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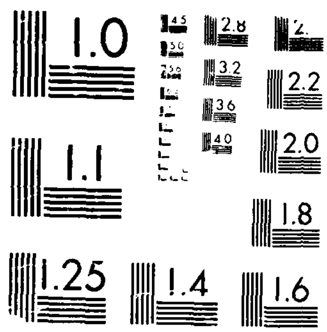

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REMOTELY OPERATED VEHICLE (ROV)
RELIABILITY STUDY

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Report Number: MIS 8712001

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December, 1987

Phase I Report Of Study
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A Remotely Operated Vehicle (ROV) reliability study was initiated to determine how ROVs can be designed and built to achieve enhanced operational reliability when operated during extended underwater deployment. The contractor was to examine the technology used in the design and construction of representative ROVs which are currently state-of-the-art and document proposed design or construction methodology to effect high reliability. This study report is the result of the contractor's study efforts.

The study result revealed that the process of development and procurement of ROVs for Navy use presently involves modification of off-the-shelf commercial vehicles. Long term reliability is not a design criteria for commercial vehicles and is certainly lost in the development process due to cost competition. (con't)

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As a result, commerical grade vehicles with broad applications are modified for specific requirements. These vehicles have reliability and other problems as described in detail in this report.

Present state-of-the-art ROVs cannot be modified to meet the requirements for reliability of extended deployment vehicles. Development of a highly reliable long term deployment vehicle requires the rigorous use of a thorough development process. Simultaneously with any development, efforts should be initiated now to develop technological approaches and design and manufacturing criteria to address the long term reliability problems identified in this study.

The results of the study have been compiled and detailed in this report. A prioritized listing of recommended theoretical and experimental work was developed from the study results.

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I. EXECUTIVE SUMMARY

A Remotely Operated Vehicle (ROV) reliability study was initiated in two phases to determine how ROVs can be designed and built to achieve enhanced operational reliability when operated during extended underwater deployment. The contractor was to examine the technology used in the design and construction of representative ROVs which are currently state-of-the-art and document proposed design or construction methodology to effect high reliability. This study report is the result of the contractor's Phase I study efforts.

The study result revealed that the process of development and procurement of ROVs for Navy use presently involves modification of off-the-shelf commercial vehicles. Long term reliability is not a design criteria for commercial vehicles and is certainly lost in the development process due to cost competition. As a result, commercial grade vehicles with broad applications are modified for specific requirements. These vehicles have reliability and other problems as described in detail in this report.

Present state-of-the-art ROVs cannot be modified to meet the requirements for reliability of extended deployment vehicles. Development of a highly reliable long term deployment vehicle requires the rigorous use of a thorough development process. Simultaneously with any development, efforts should be initiated now to develop technological approaches and design and manufacturing criteria to address the long term reliability problems identified in this study.

The results of the Phase I study have been compiled and detailed in this report. A prioritized listing of recommended theoretical and experimental work was developed from the study results (Appendix C) and is forwarded in the form of a proposal for Phase II tasking approval.

II. ACKNOWLEDGMENTS

The contractor would like to acknowledge the assistance of the laboratories, operational groups and manufacturers contacted, for their assistance in this phase of the study. The laboratory groups involved include: the Naval Explosive Ordinance Disposal Technical Center, Indian Head, MD; Naval Ocean Systems Center, San Diego, CA; and David Taylor Naval Ship Research and Development Center, Annapolis, MD. The operational groups involved include: the National Undersea Program, St. Croix, USVI; Eastport International, Marlborough, MD; Submersible Engineering and Operations, Woods Hole Oceanographic Institution, Woods Hole, MA; US Navy Submarine Development Group-1, San Diego, CA; and General Offshore Corporation, St. Croix, USVI. The manufacturers involved in the study included: Straza Division Ametek, El Cajon, CA; Hydroproducts Division, Honeywell Incorporated, San Diego, CA; and Perry Offshore Incorporated, Riviera Beach, FL.

The contractor would also like to acknowledge the members of the Technical Advisory Board who supplied technical expertise for this phase of the study. They are: Barry Walden, ALVIN Operations Director, Woods Hole Oceanographic Institution, Woods Hole, MA; William D. McElroy, Chief Engineer, Benthos Incorporated, North Falmouth, MA; and Wayne Bywater, President, Northeastern Underwater Services, Troy, NY.

III. INTRODUCTION

1. Summary

A Remotely Operated Vehicle (ROV) reliability study was initiated in two phases to determine how ROVs can be designed and built to achieve enhanced operational reliability when operated following extended underwater deployment. The contractor was to examine the technology used in the design and construction of representative ROVs' state-of-the-art and document proposed design or construction methodology to effect high reliability. This study report is the result of the contractor's Phase I study efforts.

The results of the Phase I study have been compiled and detailed in this report. A prioritized listing of recommended theoretical and experimental work was developed from the study results and is forwarded in the form of a proposal for Phase II tasking approval.

2. Program Overview

2.1 Description of Work

The program is a two-phased study contract to determine how Remotely Operated Vehicles (ROVs) can be designed or built to achieve reliability of 0.95 or better when operated during extended underwater deployment. The contractor was to examine the technology used in the design and construction of representative ROVs which are currently state-of-the-art (e.g. the Perry Offshore Systems' TRITON or AMETEK's SCORPIO) and document proposed design or construction methodology to effect high system reliability. The ROV system includes the launch, recovery and storage system, power and control cables and the tether storage and management subsystem that would be required to support the ROV when installed on platforms from which the ROV would be deployed.

2.2 Study Description

The contract for the study consists of two phases: the first to review the design, manufacturing processes, materials used, sensors, lights, cables, connectors, handling systems and electronic component reliability of ROV systems; and the second, to develop, recommend and document specific design and manufacturing methodology to use or change current practice as necessary to achieve the desired reliability. To satisfactorily complete this work, the contractor is to use consultants who are experts in the various ROV components and subsystems. The government considers the use of expert consultants as both necessary and desirable to establish the needed ROV and system reliability criteria. The deliverable from the contract is a comprehensive technical report detailing technological approaches and design and manufacturing criteria to design, construct, and operate an ROV system having the desired reliability.

2.3 Deliverable and Schedule

The contractor is to provide a written report at the end of Phase I which must be accepted and approved by the government prior to proceeding to Phase II. A program plan was developed and oral progress reports made as necessary. The period of performance for Phase I of the contract is three months, and for Phase II, eight months.

IV. STUDY METHODOLOGY

1. Study Phases

The 3-part phase I study was performed over a three month period.

1.1 Scope Definition

The first part was to determine the tasking limits or scope of the study. The scope allowed description of a generic system, which, was used to develop a Work Breakdown Structure (WBS). Subsequently, the WBS provided the discipline required to organize study data and to present and track problem areas.

The nature of the study required reasonable flexibility to insure a broad focus on reliability problems, and not be limited by specifics of vehicle tasking or design functions required to support a given capability. This broad focus was a main consideration during the conduct of the study.

1.2 Data Collection

The second part of the study consisted of a series of meetings and communications with numerous commercial, military and scientific and manufacturing users of state-of-the-art ROVs who have experienced various levels of reliability. As a result of these meetings the study group detailed all reliability problems identified by the users and reviewed several of the solutions developed to solve these problems. With the focus on long term deployment, the study showed that only one of the canvassed user groups meet the criterium. Therefore, a major goal of the study was to obtain feedback on changes that would allow ROV deployments of longer than 12-48 hours.

For this second part of the Phase I study, the contractor met with 12 groups. These were divided into three categories. They are: Operators, Laboratories and Manufacturers. In the Operator group, four vehicle users and one long term deployment system operator were chosen for their experience with vehicle design and component reliability.

1.2.1 Vehicle Operators

The long term deployment group has managed and engineered US government life support habitat (HYDROLAB and AQUARIUS) systems that have had deployments of over 24 months in duration. Although not primarily an ROV user, this group was chosen for its experience in assessing the reliability of a large number of vehicle components that are used on saturation systems; its management is primarily made up of experienced commercial ROV operators.

Eastport International was among the operators selected for their experience with vehicles in deep water. Of all the operators interviewed, Eastport has had the longest ROV deployments with some exceeding 72 hours. The company maintains the US Navy DEEP DRONE and continually works to maintain a high reliability factor in this system.

The third vehicle operator group interviewed was the ALVIN operations Deep Submergence Group at the Woods Hole Oceanographic Institution. Although not continuously operating an ROV, the group operates the deep manned submersible ALVIN and has deployed an ROV using ALVIN as a platform. The ALVIN operations group also has extensive data on reliability of deep ocean motor and thruster assemblies which are crucial components of ROVs.

Operator Group four was the US Navy's Unmanned Vehicle Detachment of SUBDEVGRP-1. This group operates a number of vehicles and towed systems. One of these, the Surface Towed Search System (STSS), has undergone an extensive reliability assessment which is well documented (reference Westinghouse STSS Reliability Study Program Technical Report, Contract N00140-82-G-BZ43,7H19). Another reason this group was chosen was that it is in the process of accepting 2 new SCORPIO vehicles, which represent the state-of-the-art in hydraulic work vehicles.

A fifth group, General Offshore Corporation, manage the Sonobuoy quality assurance and test program (SQUAT) in St. Croix, USVI. This group operates a Perry RECON and has had extensive experience with the system. Also, because of the company's location in the tropical zone, the group has a wealth of well documented experience in the organization of marine systems exposed to high temperatures before and after deployment.

1.2.2 Laboratories

Four design and testing laboratories were contacted for their inputs on reliability for components, technology and manufacturing.

The first Laboratory was the US Navy Explosive Ordinance Disposal Technical Evaluation Center (NEODTEC). This group has been evaluating various commercial designs of specifically tasked ROV systems and has extensive experience with both domestic and foreign designed ROV systems.

The second laboratory group was the Naval Ship Research and Development Center (NSRDC) at Annapolis, MD. Having considerable experience in the design of propulsion systems and electric fields on underwater platforms, the lab staff provided important information on these facets of the study.

The third Laboratory group was the Naval Ocean Systems Center (NOSC) in San Diego, CA. This group designed and tested the Autonomous Underwater Survey System (AUSS), an untethered ROV, and has considerable experience with non metallic composite materials.

The fourth Laboratory group was also at NOSC. The group originally designed and tested the specifically tasked Mine Neutralization Vehicle (MNV). This vehicle, presently being manufactured by Honeywell Corporation, is a militarized version of the design that was developed by the NOSC group.

1.2.3 Manufacturers

The contractor interviewed three major domestic manufacturers who are presently supplying both commercial and militarized vehicles to the US Navy. The first of these manufacturers was Ametek Straza. The company has over 100 vehicles out in the field and is in the process of delivering two SCORPIO vehicles to SUBDEVGRP-1. Ametek is a major manufacturer of heavy work vehicles in the United States.

The second manufacturer interviewed was the Hydroproducts division of Honeywell. It is under contract to the US Navy to supply the MNV system, which is one of only a few systems being manufactured to stringent shock and vibration requirements.

The third manufacturer contacted was Perry Offshore, Inc. This company has provided a number of systems to the US Navy including the RECON being used at the SQUAT range in St. Croix, USVI.

1.3 Study Results / Problem Assessments

Using inputs from these twelve groups, as well as other ROV specialists, the contractor completed the third part of the Phase I study by developing a composite list of recurrent reliability problems in state-of-the-art Remotely Operated Vehicles. During these meetings, it became apparent that many of the existing problems are directly related to competitive costing, poor design or lack of adequate testing of the product. It was also determined that some problems have not yet materialized in existing ROVs due to their tasking (ie., no commercially available ROVs are designed for long term exposure to the marine environment). Theoretical problems concerning long term deployments were developed in conjunction with actual existing problems.

There are two major basic categories of problems that may impact the reliability of today's ROVs upon deployment for extended periods. The first category includes problems that currently exist during short term deployment.

The second category includes the theoretical problems that might be expected if present designs were to be deployed for extended time periods. Because the study user groups have experienced few deployments longer than 72 hours, the contractor has defined long term deployment as longer than 5 days with an expected duration of 60 days.

In order to accurately assess the problems in both short term and long term categories, a functional Work Breakdown Structure (WBS) was formulated which outlines technological and component related reliability problems for review (Appendix C).

The technological problems are those that are general in nature and affect the overall system. These problems, such as acoustics, corrosion or manufacturing, can affect many different component parts of an ROV system. The component related problems are specific to individual components in the system such as connectors, thruster assemblies or tether management systems.

The WBS is provided as a guide for tracking the technological and component related reliability problems, considerations, and non-problems. The study results in Section V and their discussion in Section VI are outlined in the WBS format.

V. STUDY RESULTS / PROBLEM ASSESSMENT

A. Study Results

1. Technology

1.1 Seals

Seals, including those on main electronics housings, were not cited by any particular group as being a reliability problem. This is primarily because, for most existing systems, seal life is clocked and this component is replaced before failure. These seals experience very low wear levels, primarily friction from the pumping action resulting from repeated exposures to high pressure environments. Some users were divided on the use of "back up" o-rings in conjunction with these sealing systems. Users expressed concern about reliability problems for seals on rotating shafts, particularly when experiencing differential pressures across the seal. Existing seals on air backed direct shaft thrusters have a fairly short life and would not be sufficiently reliable for long term deployments. These seals would require further study if oil filled assemblies are rejected because of oil leaks into the environment and non-direct shaft drives are deemed inadequate. [Shaft seal technology requires further study to increase reliability to the level required for long term deployments.]

The reliability of seals on hydraulic systems would have to be increased in order to permit extended deployments. Many hydraulic systems are shipped from factories after undergoing a standardized seal assembly process. These seals often loosen with shock and vibration during transport and must be disassembled and resealed by the user on site. Several users indicated that they would prefer to eliminate these seals altogether, replacing them with as many welded joints as possible in order to prevent hydraulic seal failure. [Hydraulic seal technology requires further study in order to produce design concepts that will increase the reliability in these systems.]

1.2 Acoustics

Vehicle generated noise is not a problem for most of the existing ROVs with the exception of vehicles tasked specifically for mine counter measures and some vehicles used in scientific work. In fact, most vehicle operators are happier with noisy systems because they can often hear them through the hull of the support vessel confirming their proper operation.

For an ROV to be used in certain other applications, it may be very important to minimize the system generated noise, including cavitation, within clearly defined spectrums in order to avoid detection. There may be reliability risks encountered with such a design and it would be important to consider them at the time. Sensor generated noise may not be as serious a consideration because these sensors can be commanded by the operator in most cases. [The acoustic requirements for a long term deployment system and its tasking should be studied; its components should be specified in order to prevent detection and main platform sensor blanking.]

1.3 Corrosion

Corrosion is a reliability problem for most of the ROV users, laboratories and manufacturers but, as in the case of connectors and cable assemblies, all agree that with use of today's technology this problem can be eliminated. Almost all corrosion problems have arisen as a direct result of either construction from low nobility metals or the use of dissimilar metals. There are several ROV types and other oceanographic electronic housings that combat this problem with the use of composites such as carbon tapes, graphite tapes and filaments, and glass filament coupled with epoxies. Further development should be done on these composite materials for use as housings in the deep ocean because they have the advantage of being both light weight and corrosion resistant. However, cost effective techniques for manufacturing these materials consistently have not yet been developed. The products manufactured today are often unpredictable and many designs have demonstrated failure at rated working pressures. As a result, composite housing construction does not appear to be a near term solution. NOSC is experimenting with this type of design in its AUSS vehicle.

All groups contacted agree that corrosion could be eliminated as a reliability problem if the construction were from a metal of high nobility, with no dissimilar metal in any external component of the vehicle. But this solution leads to the problem of moving parts of similar consistency in contact with one another. [Studies should be performed to address galling problems or other "similar metal" problems. Also, studies should be performed on the effects of corrosion resistant designs on host platforms.]

1.4 Manufacturing

Manufacturing reliability was mentioned by both the users and the laboratories contacted. A number of systems that are in use today exhibit major reliability problems resulting from faulty manufacturing processes and production designs. The manufacturing groups reported that they were not satisfied with the level of user training demanded of them. This was reaffirmed by Navy users, where personnel turnaround is high. The manufacturers indicated that they were often called upon to solve problems that could be handled effectively by the vehicle user if they had the proper training. The manufacturers also were called upon to provide the same solutions repeatedly. Another problem that affects system reliability is inadequate documentation to support maintenance, trouble shooting and training. Both laboratories and manufacturers indicated that suppliers have become a major system reliability problem. One manufacturer said that they had to verify even certified materials and sub-components for correctness. A thorough QA/QC program on incoming parts should be specified and implemented for development of any high reliability vehicle. [It was noted through the various interviews that there are manufacturing processes existing today that reduce vehicle reliability. These processes should be defined and identified as necessary to increase vehicle reliability.]

1.5 System Requirements

One group indicated that one of the biggest reliability problems that they have encountered is the problem of defining system requirements. Falling under the category of both operations and manufacturing, this problem has occurred when the system attempts to perform tasks for which it was not originally designed. If the design requirements for the system are clearly understood and designed into the system, then it's ancillary components reliability can be more easily maintained.

1.6 System Maintainability

A number of the systems studied have experienced extended downtime due to a lack of easy access to internal components. Although this is not a reliability factor per se, it is important to consider in system design. Maintainability of the accessible components, such as displays and pilot control console electronics, has been mentioned by the groups contacted. For any high reliability system, maintainability and component accessibility requirements should be specified.

1.7 Testing

The problem of testing, part of the manufacturing process, was brought up by a number of the groups. Most systems now in use fail at one time or another as a result of random component failure. This problem can be avoided by extensive burn-in tests on the system. Most vehicles now in production do not undergo sufficient testing after production. This problem could be remedied by the development of a detailed test program to be implemented after assembly of high reliability vehicles.

1.8 Biofouling

Biofouling was not considered a problem for the existing ROVs because their present tasks do not entail long term exposure to the environment. It is expected to be a problem for any deployment longer than 25 days in the photic zone of the marine environment. Only one laboratory had considered the problem. That user, the Habitat group at St. Croix, experienced biofouling problems on numerous occasions. Fortunately, the depth and tasking of the two habitat experiments made them accessible to divers on a daily basis, allowing manual cleaning of soft algae from viewports. The rotating shafts present a more severe problem. These shafts often remain immobile for long periods of time, becoming encrusted with coraline algae that covers both the shafts and their housings. Extra force is required to break these encrustations loose. Shaft action compounds the problem by grinding the encrustation residue into a rouge-like substance that is detrimental to seals and other friction points. [A study of methods to protect against biofouling is recommended.]

1.9 Silting

Not unlike the conditions for biofouling, silting is not a problem for existing ROV designs, but has been experienced by long term deployment systems. Detritus in the water column as well as effluents from coastal zones contribute to the silting process. In certain conditions, this silt can accumulate in areas of rotating shafts causing problems similar to those of coraline biofouling. [A study should be done to develop methods to prevent build up or to remove silts that can accumulate on the vehicle during long term deployments.]

1.10 Integration and Design

The reliability of many of the electronic components and subassemblies used in the manufacture of ROVs is linked to the ability of the system to dissipate self-generated heat. The most effective integration of subassemblies and internal components is a consideration that must be made during the design of the system. Ceramics and certain metals used in construction can create heat dissipation problems. [A high reliability ROV system requires a detailed study of the system's ability to eliminate heat build-up.]

2. Components

2.1 Tether

Tether and umbilical cables are fairly reliable in existing systems. At present, copper conducting cables exhibit far greater reliability than fiber optic cables. Low reliability factors typically stem not from the cable itself but from problems with Tether Management Assemblies (TMAs) or operator faults.

2.1.1 TMA-Vehicle

The tether cable which connects the TMA to the vehicle is the cable that is most susceptible to damage and appears to be the highest reliability risk. Often these cables are not armored for reasons of flexibility, neutral buoyancy and low drag. Most users of large vehicle systems replace their cables after 50-100 deployments, however, this is usually due to abrasion problems from contact with structures or rugged bottom terrains. Further work should be done to develop low profile abrasion resistant cables for systems used in their rugged environments. Additionally, although the number of umbilical cycles before failure is expected to be high (100,000±), temperature fluctuations may adversely affect some cable materials. [It is recommended that a copper based, low profile, abrasion resistant tether assembly be developed for use in tropic and arctic environments.]

2.1.2 TMA-Platform

The cable which connects the TMA to the platform has not been cited as a serious reliability problem, if it is easily inspectable during winching operations. These cables are often armored. Flexibility requirements are much less stringent than for the TMA-Vehicle cable and added weight is attractive to assist with cable depression.

2.2 Vehicle

2.2.1 Housing Configuration

There were no particular reliability problems associated with the open frame versus single housing design for ROVs, although design personnel were divided as to a preferred style. Other factors effecting the design of the vehicle will drive this decision.

2.2.2 Interconnecting Cables and Connectors

2.2.2.1 Wet

All contacted groups repeatedly replaced connector and cable assemblies exposed to the marine environment. It was a common statement that connectors are a potential source of problems regardless of the manufacturer, but that this problem could be easily solved. All groups agreed that there are technologies now available that would maintain a higher reliability factor for connectors and cables. If connectors have to be used in any particular part of a system, the high corrosion resistance of properly specified metal shell connectors is a desirable feature. In addition, the history of certain glass filled connectors would add considerably to the reliability of this component. Many of the problems experienced by users and manufacturers are related to the use of less expensive and less reliable assemblies for competitive cost reasons. A clearly attractive alternative that has been expressed by operators is the elimination of many of the system connectors altogether. This has been done in certain cases. The concept of a wet connector free system should be studied with the understanding that the design would greatly increase the MTBF figures at the direct expense to MTTR figures. [A study should be performed to determine the minimum number and type of wet connectors and the best connector design while maintaining a high reliability figure for the vehicle.]

2.2.2.2 Dry

High levels of shock and vibration adversely affect some types of internal, dry connector and cable assemblies. For one manufacturer, card edge connectors are a continual problem even though bifurcated contacts have been used. The manufacturer has now turned to pin and socket connectors. [Shock and vibration effects on connectors should be studied further.] In order to eliminate any corrosion on the dry connector assemblies, one manufacturer used a dry nitrogen backfill. The lack of oxygen in the back fill caused gold-coated contacts to weld together, leading to part failure. It is expected that dry filling with air and the use of a desiccant would solve this problem. Just as with wet connectors and cable assemblies, it is recommended that stringent specifications be developed for cases in which the connector and cable assemblies cannot be eliminated.

2.2.3 Optical Imaging Systems

2.2.3.1 Cameras

Most of the groups contacted in the study indicated that camera systems, both still and video, used on existing vehicles do not contribute to system reliability problem. Although the video camera is the operator's eye and is crucial to most operations, a carefully specified camera system will minimize reliability risk. There are a number of different types and sensitivities of video cameras available and the system may have more than one type of camera installed. These cameras can be further defined as the vehicle tasking becomes specific. Most of the groups also indicated that state-of-the-art still cameras and associated electronic flash units would not contribute to long term system reliability problems. Various film formats are available to meet most user needs and are not a reliability issue.

2.2.3.2 Lighting

Lighting components are not a serious problem for most existing short term deployment vehicle systems. These systems typically use commercial, off-the-shelf incandescent lights, which are designed for a multitude of applications. When failures occur, the lamps can be easily replaced between deployments. These lights are usually used in multiples, so failure of one would not be cause for mission termination. [For long deployments, the problem of selecting a long term lighting system which operates in the proper wavelengths should be examined.] Since there may be more than one type of video camera on board, these lights would have to be complementary as well.

2.2.4 Propulsion

Power assemblies for propulsion have produced problems primarily for the users of hydraulically powered vehicles. These problems are outlined in the sections for acoustics (Technology 1.2) and power (Components 2.2.5).

Although they do have limitations electric propulsion systems using electronically commutated, brushless DC motors have a far higher reliability than hydraulic systems and are used on a number of vehicles. Seal technology heavily impacts the reliability of thruster assemblies and needs to be considered when designing a high reliability system (see Seal Technology, Section 1.1). Contamination of oil in electric thrusters and low torque of magnetically coupled thrusters were cited as additional problems. [Oil contamination build-up in these systems as well as improved seal-less magnetically coupled thrusters should be examined.]

2.2.5 Power System

The hydraulic system is another serious problem common to large, work vehicles that require high levels of power to maintain headway. These vehicles are often unstreamlined; since they require hydraulics for other reasons, they do not require streamlining. Smaller, streamlined observation vehicles capable of limited work rely strictly on electric power and do not fall into this problem category. The hydraulic problems that are encountered during short or long term deployments include leaking, flooding and contaminate build-up. These problems typically stem from faulty hoses, corrosion in hoses, faulty seal construction, line collapse, vibration and poor filtration. Many of these conditions are tolerable in short term deployment scenarios but not in long term deployments. All of the manufacturers, laboratories and users of large hydraulic work vehicles agreed that a hydraulic power system, if used on a long term deployment vehicle, would be a major reliability risk. [A solution should be found either for improvement of hydraulic technology or development of a streamlined vehicle that can meet mission objectives without requiring the use of hydraulic systems.]

2.2.6 Tools

Tool packages come in a wide variety of sizes, capabilities and complexities. Most tool packages on existing vehicles were either originally designed or heavily modified by the user. Reliability appears to fall off rapidly when these tool packages are redesigned to do more tasks or when they are used on tasks for which they were not designed (see requirements 1.5). In cases where high power tool packages utilize hydraulics, the power system becomes the low reliability component. Conversely, limited work vehicles utilizing electric power sources significantly increase their reliability. If the vehicle could utilize electric power for propulsion and were to require a high-power work package, it has been suggested that the hydraulics be used only for the work package and not tie into the main vehicle power package. [A study should be made on the design of a high-power electrical tool package.] [A study should also be made of a high reliability hydraulic tool package that operates independently from the power system.]

2.2.7 Acoustic Sensors

The primary sensor mounted on most ROVs is the collision avoidance or target-locating, forward-looking sonar, which is reasonably reliable when tasked properly. The most unreliable component of this system is the mechanically rotating transducer assemblies. Correction of this component problem will produce the highly reliable sonar system needed for long term ROV deployments. This sensor will have to be carefully specified when requirements are defined. [Solid state phased array type sonars should be studied and applied to vehicle technology in order to develop a specification for a high reliability forward looking sonar]. Other sensors should also be examined as they may be required by tasking.

2.2.8 Redundancy

It was felt by most of the laboratories interviewed that if the original definition and design requirements are done properly, redundancy, a technique used to increase reliability, would not be necessary. It is felt that carefully specified and tested components coupled with the proper design would meet the reliability objectives of the system.

2.2.9 Buoyancy

Although most of the manufacturers and labs have reported problems with buoyancy materials for their vehicle systems, they have continued to base their selection criterium on cost competitiveness. With its relatively low cost, syntactic foam has been chosen for most short term deployment vehicles, even though they feel that quality material is unavailable domestically. Many of the vehicle manufacturers are employing syntactic foam from a manufacturer in the United Kingdom. They feel that the American manufacturers are not able to supply them with a consistent, quality product. Preferably, another buoyancy material, exhibiting none of the historical syntactic reliability problems such as chipping, cracking, and water pickup, should be selected. Since a specially tasked vehicle is expected to be mobile and used in different water types, it will also require a highly reliable variable ballast system. [Different methodologies to address this problem need to be examined.]

2.2.10 Corrosion Protection

The corrosion protection now used is sufficient only for systems that have short term deployments and uses an anodic reaction to provide marginal protection from corrosion caused by dissimilar metals. If the root of the corrosion problem is solved (Technology 1.3), corrosion protection of this type will be unnecessary.

2.2.11 Control/Data Link

2.2.11.1 Software

In some systems, both users and manufacturers indicated that software has provided a reliability problem. This appears to be primarily due to improper debugging of the software due to time constraints. This problem can be avoided with proper design, verification, documentation and testing.

2.2.11.2 Data Link Subassemblies

Electronic subassemblies, such as power supplies, motor drivers and multiplex units, did not appear to be a major reliability factor. Some of these subassemblies are not required for all vehicles and this, of course, increases the subassembly's reliability.

2.3 Garage

The vehicle is expected to be mounted or housed on a host platform during periods of inactivity. Among the numerous mounting configuration possibilities are two specific scenarios that should be more carefully considered: whether the mounting should be done inside an existing enclosure, and whether or not the enclosure can be blown dry. These options should be defined and studied to determine an optimal configuration with regard to reliability.

2.3.1 Location

The location of the enclosure or garage to hold the vehicle when not actively deployed is important with respect to any electrical fields generated by the host platform, as well as the expected physical limitations of the potential locations. [A study should be done to determine the best possible location for the garage with the least effect on the vehicle or host platform.]

2.3.2 Test Electronics

It is assumed that the vehicle, when housed in the host enclosure, should be designed to provide data on the status of its subcomponents for the operator. This can be accomplished through a testing system that can connect to the vehicle when it is enclosed in the garage, and electronically analyze the vehicle's components. This test system should be part of the garage in order lessen the complexity of the vehicle.

2.4 Tether Management Assembly (TMA)

The most unreliable component of all large tethered ROV systems as reported by operators, manufacturers and laboratories is the submerged Tether Management Assembly (TMA). Many of the problems that have occurred with the TMAs are related to the hydraulic system with the most common end result was damage to the umbilical connecting the TMA to the actual vehicle. Although the problem rarely results in vehicle loss, it does cause excessive down time for the system while the umbilical is either repaired or replaced. [A study should be performed to design and specify a Tether Management System that is highly reliable and can maintain this reliability on long term deployments.]

2.5 Control Systems

Reliability problems can arise even when the mechanics of the system are reliable if the operator is unable to accomplish his tasks properly. This problem arises from operator fatigue or Failure of p[art of the system to provide the operator with sufficient feedback about system status and performance. A good example is feedback from tool packages. Force feedback subsystems on manipulators may help the operator in determine task progress. Other informational feedback systems should be examined, such as vehicle mounted hydrophones, to indicate minor collision or contact situations. [A study should be performed to maximize informational feedback to the operator of a high reliability vehicle.]

2.5.1 Displays

Camera data displays are important for the operator to properly control the system with a minimum of fatigue. Placement, resolution and adjustability are important features in the display component of the system. A subcomponent that would give the operator an omnidirectional view of the environment surrounding the vehicle will also increase the amount of information necessary to the operator. Other displays for information such as that which may indicate the status of tool packages also need to be considered.

2.5.2 Controls and Ergonomics

Ergonomics are important for the operator of the system. Poorly designed operator consoles and "cockpits" can cause system failure due to excessive errors made by the operator. For short duration system missions this is not important but, as the mission time grows, operator fatigue can play an important role in degrading system reliability. One of the users has found this ergonomics problem particularly important and is designing new control consoles for their ROV operators. [Further study should be done on the design and layout of the operator's control console.]

2.6 Ancillary Systems

2.6.1 Vehicle Navigation Systems

The navigation systems that are used for vehicle positioning during operations do not seem to contribute significantly to reliability problems. Many of the systems used in deep water are based on acoustic transponders and require placement of a large area net of instrumentation at the work area boundaries. In shallower applications, the vehicle position is determined using a short baseline acoustic system with a receiver on the platform and a responder on the vehicle. These systems have the ability to position the vehicle accurately (several feet) within the navigation grid. For vehicles working on precision tasks, in very low visibility, or other instances where extreme accuracy is required, there is a need for more precise vehicle or subcomponent positioning systems. [A study should be undertaken to apply the recent technology of high accuracy short range positioning to ROV technology.]

B. Experimental and Theoretical Problems Requiring Further Study

1. Technology

1.1 Seals

Short Lived Shaft Seals on Air Backed Thrusters

The highest reliability thruster design uses electric thruster motors. If the assemblies are filled with air and there is a pressure differential across the shaft sealing area these shaft seals wear, reducing the overall system reliability. A study should be made to develop extremely long life seals for air backed thruster assemblies. This design would allow the use of the high reliability designs of air backed electrical thrusters on a long term deployment ROV.

1.2 Acoustics

High Acoustic Levels of Hydraulic Thrusters

Under certain tasking conditions, hydraulically powered ROVs will have to both minimize their effect upon blanking the mother platform's sensors and minimize the potential of acoustic detection, a study should be made of hydraulic ROV propulsion and work systems in order to provide a specification for the design of a system that has limited acoustic output within the specific parameters required. This study would require knowledge of the frequencies that should be minimized as well as the acceptable output levels.

Cavitation

Since detection and blanking could occur from propeller blade cavitation on both hydraulically and electrically powered systems, a study should be made to propose various designs for minimal cavitation propellers for different speed, size and type (electric and hydraulic) thruster assemblies.

1.3 Corrosion

Dissimilar Metals

Since a majority of the corrosion problems expected to occur in a long deployment ROV system would be from dissimilar metals, a study should be conducted to design an ROV that contains no dissimilar metals. Also in this study, consideration should be made to replace any materials that may result in galling between similar metals on a system of this type. An example of this would be replacing some components with non-metallic parts, such as ceramic and synthetic materials.

Use of Materials of Low Nobility

Noble metals have been proven in the marine environment to be highly resistant to deterioration and many instruments for use in the marine environment have been constructed from this material. A study should be performed to determine the best configuration and design of an ROV built of a noble material. The design will consider minimizing the production costs of such a system. Problems related to this type of design, such as heat dissipation will also be considered.

Electrically Driven from a Mother Platform

If an ROV is to be mounted on and deployed from another platform which may have active electrical fields around it, the ROV may be adversely affected by these fields thereby reducing its reliability. A study should be performed to address the effect of these fields on the ROV system. This would include studying the best possible mounting method of the system garage, the location of the ROV and materials for the garage.

1.4 Manufacturing

Manufacturing Processes that Reduce System Reliability

Manufacturing is an area that can impact the reliability of any ROV design. Shortcuts and cost saving procedures also impact a system's reliability. A study should be done to specify manufacturing processes that will assure that reliability requirements will be met in the final ROV assembly.

1.8 Biofouling

Build-up of Coraline Algae on Shafts and Seals

The growth of certain coraline marine organisms of the surfaces of ROVs that are deployed for extended periods in the ocean's photic zones can case system failure, particularly on the seals of moving system parts. A study should be made of the best methods for prevention of attachment and growth of hard coraline algae on an ROV system deployed for long time periods. A related study problem is the cleaning of any such materials after they have formed on the ROV surfaces.

Build-up of Soft Algae on Optical Ports and Transducers

Another type of marine growth is that of the softer algae that can obscure the camera ports and other optical ports on an ROV. A study should be performed to determine the best possible methods to prevent the build-up of soft algae on viewports on an ROV that will be deployed for extended periods. This could include using various antifouling methods including ultra-violet light baths for the specific components of the ROV.

1.9 Silting

Build-up of Silt on Shafts and Seals

Like the coraline algae problem, silt can be destructive to seals on ROVs undergoing long term deployments. A study should be performed to determine the severity of the problem of silting on ROVs used in extended deployments and, if required, determine the best methods of reducing the effect of silting on the ROV shafts and seals.

1.10 Integration and Design

Poor Heat Dissipation in Electronic Components

One of the main problems that engineers and manufacturers have with ROV design is that of heat dissipation from within the electronic housings to the environment surrounding the ROV system. A study should be made to develop reliable methods of heat dissipation for the ROV electronics. This will be particularly important in housings made from ceramic, composites and titanium.

2. Components

2.1 Tether

2.1.1 Tether Abrasion and Breakage

A low reliability component of many ROV systems is the control cable connecting the ROV with the TMA. This cable is susceptible to abrasion and breakage from temperature variations. Since a high reliability ROV would be expected to operate in waters of great temperature variation and also around structures on the seafloor which represent a hazard to the ROV cabling, a study should be performed to design a low profile neutrally buoyant control cable that is resistant to temperature changes and abrasion.

2.2 Vehicle

2.2.1 Housing Configuration

2.2.2 Interconnecting Connectors and Cables

2.2.2.1 Short Component Life of Wet Connectors

Although most ROV users have reliability problems with the connectors used on their vehicles, all agree that in some cases better specified connectors would solve some of their connector problems. A number of groups indicated that the elimination of connectors would further increase system reliability. This would be a tradeoff between maintainability and reliability. A specification should be developed of existing connectors that can be used on a system that requires high component reliability. These specifications would outline all of the types and designs that would be used throughout the high reliability system. Also, the system should be further defined in relation to the desired MTBF and MTTR figures.

2.2.2.2 Failure of Dry Connectors from Vibration

A specification similar to the one above should be developed for dry connectors that would be used inside a ROV designed for high reliability. These specifications would also detail the assembly and production methods for these connector assemblies.

2.2.3 Optical Imaging Systems

2.2.3.1 Cameras

2.2.3.2 Lights

Short Lamp Life in Lights

Although lighting systems are used in multiples on ROV systems, failure of these units would impact on the system's ability to perform. Most of the existing light designs have a specific life which is not compatible with long term ROV deployments. A study should be made to develop a long life incandescent light design for use on high reliability ROV systems that would be deployed for extended periods. This design would also maintain the lamp life in conditions of high shock levels.

Limited Illumination Range

One of the limitations to ROV operations is that of limited visibility. Often this is due to mismatching the lighting systems with the optical sensors. A study should be conducted to develop a light that would extend the range of existing optical systems by putting the maximum percentages of the lights' available energy into frequencies matching the optical system sensitivities while meeting the objectives of the long life and shock resistance stated above.

2.2.4 Propulsion

Contaminant Build-up in Oil Filled Thrusters

In thruster assemblies that are oil filled with no pressure differentials across the sealing areas, contaminants build up in the oil surrounding the motors. This also impacts the system reliability. A study should be performed to design an oil filled thruster assembly that uses electrical motors but does not demonstrate the contaminant build-up common to existing designs.

Low Torque Tolerance of Magnetically Coupled Thrusters

One of the most reliable thruster designs uses air backed electric thrusters with no shaft seal. Rather than penetrate the thruster housing, this design uses magnetically coupled drive assemblies. These designs, however, are heavy and do not tolerate high torque levels well. A study should be made to increase the power levels that can be applied to small magnetically coupled thruster assemblies.

2.2.5 Power System

Leaking Hydraulic Systems
Flooding Hydraulic Systems
Hydraulic Line Collapse

In hydraulic vehicle systems, the least reliable component is the power system. Problems with these systems result in very low reliability, making them unsuitable for even short term deployments, as they are presently designed. A specification should be developed for a hydraulic system that will not exhibit leaking, flooding or line collapse that is common to existing designs.

Contaminant Build-up in Hydraulic Systems

Another problem in hydraulic systems is the build-up of contaminants in the hydraulic fluid. This can cause system failure if not corrected, thus impacting system reliability. A study should be conducted to eliminate sources of contamination in hydraulic power systems. The possibility of water soluble hydraulic fluids and contaminant tolerant hydraulic systems should also be studied.

2.2.6 Tools

All Problems as in 2.2.5 above, in Hydraulic Tool Systems
Lack of High Power Electric Tool Package

Hydraulic systems are one of the most unreliable components of ROV systems and will heavily impact reliability on a system that is deployed for long time periods. If this method of power distribution can be eliminated, reliability is expected to increase significantly. A study should be made to develop a high-powered electrical tool package that can be deployed on a high reliability electrically powered ROV used in long term deployments. Also, a study should be made to develop a high reliability hydraulic tool package that operates independently of the vehicle's main power system.

2.2.7 Acoustic Sensors

Mechanical Failure of Collision Avoidance Sonar

A low reliability component of many ROVs is the forward-looking sonar systems. In environments of low visibility or during tasks over large areas, this is an important system component. The failures that occur with these acoustic imaging systems most often involve the mechanical rotating transducer head. Reliability of these systems would be increased through the use of a non-rotating transducer head. A study should be conducted to adapt an existing non-mechanical high reliability, high resolution forward-looking sonar to small ROVs.

2.2.8 Redundancy
2.2.9 Buoyancy

Syntactic Foam Chipping
Syntactic Foam Cracking
Water Pickup

The present materials used in the buoyancy modules for ROV systems exhibit low reliability through physical degradation of chipping and cracking. They also has a tendency to lose their buoyancy over a period of time. For long deployment, high reliability systems, a more advance type of buoyancy material needs to be evaluated. Potential study areas might be glass flotation, independent of epoxy foams and titanium spheres rigidly fixed to the ROV. A study should be performed to develop a new buoyancy material that can be used on a high reliability ROV.

Lack of Design of Variable Buoyancy System

Since a high reliability, long term deployment ROV may encounter water conditions that vary, a fixed buoyancy module would not be applicable to efficient operations. The system's buoyancy and trim would have to be changed for operations in different environments. A study should be performed to develop a remotely operated variable buoyancy system for use on ROV systems that will encounter environments of different density.

2.2.10 Corrosion Protection
2.2.11 Size
2.2.12 Control/Data Link

2.3 Garage

2.3.1 Location
2.3.2 Maintenance/Assembly
2.3.3 Test Electronics

2.4 Tether Management Assembly (TMA)

Kinking, Breakage of Tether by TMA

The most unreliable portion of many ROV systems that are operating today is the Tether Management System or TMA. During operations, these systems often damage the ROV control cables through kinking or overloading. A study should be made to design and develop a tether management system that has high reliability on long term deployments.

2.5 Control Systems

2.5.1 Displays
2.5.3 Controls and Ergonomics

Operator Fatigue due to Poor Ergonomics

The demands made on an ROV pilot are unique and involve high intensity work conditions. Similar to air traffic controllers, ROV operators are often required to work under high stress levels. In contrast to air traffic controllers, the ROV pilot is in direct control of the equipment he is directing. A study should be made to determine the best method of reducing errors resulting from operator fatigue.

2.6 Ancillary Systems

2.6.1 Vehicle Navigation

Better Presentation of Navigational Data

Since the limited range sonar and the TV camera are the eyes of the operator, it is important to establish effective navigation for better orientation. Often, the displays of this information are not integrated and the operator is not effectively presented with the data he requires. More effective displays of navigation information needs to be studied to better orient the operator to the position of the ROV.

Low Resolution on Existing Positioning Systems in Low Visibility

Operating an ROV system in low or limited visibility without high accuracy positioning can increase the stress on the pilot, reduce the effectiveness of the system, and increase the risk of vehicle loss. While existing positioning systems provide gross indications of vehicle position, often it is necessary to position the ROV or a vehicle mounted probe to centimeter accuracy. A study should be made to determine the best methods of navigating and position an ROV system with extremely high accuracy during inspection tasks as well as ROV docking maneuvers.

VI. CONCLUSIONS / RECOMMENDATIONS

A. Conclusions

1. The state-of-the-art and maturity of the ROV market, with regard to the US Navy, has led to the use of commercial grade vehicles that have broad applications modified for specific requirements. Long term reliability is not a design criterium and is certainly lost in cost competition. Vehicles are required to operate for hours, not weeks, and the ROVs can be easily retrieved and repaired if necessary. Extensive maintenance is performed between the short operational periods. Present state-of-the-art ROVs cannot be modified to meet the requirements for reliability of extended deployment vehicles. Instead a vehicle will have to be developed to meet the stringent requirements for extended deployments.

2. Development and procurement efforts of Navy ROVs presently involves modification of off-the-shelf commercial vehicles to meet specific Navy requirements. This process provides vehicles which have problems as described in the study report. Only two groups have used or are utilizing the Navy's acquisition management process in developing their vehicles. The Mine Neutralization Vehicle (MNV), developed by Naval Ocean Systems Center (NOSC), is one of the programs. The MNV production units are being delivered to the Navy. The other is the Navy Explosive Ordinance Disposal Technical Center (NEODTC) ROV development program, now in the engineering development phase. These programs should provide vehicles meeting the Navy's specific requirements.

3. To develop a highly reliable, long term deployment vehicle requires the rigorous use of a thorough development process. This process should include requirements definitions, prototype design and development through full scale engineering development, and the associated test programs to insure that the product being developed will meet the system design requirements.

4. The study has identified several reliability problem areas that need to be addressed. A thorough assessment of these problems along with identification of solutions can insure that the reliability problems will be adequately addressed in any vehicle development.

5. A synopsis of the reliability problems considered significant for a long term exposure system to be deployed in the near future, affect both the design and the manufacturing processes. If the construction of the system is not done properly corrosion will impact the system's reliability. The design of a system that minimizes the use of hydraulics will increase the reliability of the underwater system and this will affect the type of hull construction around which the system is designed.

6. Lighting and navigation are both reliability concerns that affect the ability of the operator to properly control the system. Another feature that affects operational reliability is the limited amount of operational data that are available to the operator. High reliability force feedback on manipulators is one method of getting work accomplishment information to the operator. Acoustic sensors could provide provide further information to the operator in the environments where collisions are likely. A problem outlined by many operators is that of operator viewing. High operations reliability will include providing the operator with multiple or omnidirectional viewing systems.

All of these problems must be addressed in order to bring an ROV system to a state of high reliability. In a majority of cases, however, this design for increased reliability will be at the expense of ease of maintenance. In most design changes to increase reliability, Mean Time Between Failures (MTBF) figures and those for the Mean Time To Repair (MTTR) are related in that an increase in the time between failures will increase the time required to repair the system.

Most of the groups contacted during the study also indicated the simplicity of design and requirements is closely related to reliability. The more complex the system becomes and the more varied its requirements, the more unreliable it will become.

B. Recommendations

As can be seen by the study results, there are a number of problems that need to be addressed and solved in order to provide the target reliability in Remotely Operated Vehicles (ROVs). There are also a number of areas outlined that do not fall directly into the problem category but remain concerns for the development of high reliability ROV systems.

The results of the Phase I study are listed in Section V. They comprise a listing of proposed tasks to pursue in Phase II of the program.

The Phase II efforts are to be theoretical and experimental tasks approved by the Sponsor. The results of these tasks will be compile and evaluated and a comprehensive technical report will be prepared detailing technological approaches, design and manufacturing criteria.

The following recommendations are made with regard to the Phase I study reliability tasks:

1. The Program Sponsor approve the tasks of interest for Phase II.

2. The Program Sponsor turn-on the contractor for Phase II.

The contractor will pursue the approved tasks as follows:

1. Prepare detailed statements of work for each task.

2. Identify qualified experts in the various fields of interest to conduct the specified work.

3. Obtain proposals and select the best qualified proposals to pursue.

4. Conduct the proposed work after approval from the Program Sponsor.

5. Manage and coordinate the approved tasks/subcontracts.

6. Prepare a comprehensive technical report of the results of the task efforts per the contract SOW.

7. The cost and schedule for the Phase II efforts is dependent on the costs and schedules proposed for the approved tasks (see item numbers 3 and 4 above).

APPENDIX A

Functional Work Breakdown Structure (WBS)

1. Technology:
   - 1.1 Seals
   - 1.2 Acoustics
   - 1.3 Corrosion
   - 1.4 Manufacturing
   - 1.5 System Tasking
   - 1.6 System Maintainability
   - 1.7 Testing
   - 1.8 Biofouling
   - 1.9 Silting
   - 1.10 Integration and Design
2. Components:
   - 2.1 Tether
     - 2.1.1 TMA-Vehicle
     - 2.1.2 Platform-TMA
   - 2.2 Vehicle
     - 2.2.1 Housing Configuration
     - 2.2.2 Interconnecting Connectors and Cables
       - 2.2.2.1 Wet
       - 2.2.2.2 Dry
     - 2.2.3 Optical Imaging Systems
       - 2.2.3.1 Cameras
       - 2.2.3.2 Lighting
     - 2.2.4 Propulsion
     - 2.2.5 Power System
     - 2.2.6 Tools
     - 2.2.7 Acoustic Sensors
     - 2.2.8 Redundancy
     - 2.2.9 Buoyancy
     - 2.2.10 Corrosion Protection
     - 2.2.11 Control/Data Link
   - 2.2.11.1. Software
   - 2.2.11.2. Data link Subassemblies
   - 2.3 Garage
     - 2.3.1 Location
     - 2.3.2 Test Electronics
   - 2.4 Tether Management Assembly (TMA)
   - 2.5 Control Systems
     - 2.5.1 Displays
     - 2.5.2 Controls and Ergonomics
   - 2.6 Ancillary Systems
     - 2.6.1 Vehicle Navigation

APPENDIX B

Cross Reference of Problems / Considerations / NonProblems

System Element	Problem / Non Problem
1.1 Seals	Problem
1.2 Acoustics	Problem
1.3 Corrosion	Problem
1.4 Manufacturing	Problem
1.5 System Tasking	Consideration
1.6 System Maintainability	Consideration
1.7 Testing	Consideration
1.8 Biofouling	Problem
1.9 Silting	Problem
1.10 Integration and Design	Consideration
2.1 Tether	
2.1.1 TMA-Vehicle	Problem
2.1.2 Platform-TMA	Non Problem
2.2 Vehicle	
2.2.1 Housing Configuration	Non Problem
2.2.2 Connectors and Cables	
2.2.2.1 Wet	Problem
2.2.2.2 Dry	Problem
2.2.3 Optical Imaging Systems	
2.2.3.1 Cameras	Non Problem
2.2.3.2 Lighting	Problem
2.2.4 Propulsion	
2.2.5 Power System	Problem
2.2.6 Tools	Problem
2.2.7 Acoustic Sensors	Problem
2.2.8 Redundancy	Non Problem
2.2.9 Buoyancy	Problem
2.2.10 Corrosion Protection	Non Problem
2.2.11 Control/Data Link	Consideration
2.2.11.1. Software	Problem
2.2.11.2. Data link	Non Problem
2.3 Garage	
2.3.1 Location	Consideration
2.3.2 Test Electronics	Non Problem
2.4 Tether Management Assembly (TMA)	Problem
2.5 Control Systems	
2.5.1 Displays	Consideration
2.5.2 Controls and Ergonomics	Consideration
2.6 Ancillary Systems	
2.6.1 Vehicle Navigation	Problem

APPENDIX C

Prioritized List of Problems

The following list of problems are prioritized in order of severity as indicated through the interviews and telcons with the Operator, Manufacturing and Laboratory groups.

1. Tether Management Assembly failure
2. Wet connector unreliability
3. Corrosion of system components
4. Hydraulic propulsion system failures
5. Low levels of precision in vehicle navigation
6. Short life of seals
7. Short component life of lighting systems
8. Use of manufacturing processes that result in low system reliability
9. Improper system tasking
10. Inadequate system testing after manufacture
11. Operator fatigue due to poor ergonomic and feedback design
12. Low reliability of bouancy materials
13. Low life of tether assemblies
14. Poor integration and design of electronic subassemblies
15. Low penetrating range of lights
16. Failure of Hydraulic tool systems
17. Contaminant buildup in oil filled thrusters assemblies
18. Low torque tolerance of magnetically coupled thrusters
19. Dry connector failure from vibration
20. Failure of forward looking sonars
21. High acoustic levels of hydraulic systems
22. Vehicle system biofouling
23. Vehicle housing configuration
24. Silting on vehicle system components

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