. Phase 2 of the ROVCO$_2$ program includes the addition of a vacuum filtration containment subsystem and a tether management subsystem. Phase 2 also includes a few modifications including: increase in swept area and automation of linear path blasting.

The Phase 1 testing included:

- ROV motion and control
- COYOTEE function
- Coverage
- Rate
- Operator control unit evaluation
- CO_2 blasting coverage and flow rates

Testing in the second phase will produce quantitative results for the reliability, productivity, and effectiveness of the system.

2.0 OBJECTIVES

Phase 2 testing will verify that the system and subsystems meet the ROVCO$_2$ Success Criteria and derived requirements. Verification will be accomplished by repeatable, documented experiments that prove performance of the ROVCO$_2$ system and subsystems. These experiments will specifically measure the parameters defined in the Success Criteria.

Experiments to be carried out include:

- Cold Test
- Decontaminability Test
- Tether Management Subsystem Test
- System Productivity Test
- System Reliability Test

A secondary objective of the tests is to provide a second operating demonstration of the ROVCO$_2$ system concept. The demonstration will confirm the integrated function of the system.

3.0 SUCCESS CRITERIA TO TEST VERIFICATION MAPPING

In the following table, the ROVCO$_2$ Success Criteria are mapped to the planned verification tests by titles. This provides a high-level reference to check for adequate verification coverage. Only a brief discussion of each test is included in the table. Refer to the next section, Test Descriptions, for details about each test.

Table 3.0-1: Success Criteria to Test Verification Mapping

SUCCESS CRITERIA	TEST TITLE & MEASURED QUANTITY
2.1 Tether Management System	
2.1.1 The TMS shall be capable of managing tether payout and reel in as required for effective ROV motion.	**Tether Management Subsystem Test** Demonstrates tether payout and reel-in as the vehicle maneuvers around typical obstacles, at angles, forward and reverse Data: Observations and video tape
2.1.2 The TMS shall be capable of ROV recovery in a contingency situation.	**Tether Management Subsystem Test** Demonstrates the ability of the TMS to retrieve the ROV with the brakes released Data: Observations and video tape
2.1.3 Exposed surfaces of the TMS shall be decontaminable by either CO_2 blasting or high pressure water washdown techniques.	**Decontaminability Test** Verifies the effectiveness of decontamination by CO_2 blasting Data: Visual observation from the TMS
2.2 Vacuum Filtration and Containment Subsystem (VFCS)	

SUCCESS CRITERIA	TEST TITLE & MEASURED QUANTITY
2.2.1 The VFCS shall employ a HEPA filtration unit to remove separate contaminants for disposal.	**Filtration Subsystem Specifications** Specifications provided by the manufacturer of the filtration system
2.2.2 The VFCS shall be sealed to provide effective contaminant containment.	**Cold Test** Verifies seal effectiveness by placing leak indicators at the seals of the VFCS Data: Visual observation and video tape of leak indicators
2.2.3 Exposed surfaces of the VFCS shall be decontaminable by either CO_2 blasting or high pressure water washdown techniques.	**Decontaminability Test** Verifies the effectiveness of decontaminating by CO_2 blasting Data: Visual observation of VFCS
2.3 CO_2 Blasting	**System Productivity Test**
2.3.1 The CO_2 Blasting unit shall incorporate a substrate heating unit to enhance contaminant removal.	Measures the blasting rate at (sq ft/hr) maximum CO_2 pellet rate and blast air/N2 pressure for both epoxy paint and sealant Data: Time, area swept, motor/indexer commands, blast air/N2 pressure, and CO_2 pellet rate.

SUCCESS CRITERIA	TEST TITLE & MEASURED QUANTITY
2.4 System Effectiveness	**Cold Test**
2.4.1 ROVCO$_2$ shall be capable of removing 75-99% of smearable contamination from concrete floor surfaces.	Determines the effectiveness of removing smearable contamination from concrete floors by laboratory analysis of smearable contamination applied and remaining Data: Smearable contamination applied and remaining
2.4.2 ROVCO$_2$ shall be capable of removing 50-99% of fixed contamination from surface pores of the concrete in a single pass.	Determines the effectiveness of removing fixed contamination from the surface pores of the concrete in a single pass by laboratory analysis of fixed contamination applied and remaining Data: Fixed contamination applied and remaining
2.5 System Reliability	**System Reliability & System Productivity Tests**
2.5.1 ROVCO$_2$ downtime shall not exceed more than 20% of expected operation time due to component failure.	Measures down time over 1,000 hours of operation of system except blasting. Blasting reliability is determined from history of manual operation. Data: Run time, component failures, failure effects, time down, repair time, and repetitive failures.

SUCCESS CRITERIA	TEST TITLE & MEASURED QUANTITY
2.6 System Productivity	**System Productivity Test**
2.6.1 ROVCO$_2$ shall be capable of decontaminating between 30 and 75 square feet of concrete floor space per hour, dependent upon the level of decontamination required and the contaminated surface relief.	Determination of the systems productivity by determining the average time to decontaminate the areas including CO_2 blasting and vehicle movements Data: Time, area swept, motor/indexer commands, blast air/N2 pressure, and CO_2 pellet rate
2.6.2 The OCU shall autonomously control tedious repetitive operations, allowing the operator to focus on overall system operation and monitoring.	Verification of the OCU's ability to control tedious repetitive operations Data: Command given, operation conducted, and visual observations

4.0 TEST DESCRIPTIONS

4.1 Cold Test

Table 4.1-1: Cold Test Verification to Success Criteria Mapping

Cold Test	Success Criteria	
VFCS seal effectiveness determined by observation of leak indicators	2.2.2	The VFCS shall be sealed to provide effective contaminant containment.
Determines the effectiveness of removing smearable contamination from concrete floors by laboratory analysis os smearable contamination applied and remaining	2.4.1	ROVCO$_2$ shall be capable of removing 75-99% of smearable contamination from concrete floor surfaces
Determines the effectiveness of removing fixed contamination from the surface pores of the concrete by laboratory analysis of fixed contamination applied and remaining	2.4.2	ROVCO$_2$ shall be capable of removing 50-99% of fixed contamination from surface pores of the concrete in a single pass.

Objectives:

1. Determine the effectiveness of removing smearable and fixed contamination from concrete floors
2. Verify the capability of the containment system and seals of the Vacuum Filtration and Containment System (VFCS)

In general, the Cold Test determines the effectiveness of the ROVCO$_2$ system by modelling the Oak Ridge site conditions. The Oak Ridge site will be modelled by allowing a nonhazardous contaminant surrogate to settle on a concrete surface and applying a coating over the surrogate. See Appendix A for further information concerning the selection process of the modelled contaminates, surrogates, and detection methods used during the cold test.

The four scenarios modelled include:
- Epoxy over uranium
- Sealant over uranium
- Epoxy over PCBs
- Sealant over PCBs

The concrete (portland cement) used during the test is selected based on the concrete in the site's buildings. The epoxy coating, Pittsburg® Aquapon Polyamide-Epoxy, is also the same type of coatings used at Oak Ridge. The sealant, Zeptone® Sealer, is a representative sealant used on concrete floors. A cerium salt (Cerium III Chloride, $CeCl_3 \bullet XH_2O$) has been selected as the surrogate for the uranium contamination at the site. A 90 weight gear oil has been selected as the surrogate for the PCB contamination at the site. The cerium compound in an aqueous solution will be applied as a mist. The mist application is similar to contamination process that occurred while the plants were in operation and evenly distributes the surrogate. (See Appendix A for details)

4.1.1 Methodology

CO_2 Blasting Rates

Prior to conducting the cold test the optimum blasting rate will be determined for epoxy paint and sealant. The optimum blasting rate is the sweeping rate which removes the coating from a concrete surface. Speeds will be varied from .25 ips in increments of .5 ips until a sweep speed is reached which does not remove all/most paint (visual inspection.) Then the sweep rate will be reduced by .5 ips and the testing will proceed using increments of .1 ips. Using this approach, the maximum sweeping rate for epoxy paint and sealant removal will be determined.

Removal Effectiveness

The effectiveness of removing the smearable and fixed contamination will be determined quantitatively through laboratory analysis of samples collected during the test. Materials not removed include the surrogate and coating that may have been removed but fell back to the floor and the material that was not removed by the blasting.

The concrete samples (clean, before test, and after test) and the smearable test samples will indicate the amount of fixed surrogate, smearable surrogate, and coating that was placed on and removed from the floor. Smearable test results will indicate the amount of material not removed, including material which fell back to the floor and the unremoved smearable contaminate. Floor samples taken at measured depths will indicate the penetration of the surrogate and coating before and after removal. The exact sample penetrations achieved before and after the test will not be identical but will indicate surrogate and blasting penetration. Combined results from the floor and smearable test will determine the total amount of material not removed. Laboratory analysis of the material present in the containment drum of the filtration system will also indicate surrogate, coating, and concrete removal. A scale will be used to determine when enough sample is collected. Since a scale is already required and due to the delay of the laboratory results (approximately 2 weeks), weight measurements may be taken to give an initial quantitative indication of the results.

A black light may also be used to give a visual indication. Fluorescent emission from the surrogates may be radiated when exposed to the radiant energy given by a black light. An additive, Naphthalene, can be added to the oil to give it fluorescent properties. Rare earths (cerium) have been documented as emitting fluorescent light under certain conditions. Due to the number of factors effecting cerium's fluorescent properties, the visual indication is not completely accurate. For example, cerium may be present but when exposed to the black light, fluorescent light is not emitted.

Containment System Capability

The capability of the containment system will be determined quantitatively through laboratory analysis of samples collected during the test. Materials not contained include the surrogate and coating that are removed from the floor and are not contained in the VFCS. Materials that fell back to the floor are considered unremoved.

A containment curtain around the workhead will capture substances that are projected away from the workhead. Containment curtain samples will indicate the amount of material not contained.

Laboratory Analysis

The removed effectiveness will be determined by laboratory analysis of the samples before and after testing. The major components present in the concrete aggregate are: $CaCO_3$, SiO_2, Al_2O_3, CaO, MgO, Na_2O, K_2O, Fe_2O_3, MnO, Cr_2O_3, P_2O_5, and TiO_2. Portland cement can contain combinations of Ca_3, Al_2, (OH), and/or Ca_2SiO_4. The major components present in the epoxy coating include: TiO_2, $Al_2O_3 \bullet SiO_2$, and epoxy resin. Due to the complexity

of the sealant and its insignificance, laboratory analysis on samples which contain sealant will only evaluate the amount of surrogate present.

Since the elements which are contained in the epoxy coating are also present in the concrete floor, the amount of epoxy paint applied to and remaining on the floor will be determined by the difference in SiO_2, Al_2O_3, CaO, and TiO_2 before application, after application, and after removal. These compounds will be determined by laboratory x-ray fluorescence (XRF-100).

The amount of cerium applied to and remaining on the floor will be determined by Inductively Coupled Plasma/Mass Spectrometry (ICP/MS) in floor samples before, after application, and after removal. ICP/MS will also be used on smearable and containment curtain test samples. The amount of oil in concrete and cloth samples will be determined by gravimetric determination by methylene chloride extraction (GD/MCE). Table 4.1-1, 4.1-2, and 4.1-3 list the samples taken during the test and the specific laboratory analysis that will be performed.

Table 4.1-2: Summary of Cold Test Blank/Clean Samples and Laboratory Analysis

Sampled Material	No. of Samples	Laboratory Analysis
Smearable Cloth	1	ICP/MS17, XRF-100, & GD/MCE
Concrete Floor	2	ICP/MS17, XRF-100, & GD/MCE
Containment Curtain	1	ICP/MS17, XRF-100, & GD/MCE

Table 4.1-3: Summary of Cold Test Samples and Laboratory Analysis (Cerium as Surrogate)

Sampled Material	Sample Contents	No. of Samples/Weight	Laboratory Analysis
Smearable Cloth	Smearable Ce Applied	2	ICP/MS17
	Remaining Smearable Ce & Material Fall Backs	2	ICP/MS17 & XRF-100
Concrete Floor	Ce and Epoxy Coating Applied @ Penetration Levels	4	ICP/MS17 & XRF-100
	Ce Applied @ Penetration Levels (Sealant as coating)		ICP/MS17
	Ce and Epoxy Coating Remaining @ Penetration Levels	4	ICP/MS17 & XRF-100
	Ce Remaining @ Penetration Levels (Sealant as coating)		ICP/MS17

Sampled Material	Sample Contents	No. of Samples/Weight	Laboratory Analysis
Containment Curtain	Ce and Epoxy Coating Not Contained Ce Not Contained (Sealant as coating)	3	ICP/MS17 & XRF-100 ICP/MS17
Containment Drum	Ce, Epoxy Coating, and Concrete Removed Ce and Concrete Removed (Sealant as coating)	2	ICP/MS17 & XRF-100

Table 4.1-4: Summary of Cold Test Samples and Laboratory Analysis (Oil as Surrogate)

Sampled Material	Sample Contents	No. of Samples	Laboratory Analysis
Smearable Cloth	Smearable Oil Applied	2	GD/MCE
	Remaining Smearable Oil & Unremoved Material Fall Backs	2	GD/MCE & XRF-100
Concrete Samples	Oil and Epoxy Coating Applied @ Penetration Levels Oil Applied @ Penetration Levels (Sealant as coating)	4	GD/MCD & XRF-100 GD/MCD

Sampled Material	Sample Contents	No. of Samples	Laboratory Analysis
Containment Curtain	Oil and Epoxy Coating Not Contained	3	GD/MCD & XRF-100
	Oil Not Contained ((Sealant as coating)		GD/MCD
Containment Drum	Oil, Epoxy Coating, and Concrete Removed	2	GD/MCD & XRF-100
	Oil and Concrete Removed (Sealant as coating)		

Seal Capability

The capability of the seals of the VFCS will be determined by visual inspection of leak indicators (thin films of plastic) placed at each seal during the test.

4.1.2 Equipment

- ROVCO$_2$ system
- hand held scarifier
- 250 lb scale
- 10 lb scale
- lifting crane
- vernier depth caliper
- spray bottle
- paint pan and roller
- scissors
- camcorder with tripod

4.1.3 Data Quality

Vernier Depth Caliper with ±.1 mm (for distances < 1/4"), estimated average error .2mm/1/8"⇒ 6.3%

Scale A (250 lb capacity): accuracy of 0.02 lb; repeatability of 0.01% of capacity

Scale B (10 lb capacity): accuracy of ±0.0002 lb (±0.09 grams)

Laboratory Analysis

Error analysis will be conducted to determine the accumulated percent error in the results. The error analysis will use the accuracies given below:

- ICP/MS17 - 0.1 ppm detection limit for Ce with an accuracy of ±0.3 ppm

- XRF-100 -.01% detection limit for SiO_2, Al_2O_3, CaO, MgO, Na_2O,K_2O,Fe_2O_3, MnO, Cr_2O_3, P_2O_5, TiO_2 with an accuracy ±0.5%

- GD/MCD ≈ 0.001% detection limit for 10 gram sample of oil with an accuracy of ±0.0015%

4.1.4 Procedures

I. Modelled Conditions Preparation
  A. Pour concrete slab
    1. Slab dimensions ≈ 4 ft x 4 ft x 3 in deep

    2. Allow the slab to cure 28 days

  B. Test area preparation
    1. Clean test area of concrete slab

    2. Blank/Clean sample of smear cloth
      a. Conduct smear test by wiping over clean concrete with the cloth
      b. Cut one sample from cloth
      c. Place sample in marked container
      d. Sample must weigh at least 20 grams (±0.2 grams)

    3. Cover an area to keep clean/blank from surrogate and coating
      a. Equal or greater than scarifier surface area (≈1 ft^2)
      b. Near the edge of the test area cleaned in step 1

    4. Mark the edges of the covered area

  C. Weigh the amount of surrogate (≈100 grams) applied to the floor
    1. Cerium used as surrogate
      a. Zero scale (B) between before each of the following measurements
      b. Weigh the empty spray bottle, Record
      c. Add about a cup of water to bottle, Weigh, Record
      d. Weigh surrogate compound (≈250 grams) to be added to water, Record
      e. Add surrogate compound to water, Mix

f. Spray test area evenly until bottle is empty
   (1) Spray within the test area
   (2) Do not spray near test area edges to avoid missing test area
g. Weigh the bottle, Record
h. Determine the amount (%by weight ≈100 grams) of surrogate applied to the test area

2. Oil used as surrogate
   a. Zero scale (B) between before each of the following measurements
   b. Weigh the paint pan and roller with oil, Record
   c. Apply oil to test area evenly
   d. Weigh the remaining oil, pan, and roller; Record
   e. Determine the amount of surrogate applied to the test area

D. Allow the surrogate to settle in concrete
   1. Place light\heat source over applied surrogate for 2 days

   2. Keep clean from collecting any residue on the test area

E. Smearable surrogate applied to the floor
   1. Weight
      a. Zero scale B
      b. Weigh the cloth before conducting smear test, Record
      c. Conduct smear test by wiping over the entire test area with the cloth one time
      d. Weigh the cloth after the smear test, Record
      e. Determine the amount of smearable and fixed surrogate applied to the test area

   2. Samples
      a. Cut two samples from cloth
      b. Place samples in marked containers
         (1) Cerium samples must be at least 8 grams (±0.2 grams)
         (2) Oil samples must be at least 11 grams (±0.2 grams)

F. Apply coating to the test area
   1. Zero the scale

   2. Weigh the coating, pan, and applicator before application, Record

   3. Weigh the coating, pan, and applicator after application, Record

4. Determine the amount of coating applied to the test area

5. Allow the coating to dry, keeping the test area clean

G. Samples of concrete floor
   1. Fresh/Clean concrete
      a. In the covered location, use scarifier to remove the top surface of the concrete
      b. Place 2 samples in marked containers
      c. Verify sample size, must be at least 20 grams ($\pm$0.2 grams)

   2. Fixed surrogate and coating applied
      a. In a location other than previous sample, use scarifier to remove top surface of concrete
      b. Place concrete sample in marked container
         (1) Cerium samples must be at least 8 grams ($\pm$0.2 grams)
         (2) Oil samples must be at least 11 grams ($\pm$0.2 grams)
      c. Clean sample area, measure scarifier penetration and record
      d. In same location, use scarifier to remove deeper concrete near the surface
      e. Place concrete sample in marked container
         (1) Cerium samples must be at least 8 grams ($\pm$0.2 grams)
         (2) Oil samples must be at least 11 grams ($\pm$0.2 grams)
      f. Clean sample area, measure scarifier penetration and record
      g. Repeat steps d-f until 4 samples are collected

II. Test Preparation
A. Blank/Clean containment curtain sample
   1. Cut one sample from curtain

   2. Place sample in marked container

   3. Verify sample size, must be at least 20 grams ($\pm$0.2 grams)

B. Record weights (in the order indicated)
   1. Weigh the filtration system (including containment drum)
      a. Zero Scale A
      b. Weigh the filtration system, Record
   2. Weigh the containment curtain
      a. Zero Scale B
      b. Weigh the containment curtain, Record

C. Prepare $ROVCO_2$
   1. Reattach the filtration system and containment drum

2. Attach the seal leak indicators around the seals of the VFCS

3. Attach the containment curtain around the workhead

4. Power up vehicle and OCU

5. Check vehicle, camera, and OCU controls

6. Set OCU control parameters
   a. Maximum blast air/N2 pressure and CO_2 rate
   b. Record

7. Position vehicle and mark workhead position, Record

D. Prepare camcorder
   1. Position camcorder

   2. Mark tape

   3. Insert tape

   4. Check/reset video counter, Record

III. Sweep test area while observing seal leak indicators, Record observations

IV. Record Data
   A. Weights (in the order indicated)
      1. Filtration system (including containment drum)
         a. Remove the filtration system
         b. Weigh the filtration system
            (1) Zero Scale A
            (2) Weigh the filtration system, Record
         c. Calculate weight contained in the filtration system, Record

      2. Containment curtain
         a. Remove containment curtain

         b. Weigh containment curtain
            (1) Zero Scale B
            (2) Weigh the containment curtain, Record
         c. Calculate weight contained in the containment curtain, Record

V. Collect Remaining Samples

A. Smear cloth for remaining smearable surrogate and material fall backs

1. In a location other than previous concrete samples, use cloth wipe over the concrete

2. Cover an area equal to or larger than scarifier

3. Place two samples in marked containers

4. Verify sample size
   a. Cerium samples must be at least 8 ($\pm$ 0.2 grams)
   b. Oil samples must be at least 11 ($\pm$ 0.2 grams)

B. Concrete for remaining fixed surrogate and coating

1. In the same location as above, use scarifier to remove top surface of concrete

2. Place concrete sample in marked container at least 8 ($\pm$0.2 grams)

3. Clean sample area, measure scarifier penetration and record

4. In same location, use scarifier to remove deeper concrete near the surface

5. Place concrete sample in marked container at least 8 ($\pm$0.2 grams)

6. Clean sample area, measure scarifier penetration and record

7. Repeat steps 4-6 until 4 samples are collected

C. Containment curtain

1. Cut 3 samples of containment curtain

2. Place samples in marked containers

D. Containment drum collection

1. Collect 2 samples of contained material from containment drum

2. Place samples in marked containers

E. Record any notes

F. Repeat for next scenario

4.2 Decontaminability Test

Objectives:

To verify that the exposed surfaces of the Vacuum Filtration and Containment System (VFCS) and Tether Management System (TMS) are decontaminable by CO_2 blasting.

Table 4.2-1: Decontaminability Test Verification to Success Criteria Mapping

Decontaminability Test	Success Criteria	
Verifies the effectiveness of decontaminating by CO_2 blasting	2.1.3	Exposed surfaces of the TMS shall be decontaminable by either CO_2 blasting or high pressure water washdown techniques.
Verifies the effectiveness of decontaminating by CO_2 blasting	2.2.3	Exposed surfaces of the VFCS shall be decontaminable by either CO_2 blasting or high pressure washdown techniques.

4.2.1 Methodology

The Decontaminability Test will verify the ability to decontaminate the ROVCO$_2$ System. The contaminated vehicle and Tether Management System (TMS) will be modelled by covering them with a brightly colored powder. The powder will then be removed by using the CO_2 blasting subsystem. The decontamination effectiveness will be verified by visual inspection of the vehicle and white wiping cloth.

4.2.2 Equipment

- ROVCO$_2$ system
- TMS system
- white wiping cloth
- brightly colored powder
- camcorder with tripod
- camera

4.2.3 Data Quality

Visual indication of vehicle, TMS, and white wiping cloth; before and after photograph and video tape.

4.2.4 Procedures

I. Test Preparation
   A. Setup the CO_2 blasting subsystem for manual blasting by removing the workhead and attaching substitute hoses.

II. Conduct Decontamination Test
   A. Coat the vehicle and TMS with brightly colored power

   B. Record the vehicle and TMS on the visual media

   C. Power up CO_2 blasting subsystem

   D. Remove the "contamination" powder from the vehicle

   E. Shut off CO_2 blasting subsystem

   F. Record the vehicle and TMS on the visual media

   G. Wipe the entire vehicle and TMS down with the white cloth

   H. Record the cloth on the visual media

   I. Record any comments

4.3 Tether Management Subsystem Test

Table 4.3-1: Tether Management Subsystem Test Verification to Success Criteria Mapping

Tether Management Subsystem Test	Success Criteria	
Demonstrates tether payout and reel-in as the vehicle maneuvers around typical obsticals, at angles, forward and reverse	2.1.1	The TMS shall be capable of managing tether payout and reel in as required for effective ROV motion.
Demonstrates the ability of the TMS to retrieve the ROV with the breaks released	2.1.2	The TMS shall be capable of ROV recovery in a contingency situation.

Objectives:

1. Verify the ROVCO$_2$'s capability of managing tether payout and reel-in as required for effective ROV motion

2. Demonstrate TMS's capability of recovering the vehicle in a contingency situation

4.3.1 Methodology

The Tether Management Subsystem (TMS) Test will verify the capabilities of the TMS. The test will demonstrate the TMS's capability of managing tether payout and reel-in when it is operating in expected conditions. The test will include maneuverability when the vehicle moves at angles, toward, and away from the TMS. The maneuverability around typical obstacles will also be demonstrated. Each repeated movement will be timed to help determine the constancy of the TMS.
The TMS's ability to recover the vehicle in a contingency situation is also demonstrated. The vehicle will be recovered 50 feet without the vehicle's breaks applied.

4.3.2 Equipment

- $ROVCO_2$ system
- TMS
- stop watch
- camcorder with tripod.

4.3.3 Data Quality

Stop watch	± 0.1 s, estimated maximum error .2 s/100 s $\Rightarrow$ 0.2% (assuming vehicle speed of 0.02 fps)

4.3.4 Procedures

I. Test Preparation
   A. Set up column mock up

   B. Powered up vehicle

   C. Prepare camcorder
      1. Mark tape

      2. Insert tape

      3. Check/reset video counter, record counter #

II. Conduct TMS Test
   A. Position vehicle in start location (Figure 4.3-1)
      1. At 20 feet to the left of the TMS

      2. Approximately 10 feet ahead of the TMS

B. Start camcorder

C. Conduct movements to be tested
   1. Forward, reverse, and angle movements (Figure 4.3-1)
      a. Start timer
      b. Move vehicle approximately 50 ft forward, Record time
      c. Complete the path demonstrated in Figure 4.3-1
         (1) By forward and reverse directions
         (2) Record time to reach each point
      d. Record all observations

   2. Column movements (Figure 4.3-2)
      a. Figure eight between columns
         (1) Position vehicle in start location
            (a) With the TMS directly behind vehicle
            (b) In line with the columns
         (2) Start timer
         (3) Move vehicle forward and around columns, Record time
         (4) Record observations
         (5) Reverse vehicle direction
         (6) Stop timer when vehicle reaches start location, Record time
         (7) Record observations
      b. 45° around one column
         (1) Position vehicle in start location
            (a) With the TMS directly behind vehicle
            (b) Slightly to the side of one column
            (c) Approximately 20 feet away from column
         (2) Start timer
         (3) Move vehicle forward and around column, Record time
         (4) Record observations
         (5) Reverse vehicle direction
         (6) Stop timer when vehicle reaches start location, Record time
         (7) Record observations

D. Conduct vehicle recovery
   1. Position vehicle in start location 100 feet away from TMS

   2. Make sure breaks are in the released position

   3. Start vehicle recovery and timer

   4. Record observations of the TMS and vehicle

   5. Stop timer when vehicle reaches the TMS, Record time

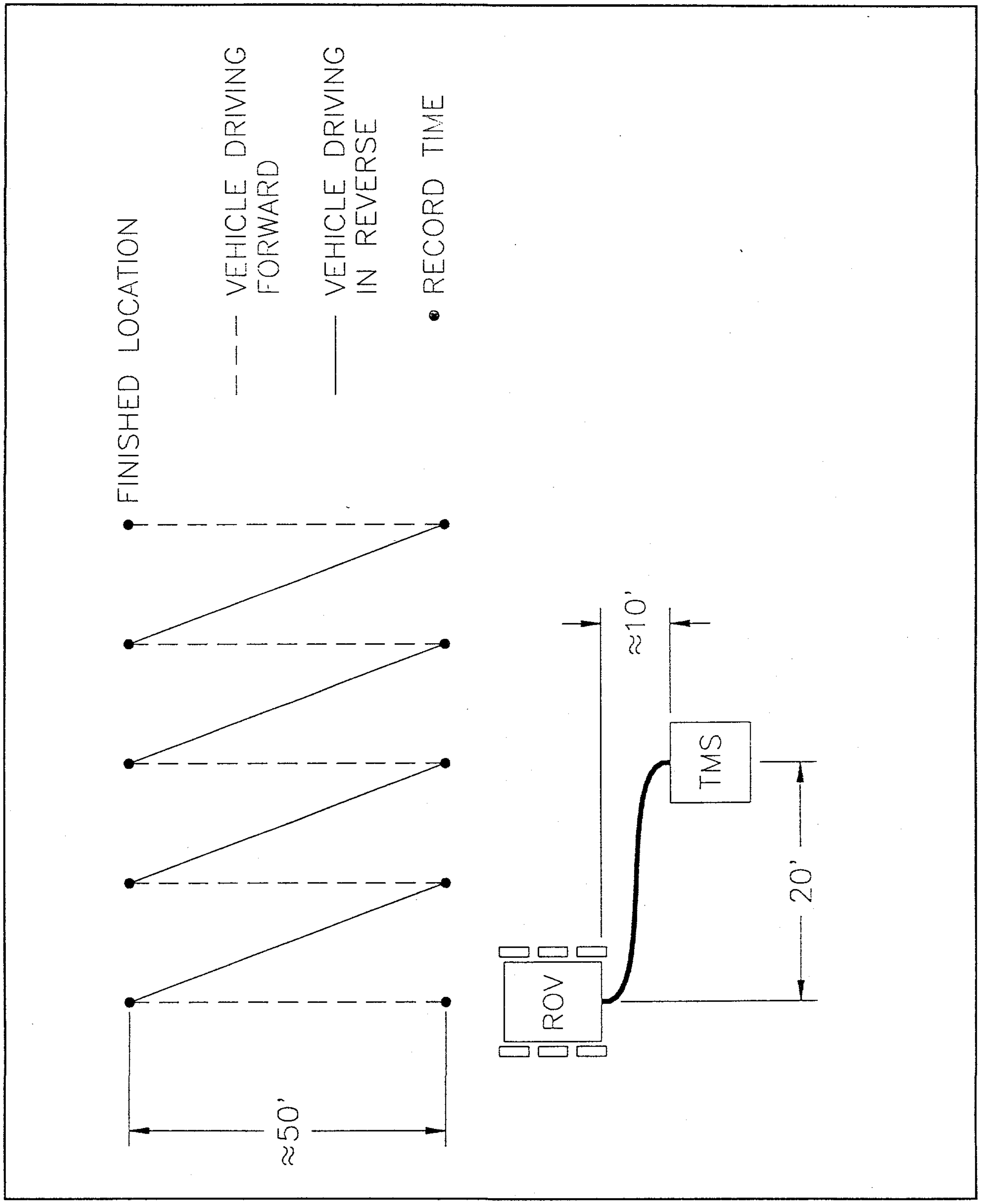

Figure 4.3-1: *Tether Management Subsystem Forward, Reverse, and Angle Movements & Set-up*

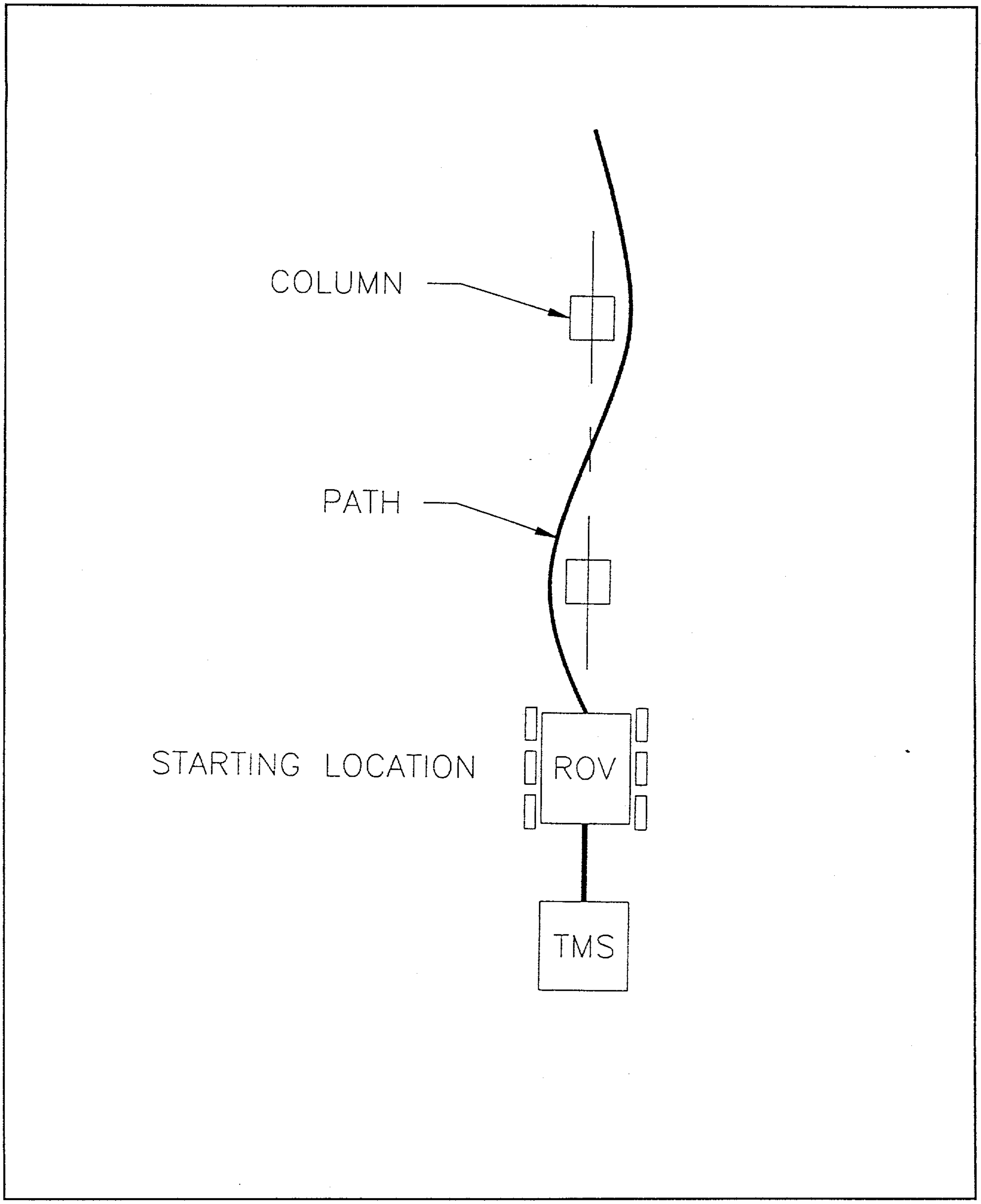

Figure 4.3-2: *Tether Management Subsystem Column Movements & Set-up*

4.4 System Productivity Test

Table 4.4-1: System Productivity Test Verification to Success Criteria Mapping

System Productivity Test	Success Criteria	
Measures the blasting rate (ft^2/hr) at maximum CO_2 pellet rate and blast air/N2 pressure for both epoxy paint and sealant	2.2.2	The CO_2 Blasting unit shall incorporate a substrate heating unit to enhance contaminant removal.
Determines the systems productivity by determining the average time to decontaminate the areas including CO_2 blasting and vehicle movements	2.6.1	ROVCO$_2$ shall be capable of decontaminating between 30 and 75 square feet of concrete floor space per hour, dependent upon the level of decontaminating required and contaminated surface relief.
Verification of the OCU's ability to control tedious repetitive operations	2.6.2	The OCU shall autonomously control tedious repetitive operations, allowing the operator to focus on overall system operating and monitoring.

Objectives:

1. Demonstrate the ROVCO$_2$ capability of decontaminating between 30 and 75 square feet of concrete floor space per hour

2. Demonstrate the OCU capability to autonomously control tedious repetitive operations

3. Determine the CO_2 blasting rate for epoxy paint and sealant

4. To obtain reliability data during blasting operations.

4.4.1 Methodology

The System Productivity Test will determine the productivity of the ROVCO$_2$ system in operating conditions similar to the Oak Ridge K-25 Site. Two test scenarios will be conducted. The first test will be conducted using sealant as the coating over an area similar in size (500 ft^2) to the area between columns in the K-25 building. The second test will be conducted using epoxy paint as the coating over a smaller area, approximately 30 ft^2. The epoxy coating, Pittsburg Aquapon Polyamide-Epoxy, is the same type of coatings used at Oak Ridge. The sealer, Zeptone Sealer, is a representative sealant used on concrete floors.

During both scenarios, reliability information during blasting operations will also be taken. Recorded reliability information includes single point failures, repeated failures, and failure effects. The blasting rate will also be determined at maximum CO_2 pellet and air flow rates by recording the time required to "decontaminate" the test areas.

4.4.2 Equipment

- ROVCO$_2$ system
- tape measure
- stop watch
- camcorder with tripod

4.4.3 Data Quality

Stop watch	± 0.1 s, estimated maximum error .2 s/100 s $\Rightarrow$ 0.2% (assuming vehicle speed of 0.02 fps)
Tape measure	$\pm 1/8$" (for distances < 10'), estimated avg. error .25"/5" $\Rightarrow$ 5% $\pm 1/2$" (10' < overall distance $\leq$ 50'), estimated minimum error 1"/360"$\Rightarrow$ 0.3% (for 30' measurement)

4.4.4 Procedures

I. Test area preparation for sealer scenario
   A. Clean test area ($\approx$500 ft^2 - 25 ft wide x 20 ft long)

   B. Apply sealer coating to the test area
      1. Must be applied evenly

      2. Area equal to 25 ft wide x 20 ft long

      3. Allow the sealer to dry the manufacturer's recommended length of time

II. Test Preparation
   A. Prepare the ROVCO$_2$
      1. Power up vehicle

      2. Check vehicle and camera

      3. Position vehicle and mark workhead position, Record

   B. Prepare camcorder
      1. Position camcorder

III. Sweep Test Area
   A. Start timer when sweeping is initiated

   B. Record reliability information if failure occurs
      1. Failed component/s

      2. Repeated failures

      3. Failure effects

      4. Mean time between failures (MTBF)

      5. Mean time to repair (MTTR)

   C. Stop timer when sweeping is complete, Record

IV. Record Data
   A. Mark final workhead position, Record

   B. Calculate swept area, Record

   C. Record any notes

V. Test area preparation for epoxy scenario
   A. Clean test area ($\approx$30 ft^2 - 6 ft wide x 5 ft long)

   B. Apply sealer coating to the test area
      1. Must be applied evenly

      2. Area equal to 6 ft wide x 5 ft long

      3. Allow the sealer to dry the manufacturer's recommended length of time

VI. Repeat procedure used during sealer scenario steps II-IV

4.5 System Reliability Test

Table 4.5-1: System Reliability Test Verification to Success Criteria Mapping

System Reliability Test	Success Criteria	
Determines the down time over 1,000 hours of operation os system except blasting	2.5.1	$ROVCO_2$ downtime shall not exceed more than 20% of expected operation time due to component failure.

Objectives:

To verify the $ROVCO_2$'s downtime does not exceed more than 20% of the expected operation time due to component failures.

The System Reliability Test will measure the down time and repair time over 900 hours of system operation excluding CO_2 blasting. The test will identify single point failures, repeated failures, failure effects, mean time between failures, and mean time to repair.

Reliability data for the blasting system will be obtained from the manufacturer of the system and the productivity test.

4.5.1 Methodology

The test will be conducted on a test stand which will allow the vehicle to run continuously in one location. The vehicle will run continuously by giving a command to the Auto ROV subsystem. The ROV can be told to clean a large area which results in 900 hours of operation time. The Tether Management Subsystem will also tested by repetitively paying-out and reeling-in the umbilical over the 900 hours.

A monitor system attached to the vehicle and TMS will identify when any single point failure has occurred and shut off the system. All single point failures can be monitored by wheel and winch rotations, COYOTEE movements, and valve actuations. When a failure occurs, the monitoring system will log the time and state of each monitoring signal identifying the specific failed component.

The test stand models the forces that act on the vehicle when it is operating on ground. A flywheel attached to each wheel of the vehicle models the inertial forces each time the vehicle begins or stops motion. A mock floor will be placed to include the frictional forces that act on the brushes around the workhead. The upwards thrust resulting from blasting operations will be modelled by applying air pressure to an air cylinder which pushes upward on the workhead.

4.5.2 Equipment

- $ROVCO_2$ system
- TMS
- Monitoring System
- Test Stand

4.5.3 Data Quality

During the reliability test, the monitoring system, vehicle, and test stand will be inspected every eight hours. The inspection will ensure that the systems are operating properly and double check for undetected failures.

The monitoring system will check each of the signals listed in the following table at the end of each cycle. A cycle consists the steps required to sweep the COYOTEE area and to move forward to the next area. If an "open" signal is identified during a cycle, a failure is identified and the listed signals are recorded.

Table 4.5.3-1: List of Monitoring System's Signals

Item Monitored	Number of Signals	Type of Indicator	Signal Received	Meaning of Signal
Wheel Rotations	6 (Each wheel)	Proximity Sensor	open	Wheel did not rotate
			closed	Wheel rotated
COYOTEE Movements	4 (One at each corner of swept area)	Proximity Sensor	open	COYOTEE did not reach position indicator
			closed	COYOTEE reached designation
Winch Rotations	1	Proximity Sensor	open	Winch did not pay-out or reel-in cable
			closed	Winch did pay-out or reel-in cable
Valve Actuation	4	Pressure Switches	open	Valve did not actuate
			closed	Valve did actuate

4.5.4 Procedures

I. Test Preparation
   A. Set vehicle on test stand using lifting crane
      1. Attach safety bars to vehicle (see Figure 4.5-1)

      2. Attach monitoring system components to vehicle

   B. Determine Auto ROV input area from productivity data

   C. Input area into Auto ROV

II. Begin Testing
   A. Record date and time test initiated

   B. Record reliability information if/when failure occurs
      1. Date and time failure occurred

2. Failed component/s

3. Repeated failures

4. Failure effects

5. Time to repair

6. Re-start vehicle

C. Continue to record reliability information for the remaining time

III. Data Analysis

A. Determine reliability data

1. Mean Time Between Failures (MTBF)

2. Mean Time To Repair (MTTR)

B. Suggest improvements to reduce failures

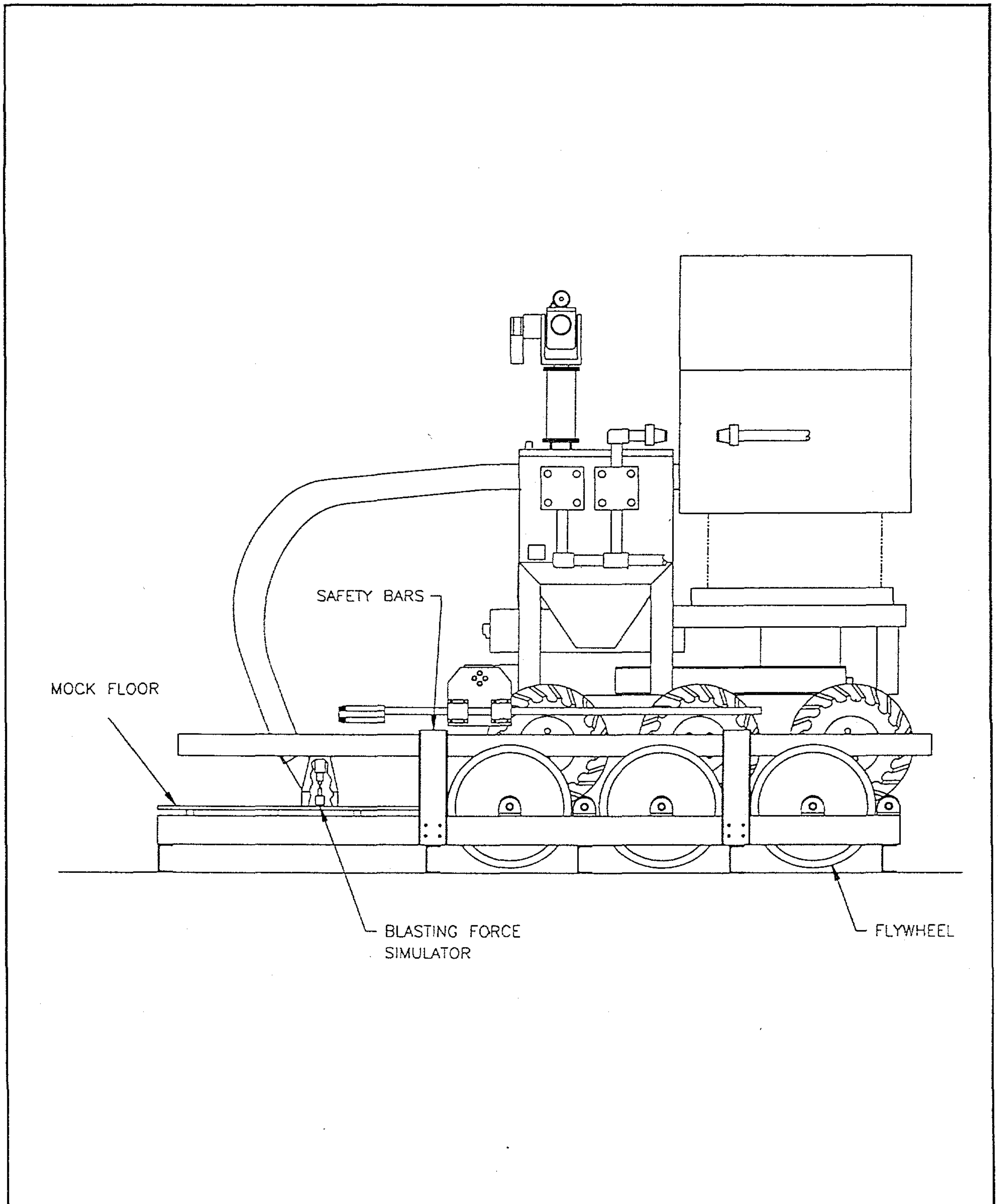

Figure 4.5-1: *System Reliability Test Stand*

APPENDIX A
COLD TEST SURROGATE AND ANALYSIS SELECTION PROCESS

A.1 Introduction

A.1.1 Background

The Cold Test determines the effectiveness of the ROVCO$_2$ system by modelling the Oak Ridge site conditions. One of the goals that must be accomplished in modelling the site is selecting a contaminate to model and a corresponding nonhazardous surrogate. Since there are a number of contaminates with a wide range in contamination levels, there is not a 100% qualified surrogate. The objective of this document is to describe the selection process of the substituted contaminates, surrogates, and surrogate detection methods.

A.1.2 Methodology

The selection process was accomplished by researching several sources. Information sources included Martin Marietta Energy Systems (MMES) at Oak Ridge, chemical manufacturers and suppliers, laboratory facilities, University of Maryland Geology Department, detection equipment manufacturers, and published literature. A number of recommendations were received relating to the appropriate surrogate and detection method to use. The selection process took into consideration all of the received information. Since a 100% applicable surrogate is unrealistic, the selection is anticipated to be more than satisfactory.

A.2 K-25 Site Radionuclides

The selected substituted contaminate is mainly based on the predominate contaminates that are expected to be found. The majority of the contaminates at the K-25 Site include uranium, technetium, polychlorinated biphenyl (PCB), and other actinides including neptunium. The contaminates at the site have either remained on the surface of the concrete floor or have migrated deeper through the concrete pore water.

Technetium: Technetium tends to diffuse deeper in the concrete since it is very mobile in porous media. Since the ROVCO$_2$ system is designed to remove surface contaminates, technetium is not an applicable contaminate for cold testing modelling.

Uranium: The actinide contaminates settle near the surface of the concrete due to the insolubility of the radionuclides in the alkaline concrete pore water. Uranium has been identified as one of the most abundant contaminates at the K-25 Site. It is selected as the actinide contaminate to be modelled based on its abundance and its surface behavior.

Polychlorinated Biphenyl: The PCB contaminates originated from the ventilation equipment used when the site was operating. During operations the ventilation equipment leaked light weight oil which is the carrier of the PCBs. Approximately 95% of the PCBs are type 12:54 (12 carbon atoms, 54 percent chlorine by weight). The PCBs are also considered a surface contaminate since oil is repelled by the concrete pore water.

A.3 Surrogates

A number of factors were considered in selecting the surrogates including: detectability, previous usage, chemical properties, applicable surrogate compound, safety, availability, cost, and reactability. The reactability of the surrogate includes incompatibilities, conditions to avoid, and reactions with the coating, water, and oxygen. The factors effecting safety are: exposure effects, first aid, fire and explosion risks, health protection, cleanup, and transportation.

A.3.1 Uranium Surrogate

Surrogates for uranium include rare earths (cerium, neodymium, and praseodymium), molybdenum, and tungsten. The rare earths (lanthanides) have been documented as having similar properties of the elements in the actinide series. Cerium has been successfully used as a surrogate for uranium in the past. One example of how cerium was used as a surrogate is its use during research efforts which developed separation techniques for uranium.

Cerium is recommended in the report, "Surrogate Formulations for Thermal Treatment of Low-Level Mixed Waste, Part I: Radiological Surrogates", prepared by the Oak Ridge K-25 Site. The report indicates that cerium phase diagrams are more similar to the uranium diagrams than those of molybdenum and tungsten. References within the report also indicate that cerium has been referred to as the lanthanide that mimics actinide behavior the closest.

After identifying an appropriate surrogate, a suitable compound must also be selected. The compound must also consider detectability, safety, availability, cost, and reactability. The type of surrogate compound has been recommended by Oak Ridge is a soluble salt. The report referenced above further indicates that in some cases a chloride salt may be more desirable and/or economical than others. Part II of the report, "Surrogate Formulations for Thermal Treatment of Low-Level Mixed Waste" also states that $CeCl_3$ salt is recommended for nonthermal applications.

A.3.2 PCB Surrogate

Recommendations indicate that only certain properties or possibly only one property of PCBs can be chosen to simulate. A couple of examples include the PCB's viscosity and solubility properties. It has been suggested that since PCBs are strongly soluble in oil, an oil (similar to the oil used during plant operation) can be used as the surrogate. Modelling the carrier of the PCBs rather than the PCBs themselves has also raised concern. Further investigation indicated that locating an oil with similar viscosity could be difficult due to the highly viscous nature of PCBs.

The oil used on the ventilation equipment has been recommended as a 40 weight lube oil or a 90 weight gear oil. Oil additive technology available when the plant was operating, was limited if not completely unavailable. Therefore, straight mineral oil has been frequently recommended as a likely lubricant used in ventilation equipment. Pennzoil's 409 Gear Lube is a 90 weight gear oil free from additives. Pennzoil refers to it as a heavy weight mineral oil.

The report, "Surrogate Formulations for Thermal Treatment of Low-Level Mixed Waste, Part II: Selected Mixed Waste Treatment Project Waste Streams", prepared by the Oak Ridge K-25 Site suggests Naphthalene as an applicable surrogate. The report also indicates that Naphthalene has been used as a destruction testing surrogate. Naphthalene also has fluorescent characteristics and can possible give a visual indication of its presents. Since Naphthalene is also soluble in oil, it can be used as an oil additive to give it a self indicating property.

A.4 Detection Methods

Several contaminate surrogate detection methods are available. The challenge in detecting the surrogate is due to determining the amount present on a concrete surface and locating available detection equipment or facilities. One of the main factors which must be considered in determining a detection method is the ability to distinguish between the epoxy coating, surrogate, and concrete.

A.4.1 Portable X-Ray Fluorescence Spectrometry (XRF)

Portable X-ray fluorescence has been documented as a valuable method for detecting the rare earth elements. XRF instruments excite the element by high energy x-rays which cause the emission of an element's x-ray photon which has unique characteristics. XRF instruments are designed to specifically measure the concentration of selected elements. The capability of XRF instruments range from approximately 100 ppm to 10 ppm. The penetration of the reading can range from .5 mm to 30 mm.

The main advantage is the units' portability and capability of quickly detecting elements in mg/cm^2 units. Unfortunately the detection of rare earths is not a common application. Obtaining an applicable XRF unit includes researching for an available unit or calibrating existing XRF instruments for detecting rare earth elements. It may be an added difficulty to obtain a unit which is also capable of determining the amount of coating on the concrete floor. Two methods for XRF calibration have been identified. One method is done by the XRF manufacturer and is based on pure elements. The other method for calibration involves taking readings from samples with known element concentrations. This method involves laboratory analysis of samples with varying element concentrations.

Another disadvantage of XRF instruments is the reading may required a homogenous sample volume. The sample volume consists of the instruments penetration ability and the diameter of measurement probe. The accuracy of the measurements strictly depends on the characteristics of the sample. Sample volumes which have an uneven distribution of surrogate will give falsely high or low readings. Averaging numerous measurements may lower the reading errors only in some situations.

Some XRF units require a trained operator and radioactive license due to the radioactivity of the unit itself. Obtaining a license requires sending an application including: an established company "Radiation Safety Program", a radiation safety training certificate, and an instrument registration with the local authorities. Once the application is submitted, the license may take five to 120 days to receive. Other XRF units can be operated under the manufacturers' general license. XRF equipment rental costs approximately $4,000-$6000/month plus training or operator costs if needed.

Since the applicable uranium surrogates are rare earths, other rare earths or elements in the concrete may interfere with the XRF readings. Analysis would be required on a sample of the concrete to determine interfering elements and to calibrate the XRF equipment. The concrete analysis may need to be done prior to selecting a surrogate for the uranium.

Summary of disadvantages and advantages:

Disadvantages
- Not commonly used to detect the rare earth surrogates
- May require calibration
- Accuracy is undetermined without prior laboratory
  analysis of samples
- Penetration is limited
- Difficulty and time required in locating appropriate unit
- Interference from rare earths present in concrete
- Cost
- Difficulty in distinguishing between epoxy coating,
  surrogate, and concrete

Advantages
- Readings are available in mg/cm^2
- Portable
- Quick results
- Approved method for detecting rare earths

A.4.2 Laboratory analysis

Several laboratory analysis methods are available to quantitatively determine the amount of surrogate in a concrete sample. Several types of inductively coupled plasma (ICP) tests have been identified as appropriate methods for identifying rare earths in an aqueous solution. The most commonly used ICP test for rare earths is Mass Spectrometry (ICP:MS). Laboratories that conduct ICP analysis must have the appropriate supplies to detect each element. The difficulty in laboratory analysis of the surrogate is locating a laboratory with the appropriate equipment and/or supplies. The detection limit for ICP:MS is as low as 0.1 ppm with an accuracy equal to three times the detection limit of the given element. The required sample size varies, depending on the type of ICP:MS and the number of elements detected.

The oil used for the PCB surrogate can be quantitatively detected by extracting it from the samples. Gravimetric methods can be used to determine the amount present after it is extracted. One applicable extraction method for concrete utilizes methylene chloride as the solvent. The detection limit for gravimetric determination is as low as 0.001% for a 10 gram sample. The detection limit will decrease if smaller the samples are used. Oil analysis by gravimetric detection with methylene chloride extraction costs approximately $40 per sample.

There are many advantages associated with laboratory analysis. One advantage is the ability to have multiple analysis methods conducted and multiple elements detected. Additional laboratory analysis and detected elements can distinguish between the epoxy coating, surrogate, and the concrete. The cost for lab analysis is relatively inexpensive when compared to renting a portable XRF unit. The average cost for detecting a rare earth is $30-$100 per sample. Samples may also be taken at various depths from the floor to give an indication of the surrogate and blasting penetrations. The only disadvantage to laboratory analysis is the time required. The average turn around time for ICP:MS is approximately 10 working days. Rush jobs are available at additional charge ranging from 50% to 200% extra.

Other laboratory analyses are neutron activation analysis, x-ray fluorescence spectroscometry, and atomic absorption spectroscopy. X-ray fluorescence spectrometry can be used to detect the elements or compounds present in the epoxy coating and concrete with a detection limit as low as 0.01%. The precision of most elements is better that 0.5%. The analysis requires at least a 2 gram sample and costs approximately $30 per sample. The sealant will not be detected due to the following reasons:

- Primary concern is the quantitative analysis of the surrogate.
- Difficulty in detection due to the lack of traceable elements.

Summary of disadvantages and advantages:

<u>Disadvantages</u>

- Time delay in results
- Assumed representative sample collection

<u>Advantages</u>

- Low detection limits
- High accuracy
- Reliability
- Approved and common method for detecting rare earths
- Penetration results
- Inexpensive
- Capable of epoxy coating, surrogate, and concrete distinction

A.4.3 UV Fluorescence

Some of the energy that is gained by rare earth elements when exposed to radiant energy may zbe radiated as fluorescent emission. Since each rare earth element is know to emit a unique emission spectra, detection of specific elements is possible. Surrogate detection and measurement could be done by reading the emission given from the floor when exposed to a black light with a photometer. The photometer may be calibrated by reading the light emitted at known quantities of surrogate. The photometer requires a trained operator and the rental rate is approximately $200 per hour.

This method is not recommended due to the documented weakness of the fluorescence spectra and the poor reliability of the fluorescent properties. Studies have determined that the fluorescent properties of elements could be a result of impurities. The fluorescent properties may also depend on the oxidation state, solvent, temperature, and ion size variation. The fluorescent properties may be used to give a visual indication of their presence but are not recommended to be used to give a quantitative result.

A.5 Recommendations

A.5.1 Modelled Contaminates

Uranium: Uranium has been selected based on its abundance and surface behavior on concrete. Uranium can also be used as the representative of other actinide contaminates present at the site.

Polychlorinated Biphenyl (PCB): PCBs have been selected as an additional surrogate to be modelled. Since PCBs are not classified as an actinide, it can not be suggested that its behavior with concrete is simulated by uranium. PCBs have also been chosen to determine if an oil based contaminate behaves differently during remediation by CO_2 blasting.

A.5.2 Surrogates

Uranium: Cerium is selected as the surrogate for uranium based on the previously discussed factors. The specific compound of cerium is cerium (III) chloride. Cerium (III) chloride, $CeCl_3 \bullet XH_2O$, is a water soluble salt and off-white crystalline solid. The Material Safety Data Sheet (MSDS) shows that the compound is relatively safe and is easily accessible. Refer to the MSDS for further details.

Polychlorinated Biphenyl (PCB): Pennzoil's 409, 90 weight gear oil with the addition of Naphthalene is selected as the surrogate for the PCB contaminates.

A.5.3 Detection Method

Laboratory analysis is recommended due to the number of factors which must be considered in selecting or finding an applicable portable XRF unit and the uncertainty involved with UV fluorescence. The specific analysis recommended to detect cerium is ICP:MS due to its availability and accuracy. The recommended method for detecting the coating and concrete is x-ray fluorescence spectrometry. The recommended analysis for oil is gravimetric determination by methylene chloride extraction (GD/MCE). The one disadvantage of laboratory analysis can be eliminated by using other methods which can indicate the results. Two methods include visual indication by fluorescent properties and initial quantitative indication by weight measurements.