Phase 3 Final Topical Report for the Remote Operated Vehicle with CO_2 Blasting ($ROVCO_2$)

Topical Report
April 9, 1998

Work Performed Under Contract No.: DE-AC21-93MC30165

For
U.S. Department of Energy
Office of Fossil Energy
Federal Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Oceaneering Hanford
660 Swift Boulevard, Suite D
Richland, Washington 99352

Disclaimer

Phase 3 Final Topical Report For the Remote Operated Vehicle with CO_2 Blasting ($ROVCO_2$)

DE-AC21-93MC30165--01 April 9, 1998

Submitted To:
U.S. Department of Energy
Federal Energy Technology Center
P.O. Box 880
Collins Ferry Road,
Morgantown, WV 26507-0880

Submitted By:
Oceaneering Hanford
660 Swift Boulevard, Suite D
Richland, Washington 99352

ABSTRACT

This report documents the third and final phase of the Remote Operated Vehicle with CO_2 Blasting ($ROVCO_2$) Program. The Program's goal is to develop and demonstrate a tool to improve the productivity of concrete floor decontamination. In Phase 3 of the $ROVCO_2$ program, the workhead and the COYOTEE end-effector were redesigned, and effectiveness and productivity tests were performed. This report documents the development activities. The results show that the $ROVCO_2$ system is an efficient decontamination tool, but with relatively slow production rates.

ACKNOWLEDGMENTS

The design team at Oceaneering Hanford would like to thank the personnel at the US Department of Energy's (DOE) Federal Energy Technology Center (FETC) for their willingness to give us an opportunity to satisfy DOE's technology needs. We thank THK Co., and Parker Hannifin Automation Actuator Division for providing us the outside resources we needed. 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 FETC.

DISCLAIMER

Available to the public from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at
(703) 487-4650.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

During the ROVCO$_2$ program DOE and Oceaneering achieved many objectives in spite of the difficulties encountered improving the productivity of the CO$_2$ blasting system. Objectives achieved throughout the program include:

- Functional Automation - bottom-up robotics.
- Reliability design and testing.
- Cold testing surrogates.
- Quantitative testing of CO_2 blasting productivity.

Each of these objectives contributed to the development of improving decontamination efficiency and effectiveness.

The ROVCO_2 program has covered three phases of development, starting with the system concept and key subsystems and completing with independent testing of the complete system. The ROVCO_2 system consists of: a remotely operated vehicle and control system, a pneumatically powered blasting system that shoots frozen CO_2 pellets at speeds of 1100 feet per second, a end-effector for sweeping the blasting nozzle across the floor, and a pneumatically powered high efficiency particulate air (HEPA) filter and vacuum system. The operator controls the system using a computer that offers automation of tedious functions.

The ROVCO_2 team took a bottom-up approach to robotics using "functional automation to eliminate repeated, sequential operations making them instead a single button push. The operator is kept in control of the system performing all unique or non-sequential operation, initiating the automated operations and responding to alarm conditions. The functional automation approach has proven, in testing, to increase the time spent blasting vs. manual operation without sacrificing reliability.

ROVCO_2 system reliability was built in to the design with reliability analysis performed on the system to identify the weak links and redesigned to improve performance. The control system reliability was high due to the open loop control thus, keeping the parts count low. System reliability was tested with over 400 hours of logged operation.

To test ROVCO_2's decontamination effectiveness Oceaneering developed a cold testing procedure that provided quantitative data on the removal of contaminants from both the surface and body of the concrete. The testing used surrogates, chemically similar to uranium and Polychlorinated Biphenyl (PCB) in interaction with concrete, that were measurable to very low levels as detailed in the Phase 2 Test Plan. The results of the testing showed that ROVCO_2 was effective at decontamination and that the cold testing procedure was effective in quantifying decontamination.

CO_2 blasting has been repeatedly proposed to DOE for decontamination based on its proven effectiveness in the commercial nuclear industry. The ROVCO_2 production testing shows that CO_2 blasting is not efficient at removing tough coatings (the commercial applications are surface decontamination without coating removal). However, ROVCO_2 is effective at removing sealant type coatings and providing complete smearable decontamination, particularly if waste disposal costs are a significant factor.

1.0 INTRODUCTION

This report documents the work performed by Oceaneering Hanford, a division of Oceaneering International, Inc., during Phase 3 of the ROVCO$_2$ development program. This report has been prepared in accordance with the DOE criteria for reporting. This report provides the following:

- a statement of the original objectives
- a concise summary of progress achieved
- a full account of current progress including enhancements, changes, and accomplishments
- an overview of testing and results
- an economic evaluation
- a description of problems encountered
- conclusions

The report is organized by including the following:

- Section 1: A summary of Phase 1 and 2
- Section 2: Details of the work accomplished in Phase 3
- Section 3: Description of Phase 3 tests performed and their respective results
- Section 4: Phase 3 conclusions

1.1 Program Background and Objectives

Oceaneering Technologies, Inc., (OTECH) in Upper Marlboro, Maryland developed the prototype ROVCO$_2$ system to improve concrete surface decontamination productivity. The goals of the program, as originally proposed, are to reduce the cost of decontamination, reduce secondary/process waste volume, reduce personnel exposure to hazardous materials and improve the speed and efficiency of concrete surface decontamination.

In Phase 1 of the project, ROVCO$_2$ subsystems were engineered and adapted to meet a unique set of functional and physical characteristics. During this first phase of the project, critical subsystems such as the Remote Operated Vehicle (ROV), enhanced CO$_2$ blasting (Cryogenesis system), CO$_2$ X-Y Orthogonal Translational End-effector (COYOTEE) and a motion control subsystem based on a programmable interface were adapted, integrated and tested. A proof-of-concept demonstration successfully verified the operation of the system by removing coatings from a concrete floor.

During Phase 2 of the project, OTECH performed a number of enhancements and modifications that greatly increased system performance and reliability. Improvements were made to all subsystems including software and hardware modifications. The Tether Management Subsystem

(TMS) and the Vacuum/Filtration/Containment Subsystem (VFCS) were integrated. Parallel to subsystem enhancements, the ROVCO$_2$ system was tested for over 1,000 hours without operation of the cryogenesis system and approximately 100 hours with operation of the cryogenesis system to determine overall system containment effectiveness, functional operating limits, reliability and productivity. Aside from workhead containment challenges, the ROVCO$_2$ system met all of its design criteria.

For Phase 3 of the ROVCO$_2$ project, OTECH proposed to address containment challenges and take part in a test/demonstration at the Hemispheric Center for Environmental Technology (HCET) at Florida International University (FIU). The ROVCO$_2$ project was transferred to Oceaneering Hanford, Oceaneering's Nuclear Site Services facility in Richland, Washington, in an attempt to make the equipment readily available for use at the Hanford Site. An engineering team was assembled and given the task of redesigning the workhead to achieve greater containment. A thorough search was made to identify vendors with extensive experience in the design of jet-abrasion equipment, that could provide off-the-shelf containment technology meeting our unique set of specifications. We recognized that containment deficiencies are prevalent in all the automated CO$_2$ blasting systems we have studied. Having identified the deficiencies of the present workhead design; primarily, the designs inability to redirect the blast flow momentum towards the upper section of the workhead, our design team produced a proof of concept workhead that has generated the desired recirculating flow pattern inside of the containment region. The concept for the new design is simple; with the aid of a deflector plate, the blast flow momentum is redirected up towards the top section of the workhead while the lower section of the workhead is pressed

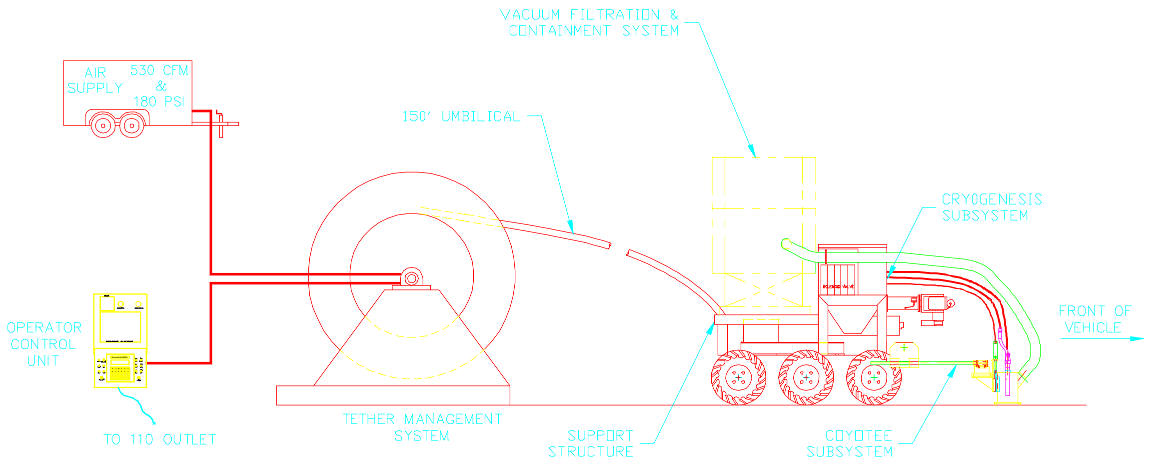

Figure 1: The control subsystems of the ROVCO$_2$ system

tightly against the floor at all times. Our team designed an adjustable deflector plate that incorporates a nylon pad. The workhead rides on this nylon pad sealing the blasting area while reducing drag and minimizing the loads on the COYOTEE end-effector. Complete sealing of the containment head is achieved by the use of a heated inflatable seal around the perimeter of the containment shroud.

1.2 Summary of Phase 1

The development of 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 & 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 & development of major systems, input to the final decisions, analysis & explanation of each subsystem and its functional allocation, testing analysis, and results & 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. During the Phase 1 demonstration the integrated ROVCO_2 system was navigated by an operator stationed at a remote console, using only cameras mounted on the vehicle, to navigate while removing 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 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 inch curbs, and crossed 6 inch trenches.
The ROVCO_2 vehicle shall be capable of indexing forward, under manual control, to sequential blast areas to a tolerance of ±5 inches.	During the vehicle indexing test, an average indexing tolerance of 0.2 inches 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 accuracy of 3.4%
The ROVCO$_2$ work arm shall sweep an area 24" X 30" (720 square inches) without holidays in the pattern	During the work area measurement test, the COYOTEE only reached an area 21.75" X 31.5" due to an error in specifying the Y-tube length. The nozzle's width increases the swept area by 0.8". Final swept area was in 22.5" X 32.3" (728 square inches) 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" ips in linear motion. (Modified FETC'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" to ≈1"
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$_2$ system during all operations.
4. Sensing	
ROVCO$_2$ shall be equipped with driving and decontamination monitoring cameras.	The operators in the testing and concept demonstration verified this configuration.
5. CO$_2$ Blasting	
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 FETC'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:

1. major decisions affecting scope and cost
2. technical achievements
3. 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 following technical achievements and the success of the concept demonstration proved the success of the major decisions during Phase 1:

- 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 Waste Management Corporation (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 specification 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

As Phase 1 ended, Oceaneering, WMC, 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.

1.3 Summary of Phase 2

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

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 ROVCO2 system Phase 1

At the end of Phase 2 of the ROVCO2 Program all but one of the success criteria were achieved*. The ROVCO2 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 averaged 52.5 square feet per hour on epoxy paint and concrete sealant with an estimated operational cost of $0.72 per square foot including waste disposal. ** This criterion shortfall was in direct result of the non-performance of the commercially procured containment workhead.*

1.3.1 ROVCO$_2$ System Costs Summary

The unit cost evaluation of the ROVCO2 system depends on the productivity rate of the system (which also depends on the type and thickness of the coating and the level of decontamination required) and the labor rate.

The ROVCO2 system meets all ALARA (as low as reasonably achievable) standards. The system reduces worker dose rates and risk of contamination. Due to the difficulty and the expected low expenses associated with exposure and contamination, the economic evaluation does not take into consideration dose or contamination levels.

The system costs were categorized as operational or capital costs.

1.3.1.1 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 2: ROVCO$_2$ System Operation Costs

Operating Cost	Unit	Cost/unit	Cost
Labor	1 ROV Operator	$34.00/hour	$175,000.00
Consumables:			
• Dry ice		$21.95/hour	$109,750.00
• Cable	0.17 ft/hour	$0.83/ft	$706.00
• Drums	351.41 drums	$39.26/drum	$13,867.00
• Diesel Fuel	10 gal/hour	$0.94/gallon	$47,000.00
Waste Disposal:			
• Primary Disposal	0.0168 in/ft^2	$12.00/ft^3	$8,400.00
• Shipping	351.41 drums	$5.00/ft^3	$3,496.00
		TOTAL:	**$358,219.00**
			$/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.

1.3.1.2 Capitol Costs

Table 3: ROVCO$_2$ System Capital Costs

Component	Estimated Capital Cost
ROVCO$_2$ system	$304,000.00
Support Equipment:	
• 900 cfm air compressor	$75,700.00
• 900 cfm desiccant air dryer	$27,700.00
• Air cooler	$9,700.00
• 250 lb. Carbon dioxide pelletizer	$39,500.00
TOTAL	**$456,600.00**

The ROVCO$_2$ system capital costs are included in table 3

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.

1.3.2 Technical Achievements

During Phase 2 of the ROVCO2 program, the following was achieved:

- The vacuum/filtration/containment subsystem was integrated on to the ROVCO2 vehicle
- The COYOTEE sweep area was increased from 21” X 31.5” to 26” X 42”
- The COYOTEE was improved by incorporating and 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 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

1.3.3 Success Criteria Performance

All subsystems were demonstrated and 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.

The performance of the developed ROVCO$_2$ system to each of the Phase 2 success criteria is presented in table 4.

Table 4: Phase 2 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 wash down techniques.	The decontaminability test successfully demonstrated that the carbon dioxide blasting system is capable of cleaning the TMS.
Vacuum, Filtration, and Containment Subsystem	
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 wash down 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 containment 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 double epoxy speed 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 smear cloths with the chemicals used in the laboratory analysis.
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 speeds 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 faster 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$_2$ down time 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% down time 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% down time. Down time will be significantly reduced in the future as the number of adjustments required decreases from operational experience and system optimization.
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 surfaces' relief.	The average productivity of the ROVCO$_2$ system is 52.4 sq. ft./hour. The productivity removing approximately 98% of sealant is 93.8 sq. ft./hour. The productivity for removing 85-95% of epoxy paint is 10.9 sq. ft./hour.
The OCU shall autonomously control tedious	The OCU successfully controlled tedious operations

repetitive operations, allowing the operator to focus on overall system operation and monitoring.	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.

2.0 PHASE 3

2.1 Introduction

This chapter reports on the work accomplished in Phase 3. All the design and fabrication work proposed for Phase 3 was accomplished including:

- Workhead development
- Workhead fabrication
- CO_2 X Y Orthogonal Translational End-effector redesign

No new subsystems were added to the $ROVCO_2$ system during Phase 3. Enhancements and modifications identified in Phase 2 include the following:

- Improved workhead containment
- Swap locations of the pan and tilt camera and the fixed camera
- Increase the size of the X direction COYOTEE cable pulley (*actually decreased explanation follows in this report)*

2.2 Phase 3 Success Criteria (Concrete Decontamination)

The $ROVCO_2$ success criteria, DOE policy factors, and requirements in the statement of work drove the criteria for evaluating the success of Phase 3 of the $ROVCO_2$ program. The success criteria for Phase 3 appear below.

Table 5: Phase 3 Success Criteria Performance

SUCCESS CRITERIA	PERFORMANCE
Clean Concrete Surfaces To Free Release	
$ROVCO_2$ shall clean the concrete test surface to free release levels achieving a decontamination factor of 5 or greater.	The $ROVCO_2$ system was successful in removing 98-99% of the smearable contamination. Phase 2 and 3 testing demonstrated the systems ability to

	remove fixed contamination depending on the production speeds needed from the system. The containment workhead achieved 99.9% containment of the smearable and fixed contaminants. Since the ROVCO$_2$ system was not able to be tested in a hot environment during the performance of Phase 3 a decontamination factor of 5 or greater could not actually be measured. Based on the percentages of containment and removal of fixed and smearable contamination it can be extrapolated that a decontamination factor of 5 or greater can be achieved.
Improve Worker Productivity Through Automation	
ROVCO$_2$ shall improve worker productivity through automation of tedious repetitive tasks.	The ROVCO$_2$ system was able to improve worker productivity through automation of tedious tasks. Phase 3 improvements made to the containment workhead and to the COYOTEE subsystem allowed for reliable operation of the complete ROVCO$_2$ system therefor eliminating the need for additional personnel to perform repetitive tasks. All blasting (paint removal) operations were automated and made reliable to eliminate operator interaction. The only operator interaction required is filling the ice hopper and to removing jams as necessary.
ROVCO$_2$ Operations Reduce Decontamination Cost	
Reducing worker exposure to contaminants, requiring less than 10 hours in a radiation controlled area per 100 hours of cleaning	Reducing worker exposure to contaminants was accomplished in several ways. Improvements made to the containment workhead allowed for complete containment of the blast materials that could not be contained previously. This eliminated the air borne problem experienced with the previous workhead designs. Also by improving the COYOTEE subsystem reliability the operator interaction required for repairs could be eliminated. A review of the operations logs from the testing performed at FIU demonstrates that for 100 hours of cleaning less than 15 hours exposure to a radiation area is required for personnel.
Reducing the number of people required on a decontamination shift from 5 to 2	ROVCO$_2$ operations have successfully reduced the number of people required on a decontamination shift from five to two. Throughout all testing and operations the ROVCO$_2$ system effectively operated with two personnel.
Reducing plant down time by 20% or more	During performance testing at FIU the system operated a total of 50 hours and only 3.67 hours were

	spent making repairs or adjustments to the system. Down time for the overall system was significantly reduced since Phase 2 testing due to improving reliability of the COYOTEE subsystem. The majority of the down time experienced was caused by ice jams in the dry ice subsystem. Down time also resulted from equipment adjustments to control for climate and to optimize blast rates for removing the specific epoxy and thickness of epoxy at the FIU test facility.
Elimination of blasting re-treatment due to gaps in the coverage of the first treatment	Elimination of blasting re-treatment, due to gaps in the coverage of the first treatment, can now be accomplished by properly controlling the speed of the X and Y actuators. Unfortunately production rates on the order of one-tenth the epoxy removal rates tested in Phase 2 were realized.

2.2.1 Clean Concrete Surfaces To Free Release

The ROVCO$_2$ system is capable of cleaning concrete test surfaces to free release levels achieving a decontamination factor of five or greater due to Phase 3 improvements.

The only way decontamination can be accomplished is by removing and containing the contamination imbedded in the concrete surface and epoxy. To be able to achieve a decontamination factor of five or greater and clean test surfaces to free release levels the VFCS design required improvement.

The first step to decontamination of concrete floor surfaces is to break the epoxy loose from the concrete floor. With the proper speed set on the COYOTEE subsystem the Cryogenesis CO$_2$ blasting system is capable of removing all of the epoxy coating and the surface layer of the concrete.
The second step is ensuring that all the epoxy and concrete debris removed by the dry ice blasting is contained. The new design of the ROVCO$_2$ blast head ensures 99.9% containment of the debris.

Thirdly, the CO$_2$, excess air, concrete and epoxy debris are processed in the vacuum system through a HEPA filter to ensure that 99.9% of the solid materials are filtered out of the air and CO$_2$ therefore preventing the contamination from being released in to the environment.

Assuming the radioactive contaminants are imbedded in the epoxy, or on the surface layer of the concrete, and the Cryogenesis CO$_2$ blasting is set to remove all the epoxy a decontamination factor of five or greater can be assured by maintaining the integrity of the VFCS.

The only method of truly testing for a decontamination factor of five or greater would be to test the equipment in a facility with radioactive contamination. Several attempts were made to find a "hot" demonstration location to test ROVCO$_2$'s capability to obtain decontamination factors of five or greater. During Phase 3 we were unsuccessful in being awarded a "hot" demonstration for the ROVCO$_2$ system. This prevented us from being able to have quantitative data to report on ROVCO$_2$ decontamination capability. Therefore we are left with the qualitative results and assumptions made during the "cold" testing conducted in Richland and at FIU.

2.2.2 Improve Worker Productivity Through Automation

In Phase 3 Oceaneering set out to improve worker productivity through automation of tedious repetitive tasks. The ROVCO$_2$ subsystems were enhanced to increase reliability of the complete system therefore reducing the operator interaction required. The redesigned containment workhead and COYOTEE subsystem were critical components in improving worker productivity. Enhancing these components enabled the operator to spend much less, if any, time adjusting and repairing COYOTEE. Also, achieving complete containment of the waste debris eliminated the need for air respirators while working near ROVCO$_2$.

Improvements made to the COYOTEE subsystem allowed the redesigned blast workhead to place much larger forces on COYOTEE without causing failure. The ball screw actuators are more durable and provide much larger driving forces. Eliminating the drive cables removed the failure mechanism for COYOTEE and also reduced, if not eliminated, any maintenance required.

2.2.3 ROVCO$_2$ Operations Reduce Decontamination Cost

ROVCO$_2$ operations reduced decontamination costs by:

- Reducing worker exposure to contaminants, requiring less than 10 hours in a radiation controlled area per 100 hours of cleaning;
- Reducing the number of people required on a decontamination shift from 5 to 2;
- Reducing plant down time by 20% or more; and
- Elimination of blasting retreatment due to gaps in the coverage of the first treatment.

2.3 Phase 3 Subsystem Enhancements

Three enhancements to the ROVCO$_2$ system increased the system performance and containment. Oceaneering engineered, designed and procured or fabricated all modifications to assure continued harmonious integration. The enhancements were to the vacuum workhead, COYOTEE and the VFCS. The following sections discuss the reasons for the enhancements and how they were achieved.

2.3.1 Workhead Enhancements

After Phase 2 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 that changes were needed to improve the effectiveness of the containment system.

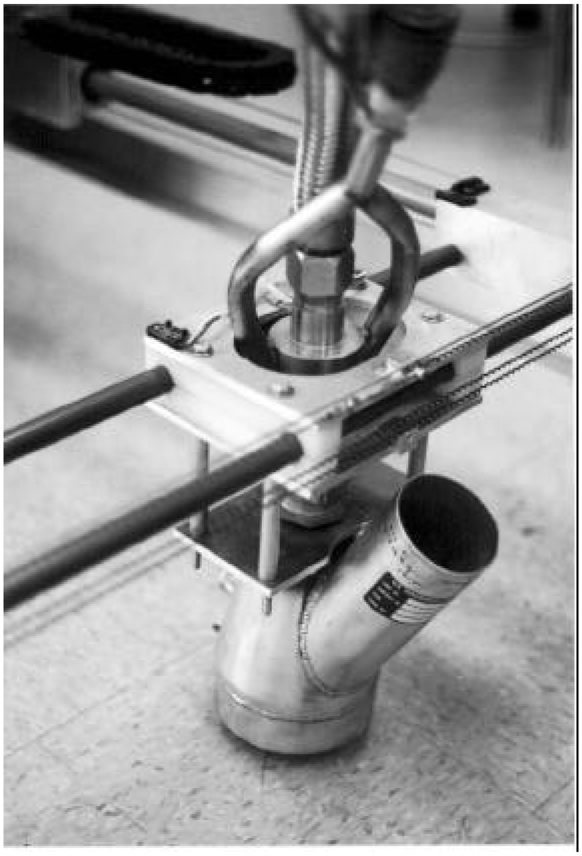

Figure 2: Blasting operation with original workhead

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

Analysis 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 at 50 percent of the nozzle velocity. Figure 1 shows the original workhead with the gap between the floor and the bottom edge of the workhead. Brushes were used in an attempt to deflect the blasting. The brushes were observed being pulled inward by the vacuum and being pushed outward by the blasting and were ineffective at redirecting the blast flow. The suction pressure in the workhead above the stream did not have a significant effect in redirecting the stream.

The WMC engineers developed a new workhead for use during the second week of testing (figure 2). This 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.

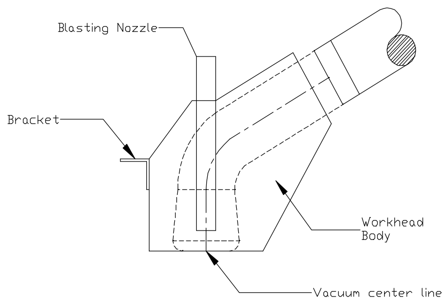

Figure 3: Second workhead

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 to an unacceptable level.

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.

During Phase 3, Oceaneering engineers developed a new workhead using our experience from the previous two designs.

The design of the first workhead used a rule of thumb, *(the suction volume should be twice the blasting volume.)*, but this ignored the system's momentum balance as described earlier. The Phase 3 workhead redesign continued to use the rule of thumb, but took further steps at redirecting the momentum of the blast flow.

The Phase 3 workhead uses a nylon pad in direct contact with the floor. The nylon pad is designed with beveled edges as shown in figure 3 to mechanically redirect the momentum of the blast air. Initial testing with this design proved to be a step in the right direction. The majority of the high velocity flow was redirected up into the vacuum shroud.

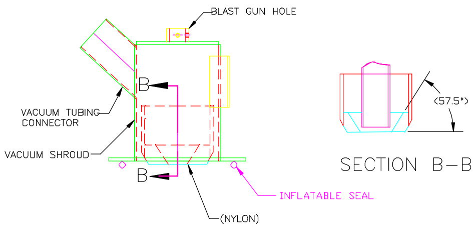

Figure 4: Redesigned workhead

To eliminate blast leaks from the vacuum shroud an inflatable seal was incorporated into the design. The inflatable seal shown in figure 4 is inflated using compressed air from the systems support compressor. The inflatable seal maintains a positive seal with the concrete surface and eliminates blast leakage form the vacuum shroud.

Further preliminary testing was conducted to test this revised design. The new design proved to be effective at containing 100% of the blast and debris.

Some unforeseen problems were realized once 100 percent containment was accomplished. By containing all the cryogenic blast the vacuum system became very cold and condensed moisture from the outside air on the system. The condensed moisture would build up and freeze on the nylon pad and rubber seal causing the vacuum shroud to lose 100 percent containment. The rest of the VFCS subsystem also developed condensation, which would then melt, or drip off into the facility causing a spill.

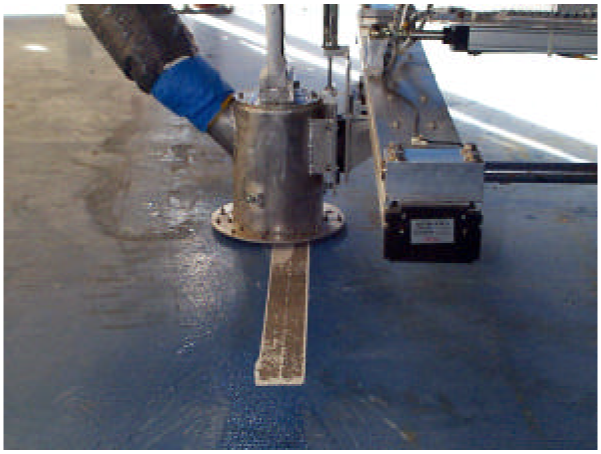

Figure 5: New workhead blasting

To reduce the problem of condensation on the VFCS the majority of the components were insulated to prevent the moisture build up. To eliminate the problem of ice building up on the rubber seal, and therefore losing the seal, the inflatable seal was outfitted with a pressure regulator and two air stems. The pressure regulator allowed the pressure to be maintained on the seal while the air was pumped in one stem of the seal and out the other. The flow of the hot compressed air through the seal acted as a heater keeping the seal flexible and capable of maintaining the seal with the floor. Both of these improvements were tested during the FIU demonstration and were proved to be effective solutions to the stated problems.

2.3.2 COYOTEE Enhancement

The successful enhancement of the ROVCO$_2$ workhead, that allowed 100 percent containment of the blast jet and waste, required upgrades to the COYOTEE subsystem in order to support the increased loads.

The redesigned workhead, which incorporated the nylon pad that slides on the floor and an inflatable seal that rides on the floor, allow the VFCS to maintain a tight vacuum with the floor. The combined forces of the friction and the suction from

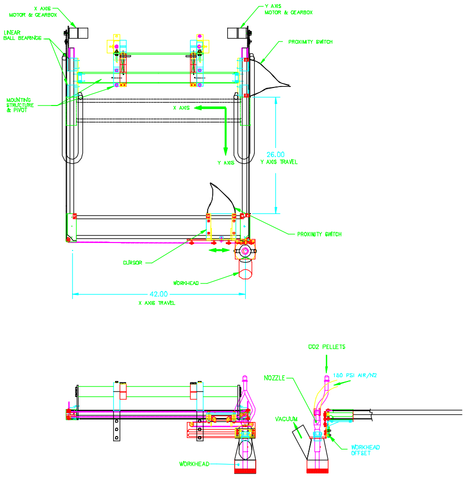

Figure 6: Original COYOTEE subsystem

the vacuum could not be overcome with the cable driven COYOTEE subsystem. The enhanced COYOTEE subsystem replaced the Synchromesh cable driven x – y orthogonal translator with a ball screw linear actuator for both the x and y translation. The increased strength and torque provided by these actuators overcame the forces applied by the redesigned workhead. The linear actuators also provide the needed reliability for operation in “hot”.

The actuators were integrated into the existing structure of the ROVCO$_2$ vehicle and controlled by the EASON control system. Minor modifications to the program were made to integrate the actuators new travel lengths and available speeds.

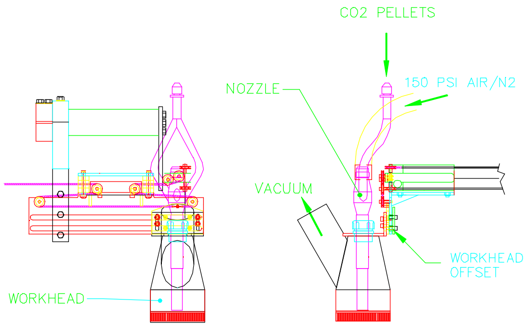

Figure 7: COYOTEE end-effector offset

As originally designed in Phase 1, the closest distance between the blast path and a wall or a corner was six and one half inches. During Phase 2 COYOTEE enhancements were made to decrease the minimum distance between the wall and the blast path. The modified design in Phase 2 reduced the total distance between the blast path and the wall to a few inches of the wall. Oceaneering modified the COYOTEE subsystems cursor to allow the workhead to travel to the side edges of the ROVCO2 envelope (see figure 5).

The implemented concept for Phase 2 (see figure 6) 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 used 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 and then at the end of the slots, the motion is transferred to the cursor assembly until the end of the cursor travel is reached.

Although the Synchromesh cable driven system offered advantages of being lightweight and reduced distance between the blast path and the wall, the disadvantage of not being able to manipulate a containment head capable of containing all the waste, outweighed the advantages.

Figure 7 shows the implemented concept

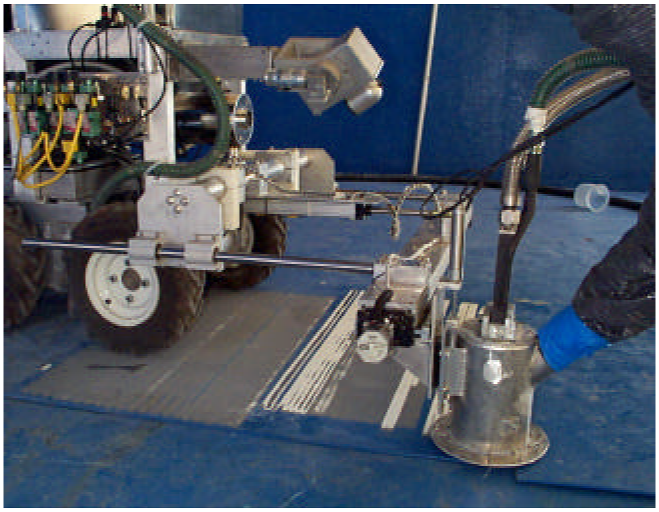

Figure 8: Redesigned COYOTEE and workhead being tested at FIU

for Phase 3. The redesigned workhead and COYOTEE enhancements reduced the capability of the workhead to blast within a few inches of the wall. The increased reliability and 99.9 percent containment of the waste stream outweighed the advantage being able to get within a few inches of the wall. The system is now capable of blasting in a range of six to eight inches from the wall.

3.0 TESTING

3.1 Background

Extensive testing of all components in the system was conducted during Phase 1 and 2 development. The testing conducted in both phases has been summarized earlier in this report. The testing for Phase 3 of the ROVCO$_2$ development was done to validate the design changes made to the complete system. This testing was performed at FIU to allow a direct comparison of ROVCO$_2$ to other decontamination technologies.

3.2 Purpose

The purpose of the testing in Phase 3 was to conduct the VFCS Cold test, ROVCO$_2$ system productivity test and the ROVCO$_2$ system reliability tests.

3.3 Testing Objectives

The testing objectives of Phase 3 were to test the redesigned workhead (a critical component of the VFCS), evaluate its performance as part of the ROVCO$_2$ system, and take part in the HCET assessment of concrete/coating removal technologies at FIU.

To evaluate the performance of the redesigned workhead, Oceaneering first conducted verification tests at our facility in Richland, Washington. The tests address the Success Criteria as outlined in the Statement of Work for Remote Operated Vehicle Dry Ice Pellet Decontamination System (DE-AC21-93MC30165) Phase 3 success criteria. Verification tests that were performed include:

- VFCS cold test
- ROVCO$_2$ system reliability test
- ROVCO$_2$ system productivity test

The Phase 3 test is designed to verify effectiveness, reliability and productivity of the ROVCO$_2$ system by building on Phase 2 operational experience.

3.4 VFCS Cold Test

Objectives

To test VFCS integrity with the aid of leak indicators, evaluate the behavior of the redesigned workhead observing that the workhead is effective in redirecting the flow momentum towards the top of the workhead and test the degree of containment achieved by the redesigned workhead.

Methodology
Visual inspection and observation of the equipment while blasting under normal operation will assisted in the verification of the process.

3.4.1 Results

The modifications of the containment workhead that were made during Phase 3 were tested both with cold tests in Richland, WA and at FIU. Observation of the workhead and the VFCS system revealed that no leakage in the system exists. The use of the deflection cup and the inflatable seal were successful at redirecting the blast momentum. Visual inspection and observation revealed no leakage. Occasionally, during blasting operations, light puffs of condensing moisture in the air could be seen. During testing leaks were searched for by feeling the component of the VFCS for air leakage. Occasional puffs of air could be felt from the bottom of the workhead. These were attributed to anomalies on the surface causing the seal to lose contact momentarily. Preliminary results from monitoring conducted by personnel from International Union of Operating Engineers (IUOE) during testing at FIU indicated that minimal if any debris was escaping form the blasting workhead.

During testing at FIU the only leakage found in the VFCS system was found on the compressed air side of the VAC-PAC System. Clean compressed air was found leaking out of an air regulator that controlled the VAC-PAC System. The system was shut down and the regulator was disassembled. A foreign object was found edged in the seat of the valve, causing it to relieve the pressure. The valve seat was damaged therefore requiring the regulator to be replaced. When the regulator failed the vacuum system could not maintain proper vacuum and leakage was observed at the blast workhead. The regulator was replaced and normal operations continued.

3.4.2 Conclusion

The results of the testing in Richland, WA and FIU concluded that the redesigned blasting containment workhead was 100% successful at achieving complete containment during normal operations.

3.5 ROVCO$_2$ System Reliability Tests

Objectives
The system reliability tests were designed to verify that the ROVCO$_2$'s downtime requiring operator interaction in a radiation controlled area does not exceed more than ten hours in 100 hours of cleaning.

Methodology
Data for this test were recorded during testing conducted at FIU. During this testing the

system was positioned in the test area, filled with dry ice and placed in Auto ROV mode from the control console. Independent evaluators maintained operations logs on the blasting operations. Each operation and failure of the system was logged. All failures requiring operator interaction with the system inside the test pad (i.e. “radiation controlled area”) were logged.

The time to repair the failure was calculated by considering only the amount of elapsed time between one of the operators discovering the failure and the time the test was restarted.

3.5.1 Results

The ROVCO$_2$ system completed approximately 60 hours of blasting operations while at FIU. During those 60 hours of operations the ROVCO$_2$ system required maintenance on three separate occasions. The maintenance actions required approximately one hour to correct the problem and begin operations again. The failures requiring maintenance are summarized in the following table.

Table 6: System Failures

Fail #	Time to fail Hours	Time to Repair	Failed Mechanism	Life Cycle period
1	30 hrs	.67 hrs	Inflatable Seal	Wear out
2	Unknown*	1 hr	VAC-PAC Air Regulator	Damage Seal
3	35 hrs	.67 hrs	Inflatable Seal	Wear out

**The regulator that had been operating on the VAC PAC system has been on the system since it was purchased.*

A foreign object caused the failure of the VAC-PAC regulator in the air system. This failure is not expected during most operational situations.

The testing at FIU included approximately 40 hours of total system operation including blasting. No statistical conclusions can be drawn from this testing because of the short duration of the testing. Measuring a reliability figure of merit is not appropriate due to its short operational period. Throughout the testing in Richland, WA and at FIU one system failure was prevalent.

Ice jams plagued the operations of the cryogenesis system. Operating in a high humidity environment lead to water based build up along the auger. The ice broke off from the wall creating large particles that restrict the flow of carbon dioxide pellets in the feed hose, resulting in ice jams. The dry ice that was supplied for the testing at FIU contained dry ice shavings (fines) that were mixed with the quarter inch pellets. The fines create condensation, which freezes to the metal components of the blasting system causing the auger to jam. The fines were manually sifted out of the ice before the ice was placed in ROVCO$_2$ reducing the frequency of jamming.

The two inflatable seal failures occurred with about 30 hours of operation on each. Physical examination of the seals determined that the failure of the mechanism could be classified as "wear-out." Investigating the use of more robust materials for the seal can increase the mean time to failure. Although, removing the fines did reduce the frequency of ice jams the efficiency of the system for tough coating removal is very low. It's important to note that the failure of the inflatable seal did not prevent the ROVCO$_2$ from operating. The breach in the seal only prevented the VFCS subsystem from containing 100% of the blast flow.

3.5.2 Conclusion

From the results of the system reliability tests it can be concluded that the phase 3 improvements met the objectives of reducing maintenance required during operation of the ROVCO2 system. Since frequent ice jams of the dry ice system occurred operator interaction was needed to unclog the system.

Maintenance activities experienced only required 4.68 hrs per 100 hours of operation. The clogging of the auger from the dry ice required much more frequent operator interaction. A review of the operating log from the testing at FIU revealed that approximately 10 hours of operator interaction per 100 hours of operation was required for cleaning ice jams. This brings the total operator interaction to 15 hour per 100 hours of operation.

3.6 ROVCO$_2$ System Productivity Test

Objectives:
Demonstrate the ROVCO$_2$ system productivity by decontaminating between 10 and 15 square feet of concrete floor space per hour, demonstrate the OCU capacity to automate tedious repetitive operations, determine the CO$_2$ blasting rate for epoxy paint, obtain COYOTEE end-effector reliability data during blasting operations, and to verify that the ROVCO$_2$'s downtime does not exceed more than 20% of the expected operation time due to component failures.

Methodology:
The System Productivity Test determined the productivity of the ROVCO$_2$ system in operating conditions similar to those found at DOE facilities. The test was conducted using Ply Mastic Epoxy coating over a concrete surface. The surfaces were prepared by FIU for coating/surface testing and analysis of potential removal decontamination technologies.

3.6.1 Results

The productivity of the ROVCO$_2$ system observed during testing at FIU correlated with the previous testing performed during Phase 2. The productivity of the ROVCO$_2$ significantly depends on the required level of decontamination and the type of coating covering the contamination.

Using the assumption made earlier (the degree of decontamination is reflected in the amount of epoxy removed from the concrete) we can conclude that the production rate for epoxy removal at FIU was very low.

The system was able to achieve productivity rates of 94 ft^2/hr (for 98 percent removal) on the blue top coat of paint placed on the epoxy and a rate of only 1.5 to 2 square feet an hour (for 85-100 percent removal) on the underlying 7 mil thick epoxy.

At these production rates the cost per square foot is not a productive or economical solution.

3.6.2 Conclusion

The economic evaluation reported in the Phase 2 topical report, categorizes the support equipment costs as capital costs. The ROVCO_2 system requires dry, cooled compressed air at the vehicle and pelletizer and the system requires 530 cfm at 150 psi at the vehicle. Compressor dryers and coolers of this magnitude are available for rent or lease. Testing conducted at Richland and FIU used rented equipment. It is important to note that if the support equipment is not purchased as part of the capital equipment the cost per square will increase considerably when looking at a particular job.

The testing of ROVCO_2 at FIU reaffirmed what was observed in Phase 2 testing. The ROVCO_2 production testing shows that CO_2 blasting is not efficient at removing tough sealant type coatings. However, the ROVCO_2 system was able to provide complete smearable decontamination and proved to be a reliable and productive system for automating the tedious tasks of decontamination.

4.0 CONCLUSION & DISCUSSION

During the ROVCO_2 program DOE and Oceaneering achieved many objectives in spite of the difficulties encountered improving the productivity of the CO_2 blasting system. Objectives achieved throughout the program include:

- Functional Automation - bottom-up robotics.
- Reliability design and testing.
- Cold testing surrogates.
- Quantitative testing of CO_2 blasting productivity.

Each of these objectives contributed to the development of improving decontamination efficiency and effectiveness.

The ROVCO$_2$ program has covered three phases of development, starting with the system concept and key subsystems and completing with independent testing of the complete system. The ROVCO$_2$ system consists of: a remotely operated vehicle and control system, a pneumatically powered blasting system that shoots frozen CO$_2$ pellets at speeds of 1100 feet per second, a end-effector for sweeping the blasting nozzle across the floor, and a pneumatically powered high efficiency particulate air (HEPA) filter and vacuum system. The operator controls the system using a computer that offers automation of tedious functions.

The ROVCO$_2$ team took a bottom-up approach to robotics using "functional automation to eliminate repeated, sequential operations making them instead a single button push. The operator is kept in control of the system performing all unique or non-sequential operation, initiating the automated operations and responding to alarm conditions. The functional automation approach has proven, in testing, to increase the time spent blasting vs. manual operation without sacrificing reliability.

ROVCO$_2$ system reliability was built in to the design with reliability analysis performed on the system to identify the weak links and redesigned to improve performance. The control system reliability was high due to the open loop control thus, keeping the parts count low. System reliability was tested with over 400 hours of logged operation.

To test ROVCO$_2$'s decontamination effectiveness Oceaneering developed a cold testing procedure that provided quantitative data on the removal of contaminants from both the surface and body of the concrete. The testing used surrogates, chemically similar to uranium and Polychlorinated Biphenyl (PCB) in interaction with concrete, that were measurable to very low levels as detailed in the Phase 2 Test Plan. The results of the testing showed that ROVCO$_2$ was effective at decontamination and that the cold testing procedure was effective in quantifying decontamination.

CO$_2$ blasting has been repeatedly proposed to DOE for decontamination based on its proven effectiveness in the commercial nuclear industry. The ROVCO$_2$ production testing shows that CO$_2$ blasting is not efficient at removing tough coatings (the commercial applications are surface decontamination without coating removal). However, ROVCO$_2$ is effective at removing sealant type coatings and providing complete smearable decontamination, particularly if waste disposal costs are a significant factor.

5.0 REFERENCES

ROVCO$_2$ Phase1 Topical Report
ROVCO$_2$ Phase 2 Topical Report
FIU Logs

6.0 LIST OF ACRONYMS AND ABBREVIATIONS

CO$_2$ blasting	Cryogenesis System
COYOTEE	CO$_2$ X-Y Orthogonal Translational End-effector
DOE	United States Department of Energy
FETC	Federal Energy Technology Center
HCET	Hemispheric Center for Environmental Technology
HEPA	High Efficiency Particulate Air
FIU	Florida International University
IUOE	International Union of Operating Engineers
OCU	Operator Control Unit
OTECH	Oceaneering Technologies Inc.
PCB	Polychlorinated Biphenyl
ROV	Remote Operated Vehicle

ROVCO$_2$	Remote Operated Vehicle with CO$_2$ Blasting
TMS	Tether Management Subsystem
VFCS	Vacuum, Filtration, Containment Subsystem
WMC	Waste Management Corporation

APPENDIX A:

Appendix A

	ABSO-LUTE DOWN TIME	ABSO-LUTE BLAST TIME	PROBLEM	RESOLUTION	AMOUNT OF DRY ICE
Blasting the rusted plate		2 min	Dry ice is spilling out of the auger	Adjusted the auger feed rate (reducing)	
		30 sec	Dry ice is spilling out of the auger		
		30 sec	Dry ice is spilling out of the auger		
		1 min	Dry ice is spilling out of the auger		
Begin Blasting		20 min	Finished 20 passes		❖ 2 gallons dry ice added ❖ 2 gallons dry ice added
Begin Blasting		8 min	Blast nozzle stopped	Reset – curve of metal may be offsetting the home position	
Begin Blasting		1 min	Blast nozzle stopped – signal is not getting to the machine therefore the blast head is not moving.	Manually testing machine	
Begin Blasting		2 min	Dry ice jammed in hopper	Clear jam	❖ 5 gallons dry ice added
Begin Blasting		6 min	Blast head stops		
Begin Blasting		1 min	Blast head stops	Turn machine off	
Begin Blasting		10 min	Blast head stops		
Begin Blasting		28 min	Programming difficulties		❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting		1 min	Basic language problems – machine moved without any commands - driving through the benches. Also only removing thin layer of paint		
Begin Blasting		2 min		Adjust the path	❖ 5 gallons dry ice added
Begin Blasting		15 min		Checking pressure and passes	
Begin Blasting		1 min		Resetting the parameters	❖ 5 gallons dry ice added
Begin Blasting		6 min			
Begin Blasting		4 min		Nozzle readjusted	

Begin Blasting		2 min			
Begin Blasting		3 min	Liquid is dripping out from the hose		
Begin Blasting		1 min	Dry ice is spilling and has clogged	Removed ice jam	
Begin Blasting		24 min	System overload		❖ 5 gallons dry ice added
Begin Blasting		16 min	Power out, monitor goes dead		
Begin Blasting		31 min	Ice clog	Clean hopper	❖ 5 gallons dry ice added
Begin Blasting		18 min			
Begin Blasting		46 min	Fuel gauge empty	Refuel	
Begin Blasting		18 min			❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting		18 min		Finished new strip	❖ 5 gallons dry ice added
Begin Blasting		11 min			
Begin Blasting		1 hour 25 min		Finished 18 40” long strips. Made adjustments to the auger to increase ice flow.	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	11 min	2 min	Auger froze with ice	Cleaned out auger	❖ 5 gallons dry ice added
Begin Blasting	2 min	2 min	Auger is overflowing	Remove ice jam	
Begin Blasting	2 min	2 hours 29 min		Turned off machine for the day	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Being Blasting	4 min	49 min	Leaking dry ice from sifter that feeds pellets into hoses	Took apart hose and cleared out the system	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	4 min	20 min	Leaking dry ice from same place	Cleared out system	
Begin Blasting		2 min			
Begin Blasting		1 min			

Begin Blasting		61 min	Leaking dry ice	Cleaned out system	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	2 min	1 min	Leaking dry ice	Cleaned out system	
Begin Blasting	2 min	1 min	Leaking dry ice	Cleaned out system	
Begin Blasting	3 min	1 min	Leaking dry ice	Cleaned out system	
Begin Blasting		10 min	Ran out of dry ice	Refill and refuel	
Begin Blasting	7 min	1 min	Regulator failure	Replace piece	
Begin Blasting	2 min	6 min	Ice jam	Use a screw driver to clear jam	❖ 5 gallons dry ice added
Begin Blasting		0	Ice jams	Use a screw driver to clear jam	
Begin Blasting	33 min	5 min	Ice jam	Clear jam – removed all ice from system. Regulator is jammed – air pressure is not getting to vacuum therefore causing the blast head to jump.	❖ Replace regulator
Begin Blasting		42 min		Change parameters to increase speed	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	10 min	31 min	Ice jam	New speed along with humidity appears to have caused ice to freeze to the metal surfaces	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	30 min	55 min	Screw that feeds the ice pellets has frozen	Ice is removed from system	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting		25 min	Ice jam	Clear with screw driver	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	4 min	4 min		Added more ice	
Begin Blasting	11 min	24 min		Operations stopped for the day	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting		32 min	Ran out of ice	Refilled	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added

Begin Blasting	2 min	12 min	Ice jam	Clear jam with screw driver	❖ 5 gallons dry ice added
Begin Blasting	4 min	27 min	Ice jam	Clear jam with screw driver	❖ 5 gallons dry ice added
Begin Blasting	2 min	14 min	Ice jam	Clear jam	❖ 5 gallons dry ice added
Begin Blasting	6 min	31 min	Ice jam	Clean auger with screw driver	❖ 5 gallons dry ice added
Begin Blasting	9 min	2 min	Block is uneven – block for CO2 blast is lower than the cone base	Re-position block	
Begin Blasting	30 min	3 min	Ice jam	Clear jam with screw driver	
Begin Blasting	5 min	5 min	Auger and blast head have ice jam	Remove ice jam	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	5 min	37 min	Auger is jammed with ice	Removed ice with screw driver	❖ 5 gallons dry ice added ❖ 2.5 gallons dry ice added
Begin Blasting	4 min	38 min	Auger is jammed with ice	Remove ice with screwdriver	❖ 2.5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	8 min	37 min	Auger is jammed with ice	Removed ice with screw driver	❖ 5 gallons dry ice added
Begin Blasting	5 min	6 min	Auger is jammed with ice	Removed ice with screw driver	❖ ½ gallon dry ice added ❖ 5 gallons dry ice added
Begin Blasting		9 min			❖ 2 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	6 min	3 min	Auger is jammed with ice	Removed ice with screw driver	
Begin Blasting	3 min	1 hour 12 min	Auger is jammed with ice	Removed ice with screw driver	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	2 min	1 min	Auger is jammed with ice	Removed ice with screw driver	
Begin Blasting	2 min	18 min	Auger is jammed with ice	Removed ice with screw driver	
Begin Blasting	1 min	2 hours 11min	Auger is jammed with ice	Removed ice with screw driver	❖ 5 gallons dry ice added ❖ 5 gallons dry ice added

					❖ 5 gallons dry ice added ❖ 5 gallons dry ice added
Begin Blasting	1 min	2 min	Auger is jammed with ice	Removed ice with screw driver	