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Technical Survey and Evaluation of Underwater Sensors and Remotely Operated Vehicles

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16. Abstract

Accurate on-site assessment of vessel hull damage in the event of grounding, collision, structural failure, or other accident is required to make timely and informed decisions relating to vessel disposition (i.e., lightering, towing, sinking.) The capabilities of underwater vehicles and sensors as they relate to the performance of damage assessment are analyzed in this report. The vehicle types analyzed include free-swimming remotely operated vehilces (ROVs), autonomous undersea vehicles (AUVs), towed vehicles, crawling vehicles, and composite vehicles. The sensor types analyzed include photographic, video, laser, and acoustic imaging systems, oil/water interface sensors, oil concentration monitors, and non-destructive test methods. A conceptual inspection vehicle system is presented based on an evaluation of the damage assessment mission.

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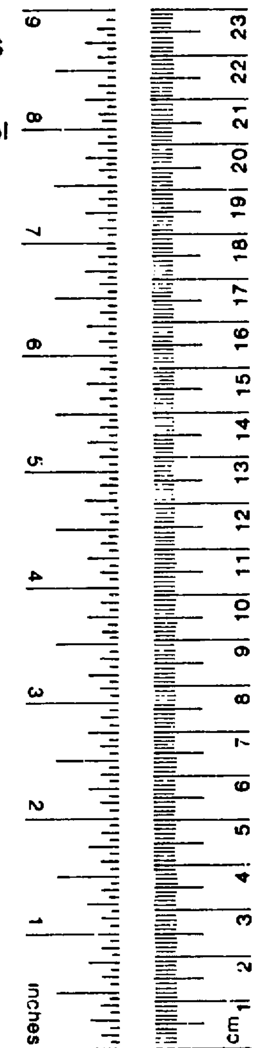
Approximate Conversions to Metric Measures

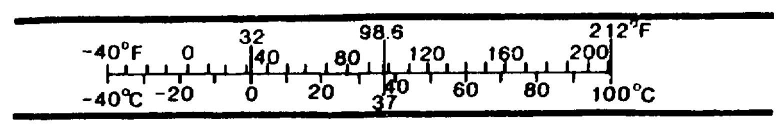
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

Currently, the U.S. Coast Guard performs vessel damage assessment by placing divers in the water or by using fairly simple free-swimming remotely operated vehicles (ROVs). The capabilities of underwater vehicles and the sensors they carry have advanced significantly over recent years. As discussed in this report, the implementation of these advances into an inspection system should allow the Coast Guard to carry out vessel damage assessments more thoroughly efficiently, and safely.

This report consists of the following:

- An analysis of the Coast Guard damage assessment mission.
- A technical overview of the underwater vehicle and sensor technologies.
- An evaluation of how well each vehicle system would be able to meet operational and environmental requirements for sensor delivery.
- An evaluation of how well each sensor would be able to meet the overall inspection requirements.
- The development of a conceptual system which integrates a vehicle, sensors, and navigation system for the performing damage assessment.
- Recommendations for research and development which will enhance the Coast Guards ability to perform damage assessments in the future.

This project found that a hull-crawling ROV with free-swimming capabilities would most adequately meet the Coast Guard's mission requirements. Such a system should be able to operate in a wide variety of sea-state conditions, and would provide the operators with operational flexibility for optimizing the damage assessment process. This conclusion must be tempered with the understanding that other vehicle types might perform specific missions more ably (e.g., towed vehicles for side-only inspections or AUVs for long standoff/hazardous environments).

As described in this report, the selection of "optimum" sensors for installation on the vehicle depends greatly on the specific inspection scenario. Operators should be provided with as much flexibility as possible with respect to sensor selection. Providing a suite of sensors that can be placed on the vehicle in a modular fashion provides the operator this flexibility. For example, two viable sensor modules that could be interchanged on a combination hull-crawler/ROV are depicted in a conceptual drawing; here, one sensor module (consisting of sonar sensors) would be suitable for imaging in extremely low visibility conditions, while the other module (range-gated laser) would be suitable for enhanced imaging under less limiting visibility conditions.

Recommendations for future development include:

- Testing sensors in a laboratory environment to assess performance capabilities as they relate to damage detection and damage characterization.
- Development of a vehicle test bed for field testing sensors.
- Analyzing sensor performance in an oil/water environment.
- Developing or monitoring the development of specific sensors and vehicles to allow enhancement of the damage assessment mission as they become available.

1.0 INTRODUCTION

1.1 Statement of the Problem

Large spills of crude oil or chemicals have focused attention on the need for a capability to rapidly assess damage to vessels that have run aground, been involved in a collision, or suffered structural failure. The primary goals in the management of a vessel casualty are timely, complete and accurate assessment of damage, prevention of further spilling of oil or chemicals, mitigation of the effects of the spill, and assurance of crew and vessel safety. Equipment and instrumentation for rapidly determining the extent and location of tank damage is necessary for assisting the Coast Guard in making strategic response management decisions. The information provided serves as critical input for the Coast Guard to use when formulating the hazard assessment and response tactics. Knowing the volume of water and oil in a hold—along with the location, size, and nature of damage to the hull— the Coast Guard can make important casualty control decisions. Such information, coupled with knowledge of the vessel's design characteristics, allows stability and residual strength to be determined. Knowing the stability and strength status of a vessel allows the Coast Guard to make educated decisions regarding the various actions that could or should be taken (e.g., towing, lightering, or evacuating personnel).

The Coast Guard and industry presently have extremely limited capability to assess underwater damage. When conditions allow, scuba divers can perform the assessment very adequately. When environmental conditions are too severe for the safe placement of divers, or when the casualty itself precludes the placement of divers in the water, the ability to gather accurate damage information is severely hindered. Recent technological advances in underwater sensors and underwater vehicles make unmanned damage assessment a viable option. In many cases, unmanned inspection systems may be able to provide better quality information more quickly than scuba divers can.

1.2 Objectives

The primary objectives of this study are to:

(1) Define the mission requirements for an underwater damage assessment operation.

(2) Perform a technical evaluation of underwater vehicle systems, sensors, and methodologies for use in vessel damage assessment. Events that may require vessel damage assessment include collision, grounding, fire/explosion, or structural failure.

(3) Establish conceptual designs that will most effectively make use of the technologies that are currently available (or being developed) to meet the Coast Guard mission requirements.

(4) Recommend areas where research and developments efforts are required to bring underwater vehicle or sensor technologies to the point where they can meet the mission requirements more effectively.

(5) Provide a method of evaluating future technologies that might be suitable for vessel damage assessment.

1.3 Organization

This report is organized into six sections. Section 1, Introduction, sets the problem, and describes the goals, objectives, and methodologies involved in the performance of system analysis and definition.

Section 2, Mission Analysis, presents an investigation of the oceanographic/environmental conditions that could be expected during the performance of a damage assessment, an operational analysis resulting from a questionnaire completed by Coast Guard personnel, characterization of vessel damage that is likely to be encountered, and a description of both the operational flow and inspection system performance requirements.

Section 3, Subsystem Evaluation Methodology and Technology Overview, presents the method of evaluation for the underwater vehicle and sensor technologies. An overview of the technology is given, methods of applying the technology to the damage assessment task are discussed, and the strengths and weaknesses of that technology are presented.

Section 4, Vehicle and Sensor System Multifactor Evaluation Process (MFEP) and Conceptual System Development, evaluates the compatibility of the different underwater vehicle and sensor systems. This section concludes with a conceptual design that addresses the mission requirements under the various environmental and operational scenarios that are likely to be encountered.

Section 5, Recommendations, presents recommendations for testing, evaluation, system integration, and future research and development activities.

Section 6, Conclusions, presents a summary of the analysis performed herein.

1.4 Investigation and Analysis Techniques

1.4.1 Literature Search and Market Survey

A literature search and a market survey were performed to identify and compile information on the vehicle and sensor technologies that are either commercially available or under development. A keyword list was developed for searching various databases. The reports, articles, books, and technical papers obtained through these searches were used as the primary source material for this report. These items are listed in the Bibliography.

The market survey consisted of surveying and interviewing commercial manufacturers and collecting and analyzing product literature. Research findings and system development status were discussed with the scientists and engineers involved in the development of technologies that are not commercially available. The commercial availability of the technologies addressed in this study is discussed in the appropriate sections.

1.4.2 Conceptual Design Development

A process flow diagram for the conceptual design development is shown in Figure 1-1. The flow process used for this study is based on a Systems Engineering approach taught at the Defense Systems Management College. The approach is often used for the development of complex

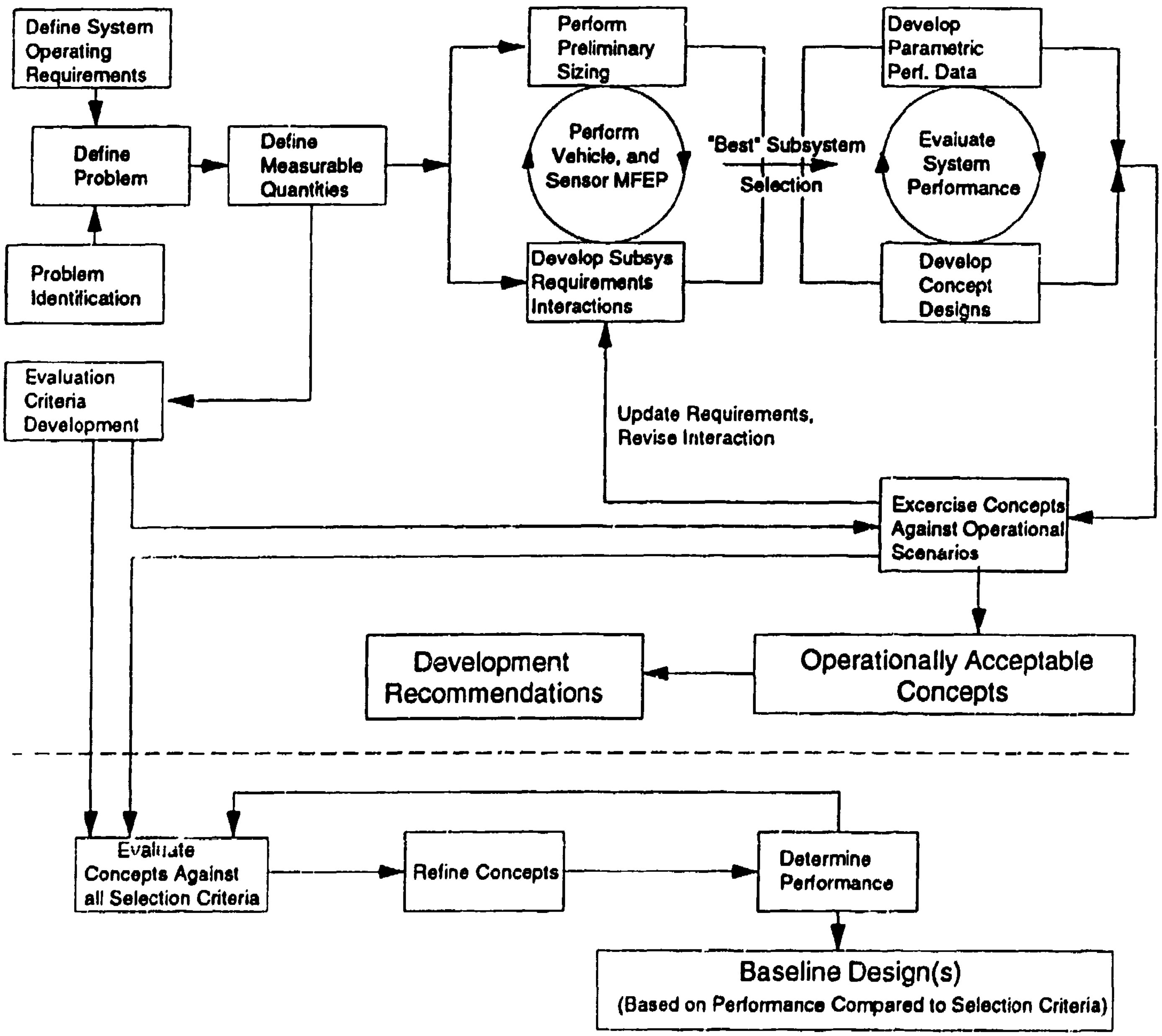


FIGURE 1-1. CONCEPTUAL DESIGN DEVELOPMENT FLOW DIAGRAM

systems. The point at which the subsystems are evaluated by the multifactor evaluation process (MFEP) is shown on the flow diagram. The MFEP is discussed in the following section, and in greater detail in Section 3. As illustrated in the flow diagram, the conceptual design development process requires that the following steps be performed:

Problem Definition. The objectives for system performance are developed. The stated objectives must generally be accomplished within a specified operating environment.

Establish Measures of Performance. Quantitative measures of performance that will be used to guide and evaluate the design are established. A system or subsystem can be characterized by being broken down into quantity, quality, coverage, timeliness, and availability attributes.

Develop Requirements Interaction and Preliminary Sizing. Since mission requirements are typically interactive, it is necessary to organize the requirements analysis in a manner that accounts for these interactions. For this study, an example of mission requirements interactions would be the surface area coverage which would be a function of the interaction between the sensor field-of-view, system traverse rate, required resolution, etc.

Define Concepts. Based on the performance of the above steps, system concepts are defined to enable the detailed requirements definition process to proceed.

Perform Parametric Analysis. Parametric analysis is employed to avoid a singular design approach (point design). It also permits the selection of a set of system design parameters that will most adequately meet the mission requirements at the lowest cost. Relationships such as sonar operating frequency versus resolution, or field-of-view versus stand off distance are examples of the types of parameters that are analyzed.

Establish Operational Scenarios. To establish the performance capabilities of a specific concept, it is necessary to describe an operational scenario or set of operational scenarios against which the concept is evaluated. The operational scenario is used to define hardware and software requirements, and also establish the human interactions required.

Select Most Viable System Concept or Concepts. From the definition of an exhaustive set of viable system concepts that satisfy key performance, cost, and operational requirements, trade studies are performed to allow the selection of the most viable or best possible system or systems. Original criteria and requirements are reviewed and refined as system capabilities are more fully developed.

It should be noted that the portion of the development process below the dotted line in Figure 1-1 occurs following the decision to pursue a particular design. Detailed "specifications" would be developed during that phase of development. This damage assessment program consisted of performing the activities above the dotted line.

1.4.3 Multifactor Evaluation Process

A Multifactor Evaluation Process (MFEP) was used as the principal technology evaluation tool for this study. This evaluation methodology is commonly used in decision making processes where many factors influence the overall acceptability of a given choice or selection (i.e., cost, size, weight, safety). By using this evaluation technique, technologies that differ significantly in design and function can be compared and ranked in relation with one another. The MFEP is used to perform subsystem analysis (sensors and vehicles) prior to the conceptual design process.

2.0 MISSION ANALYSIS

2.1 Oceanographic and Environmental Conditions

To assist in evaluating underwater sensors and vehicles used in assessing vessel damage and to establish operational scenarios, a good understanding is required of the likely environmental scenarios that may be encountered. Based on findings from a previous study performed by Battelle, two environmental scenarios have been established. The working definition of an environmental scenario is "a set of prescribed conditions that have a high probability of occurring and could impact the effectiveness of damage assessment performance." For example, a scenario for Norton Sound in the Bering Sea in January is 1/2-meter thick first-year ice (30-percent coverage), winds averaging 25 knots, air temperature -15 $^{\circ}C$, blowing snow, 1-meter wind waves, and 4 hours of daylight. The scenarios selected for the analysis of damage assessment technologies are intended to represent oceanographic conditions for the coastal waters of the United States out to 200 nautical miles, the Economic Exclusion Zone (EEZ), estuaries, intracoastal waterways, major rivers, and parts of the Great Lakes. Because U.S. coastal waters encompass oceanographic regimes ranging from arctic seas (Beaufort, Chukchi, and Bering Seas) to the tropical waters of southern Florida, a range of scenarios is required to adequately investigate damage assessment technologies. In addition, scenarios must represent conditions that are likely to occur. For these reasons, oceanographic and climate statistics provide the basis for scenario development.

Conditions that reduce the ability of the crew to operate deck equipment, deploy and operate small boats, or to visually assess the immediate surroundings of the vessel will impair their effectiveness in performing damage assessment. These conditions include low visibility due to fog, rain, or snow, superstructure icing, high sea state, high wind speed, and excessively high or low temperatures.

In developing scenarios, primary and secondary environmental conditions were defined. Primary conditions limit the selection of equipment that can be deployed and operated to perform the damage assessment. Secondary conditions do not preclude specific assessment technologies but may decrease their effectiveness.

2.1.1 Primary Environmental Conditions

Sea state has a significant influence on the position-keeping ability of underwater vehicles. Since most underwater vehicles are not designed to move rapidly in the lateral and vertical directions, even small waves can cause motion that can significantly impair position-keeping abilities. Vertical mixing of oil and water, oil-water emulsification, dynamic loads on gear deployed over the side, and personnel safety are also affected by sea state.

Current speed is also a major factor influencing position-keeping ability. Loads on systems deployed over the side and on their handling equipment can make certain underwater vehicle systems impossible to operate. Flow drag on submerged vehicles and tethers increases by a factor of about four as the current speed doubles. Even moderate current speeds can severely limit the excursion distance of an ROV due to tether drag.

Underwater Visibility significantly affects the performance of video and laser sensors, which rely on reflected light to generate an image. Light attenuation rates dictate the standoff distance that can be effectively used for some sensors.

Wind speed affects the launch and recovery process for underwater vehicles. The ease with which equipment can be transported between vessels is also adversely affected by increasing wind speed. The adverse operational effects of cold temperatures are amplified by wind chill.

2.1.2 Secondary Environmental Conditions

Tidal range and short-term water-level fluctuations (a few meters in 12 hours) mainly affect grounded vessels. The handling and operation of a vehicle system can be adversely affected by water-level fluctuations. For example, low water levels may make certain parts of the ground vessel inaccessible to a large inspection vehicle.

Low visibility and limited daylight negatively affect visual identification of damaged areas as well as crew efficiency and safety.

Precipitation (heavy snowfall, rain, or hail) contributes to low visibility, operator error, and hazards on deck.

Temperature of the sea surface and air affect crew efficiency and safety. Low air temperature or cold sea spray can hinder mobility and effectiveness with which tasks can be performed due to the need for protective covering.

Sea and lake ice affect the ability to launch and recover an underwater vehicle. Thick ice in contact with a vessel may increase the difficulty of accessing the submerged hull. Ice can produce concentrated loads that can cause fittings, lines, and cables to fail.

Superstructure icing can render equipment inoperable or hazardous to deck personnel. Icing occurs when air temperature is below freezing, wind speed is high, and there is sufficient moisture and sea spray to freeze onto vessel structures. Ice adds topside weight, covers equipment controls, makes rigging difficult to handle.

2.1.3 Geographic Areas

U.S. coastal waters were divided into nine zones for the purpose of gathering data. The zones are illustrated in Figure 2-1 and are as follows:

Zone 1: Eastport, Maine, to Cape Hatteras, North Carolina
Zone 2: Cape Hatteras, North Carolina, to Key West, Florida
Zone 3: Key West, Florida, to Brownsville, Texas
Zone 4: San Diego, California, to Eureka, California
Zone 5: Eureka, California, to Ketchikan, Alaska
Zone 6: Ketchikan, Alaska, to Dutch Harbor, Alaska
Zone 7: Dutch Harbor, Alaska, to Demarcation Bay, Alaska (Alaskan Beaufort Sea)
Zone 8. The Great Lakes
Zone 9: Intracoastal waterways and rivers.

The Intracoastal Waterway conr ters of maritime commerce from New York, New York, to Brownsville, Texas, through a system of protected channels more than 2,700 km long. Major oil terminals exist at a few locations along the waterway (e.g., the lower Delaware, Atchafalaya, and Calcasieu Rivers; Port Arthur, Texas, and Galveston Bay, Texas). The oceanographic data and a description of how this data was compiled are contained in Appendix E.

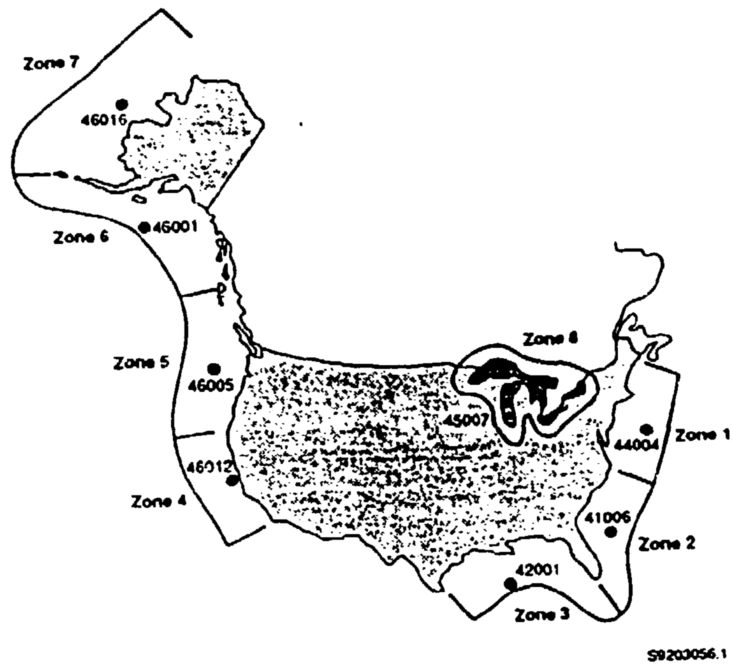


FIGURE 2-1. NINE ZONES OF U.S. COASTAL WATERS

Based on the information gathered, two environmental scenarios were selected to provide boundaries for the analysis of damage assessment technologies. The two scenarios are intended to span the range of operating environments that are likely to be encountered. The analysis and selection of underwater vehicle systems and sensors is dependent on the environmental scenario where they are required to operate. For example, some underwater vehicles may be unable to maintain position under high sea state conditions, thus affecting the accuracy of a given sensor output.

The two environmental scenarios used to provide boundaries for the analysis are listed in Tables 2-1 and 2-2. The moderate operating environment shown in Table 2-1 is an average of the "summer" characteristics described in Appendix E. These are conditions that could reasonably be expected to be encountered approximately 50 percent of the time throughout U.S. waters. It should be noted that the conditions for some given geographical areas will actually be more severe (i.e., Zone 5) while other areas will be more benign (i.e., Zone 3) than the listed "moderate" operating environment. The water visibility was selected based on inputs from a questionnaire that was sent to Coast Guard Strike Teams, and the oil presence used was based on moderate damage to a vessel with little vertical mixing resulting from wind and wave action. The water visibility listed is one attenuation length, which is described as distance at which 63 percent of the light from a source is attenuated. One attenuation length approximates the maximum distance an object can be viewed by the unaided human eye. Light attenuation will be discussed in greater detail in following sections.

The severe operating environment shown in Table 2-2 is the average of the "winter" characteristics described in Appendix E. These are conditions that could reasonably be expected in U.S. coastal waters, but less frequently than the moderate conditions. These conditions would be expected less than 10 percent of the time. The oil-water mix is based on significant vertical mixing caused by wind and wave action, and the visibility is again based on questionnaire response.

The presence of hazardous conditions which prevent operators from moving close to the ship is included as part of the more severe environmental scenario. For example, oil may be burning on the surface, or toxic vapors may be present as a result of a chemical spill. The presence of hazardous conditions will have a significant impact on system design because such conditions affect the standoff distance from which an inspection must be performed.

TABLE 2-1. MODERATE OPERATING ENVIRONMENT

<u>PRIMARY CONDITIONS</u>	
Wind Speed	11 kn
Sea State (H_s)	1.4 m (4.5 ft)
Current Speed	0.33 m/s (1.1 ft/s, .66 kn)
Water Visibility	7 ft
<u>SECONDARY CONDITIONS</u>	
Sea Surface Temperature	20.7 °C (69.3 °F)
Tidal Range	3 m (9.8 ft)
Tidal Current Speed	0.47 m/s (1.6 ft/s, .96 kn)
Oil Presence	Surface Only
Ice Presence	None
Hazardous Chemicals/Threats	None
Precipitation	None

TABLE 2-2. SEVERE OPERATING ENVIRONMENT

<u>PRIMARY CONDITIONS</u>	
Wind Speed	19.9 kn
Sea State (H_s)	2.7 m (8.8 ft)
Current Speed	0.43 m/s (1.4 ft/s, 0.85 kn)
Water Visibility	3 ft
<u>SECONDARY CONDITIONS</u>	
Air Temperature	6.6 °C (44 °F)
Sea Surface Temperature	10.6 °C (51.1 °F)
Tidal Range	3 m (9.8 ft)
Tidal Current Speed	.47 m/s (1.6 ft/s, 0.96 kn)
Oil Presence	25% oil-water mix
Ice Presence	25%-50% cover
Hazardous Chemicals/Threats	yes
Precipitation	moderate rain

2.2 Operator Survey Analysis

Coast Guard personnel were surveyed to obtain information to be used in the analysis of damage assessment system requirements. The four people who completed the survey were from either a Strike Team, Coast Guard Headquarters, or the Coast Guard Research and Development Center. A breakdown of the responses can be found in Appendix B. The following summary of system requirements was drawn from that survey. The conclusions drawn are based on an "average" of the responses. In most cases, there was some variance in the responses, therefore the information derived is not intended to provide a system specification. The intent of the survey was to obtain desirable system attributes which can be used in assessing the available technologies. As a general rule, the desirable level of system performance selected for this study was the level stated in the responses as being required in approximately one-half of all damage assessment missions.

Hole Size Detection. The ability to detect holes 3 inches in diameter is desirable. Systems unable to detect holes 10 inches in diameter are inadequate.

Crack Size Detection. The ability to detect cracks 3 inches in length is desirable. Systems unable to detect cracks 10 inches in length are inadequate. For this analysis, a crack width of 1/4 inch was assumed.

Accuracy. The ability to determine position on the hull (referenced to a known feature) to within 1 foot is desirable. The system should always be able to determine position within 3 feet.

Damage Type. The primary features which must be detected are holes, tears, and cracks. Large-scale denting of sufficient magnitude to cause significant internal damage is also a feature which should be detectable. Secondary features that would be desirable to detect are minor buckling and dents.

Damage Location. The primary areas of interest for inspections are the sides and the bottom of the vessel. Damage to bow and stern areas (including propellers and rudders) is generally confined in locale, and is therefore secondary in interest..

Wave Height. The system should generally be able to operate in an environment with wave heights of 6 feet. Occasional operation with wave heights of 9 feet may be required. Waves are considered to be wind driven and therefore quite turbulent and irregular in size, and variable in direction of propagation (as opposed to sea swell which is more regular in size and constant in direction).

Current. The system should generally be able to operate in a 1-knot current environment. Occasional operation in a 2 to 3-knot current environment may be required.

Air Temperature. The system most frequently used must be operated in a 30 °F to 100 °F environment. Operations will sometimes be required with temperatures falling between -30 °F and 30 °F.

Ice Cover. The system should be operable in an environment with up to 25 percent ice cover.

Oil Presence. The system should be operable in an environment with oil frequently present on the surface, and often oil may be mixed in the water column at concentrations of approximately 25 percent by volume.

Visibility. The visibility in the environment, as measured by the unassisted human eye, is usually less than 3 feet. Visibility to a range of 10 feet is encountered less frequently.

Data Presentation. The system should be configured such that operators are able to perform complete data interpretation with 2 to 3 hours after the completion of the inspection.

2.3 Ship Damage Categorization

2.3.1 Accident Causes and Effects

No one accident scenario can be used as a "baseline" for evaluating damage assessment technologies. Damage to a vessel may result from grounding, collision, ramming, fire, explosion, structural failure, or some other unforeseen circumstance. Accidents and damage to oil tankers have received significant attention due to the adverse affects on the environment resulting from the outflow of oil from a tanker. Much information is available on tanker accidents, and this information can be used to establish a foundation for ship damage categorization. The analysis of tanker damage statistics is important because the presence of oil in the water surrounding a ship degrades the performance of many sensors as will be discussed in later sections. Oil may also produce a hazardous environment that can prevent assessors and salvors from operating in the immediate vicinity of the ship.

Figure 2-2 shows the percentage of incidents and the oil outflow by type of incident for accidents releasing 30 tons of oil or more between 1976 and 1989. This bar chart shows that groundings, collisions/rammings, and structural/other incidents account for approximately 90 percent of the incidents, while fire and explosions account for only 10 percent of the incidents.

It is interesting to note that although the structural/other category makes up a significant portion of the incidents (30 percent), a relatively small percentage of the total volume of oil released can be attributed to these incidents. Fire and explosions result in a significant outflow of oil even though they occur less frequently. The majority of incidents involving tankers worldwide do not result in the outflow of oil. Analysis indicates that only 6 percent of the accidents reported (518 of 9,276 accidents) resulted in oil outflow (*Lloyd's Register of Shipping*, 1990). In U.S. waters during the same period, grounding events dominated in both the number of accidents and the total percentage of oil released, as shown in Figure 2-3. It should be noted that 95 percent of spillage results from less than 3 percent of the oil spillage events that occur.

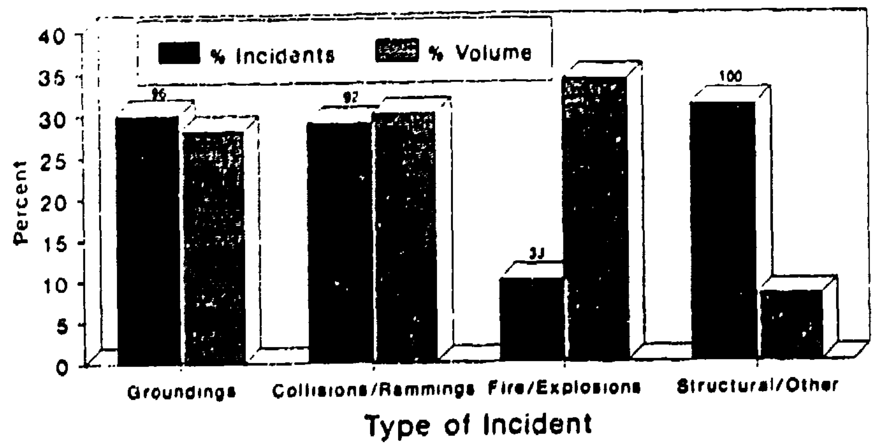


FIGURE 2-2. MAJOR OIL SPILLS FROM TANKERS AND CAUSES: NUMBER OF INCIDENTS AND VOLUME—WORLD, 1976-1989
(Lloyd's Register of Shipping)

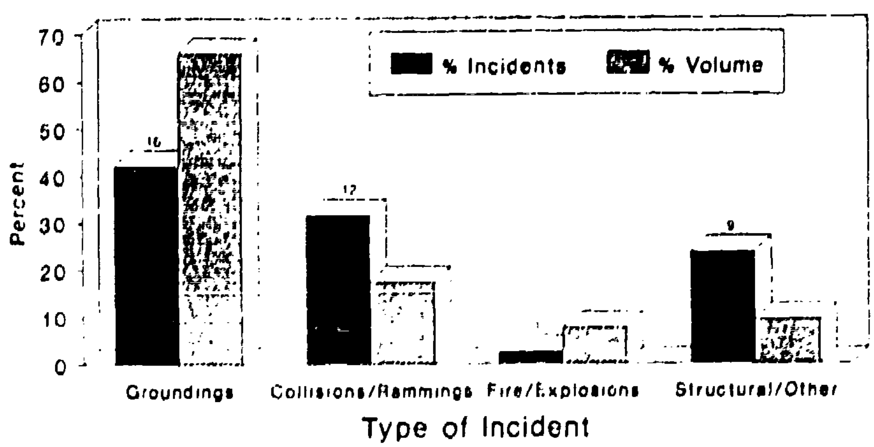


FIGURE 2-3. MAJOR OIL SPILLS FROM TANKERS AND CAUSES: NUMBER OF INCIDENTS AND VOLUME—U.S. WATERS
(Temple Barker & Sloane, Inc.)

2.3.2 Hole and Crack Distribution Analysis

2.3.2.1 Size Analysis

Studies conducted by the U.S. Coast Guard have addressed the extent of damage from the collisions and groundings of tank barges, tank vessels, and cargo vessels. The Damage Area-Frequency distribution for these events is shown in Tables 2-3 and 2-4. Table 2-3 shows the distribution for the occurrence of holes and Table 2-4 shows the distribution for the occurrence of cracks. Analyses showed that, for all vessels involved in groundings or collision, more than 40 percent of the holes are less than one square foot in area and over more than 50 percent of cracks are less than one foot in length. The size of the damage was proportional to vessel size and speed, with design material and material condition also affecting the extent of damage.

2.3.2.2 Location and Extent Analysis for Large Vessels

The Coast Guard has analyzed and characterized tanker and barge accidents and damage which could be expected for groundings and collisions of these vessels. A good understanding of typical damage locations can help in developing the operational scenarios against which the technologies are analyzed.

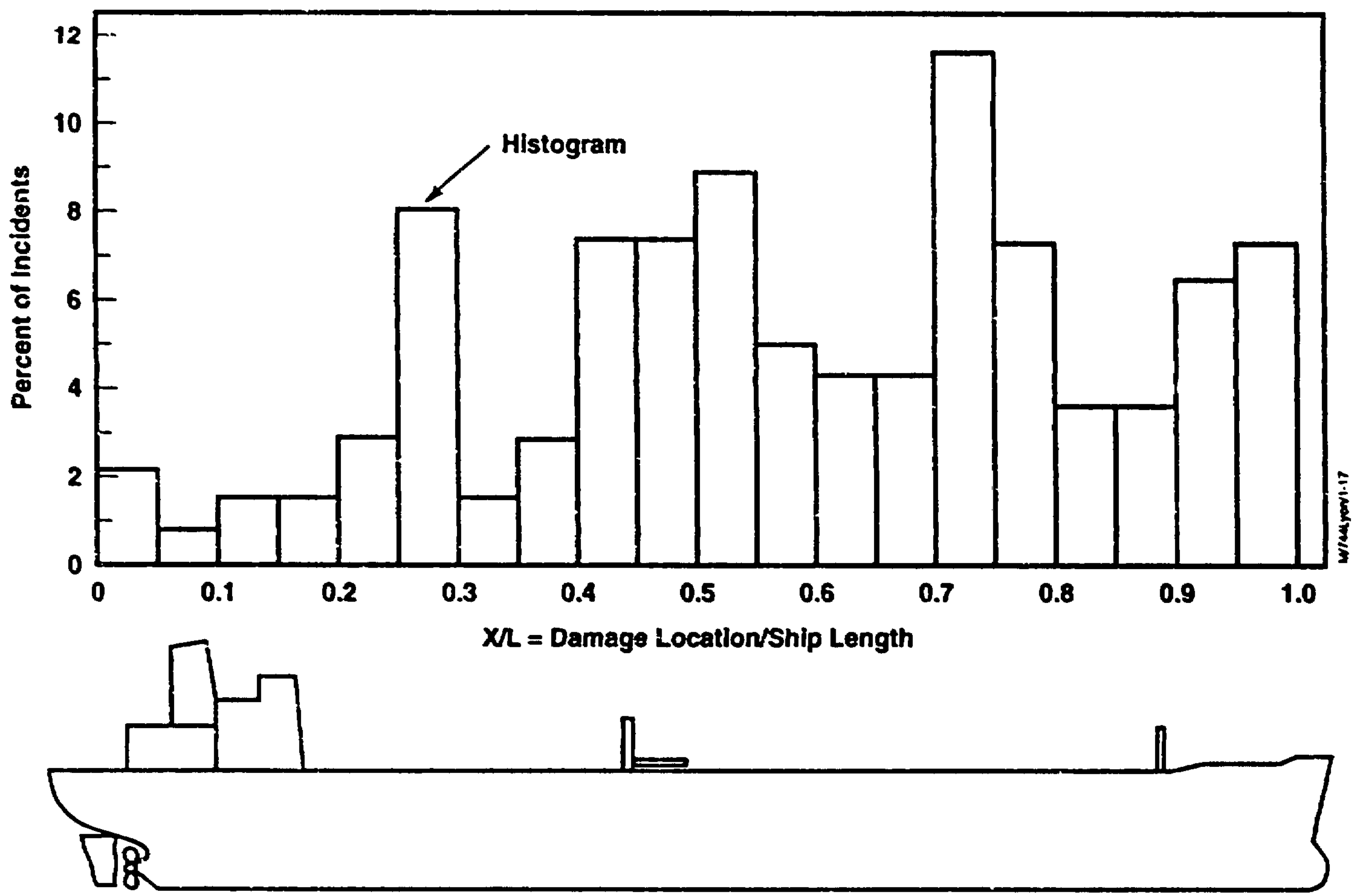
Figure 2-4 shows a damage location histogram based on 135 ship groundings. It can be seen that a smaller percentage of the damage that occurs from groundings is located near the stern of the ship. Figure 2-5 shows damage distributions derived from approximately 600 reports of damage to tankships, bulk carriers, and combinations ships over 35,000 dwt. Based on information from these reports, 220 events were plotted to discover patterns of damage location. In Figure 2-5, thin lines indicate the longitudinal location and extent of damage, and heavy lines indicate actual penetration of the hull. In this diagram port and starboard damage profiles are shown on the starboard profile. In this analysis, the vertical location of the lines on the starboard profiles and the transverse location of the lines on the bottom profile have no significance.

TABLE 2-3. DAMAGE AREA - FREQUENCY OF OCCURRENCE OF HOLES IN SPECIFIED AREA INTERVALS

AREA (ft^2)	FREQUENCY OF HOLE OCCURRENCE (PERCENT)
< 1	40.8
1-2	4.1
2-3	3.2
3-5	6.7
5-10	12.9
10-100	32.3

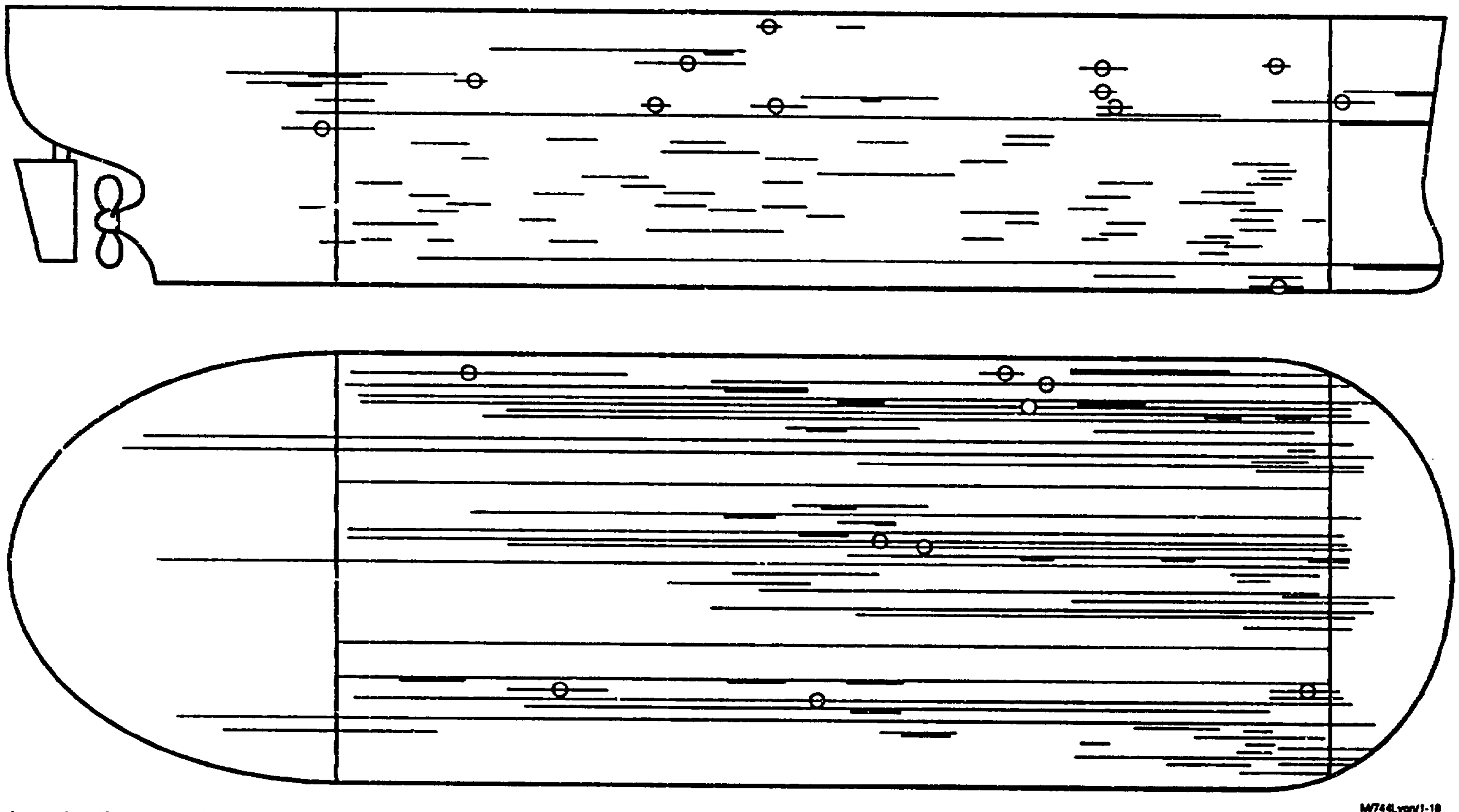
TABLE 2-4. CRACK LENGTH - FREQUENCY OF OCCURRENCE BY SPECIFIED LENGTH INTERVALS

CRACK LENGTH (ft)	FREQUENCY OF CRACK OCCURRENCE (PERCENT)
< 1	50.2
1-3	17.8
3-6	10.2
6-10	6.2
> 10	15.7



This histogram is based on 135 ship groundings reported on IMCO damage cards

FIGURE 2-4. HISTOGRAM OF DAMAGE LOCATION AS A FUNCTION OF SHIP LENGTH FOR 135 GROUNDINGS REPORTED ON IMCO DAMAGE CARDS



Longitudinal location and extent of damage:

- Location and extent of hull penetration shown by heavy line
- Report indicates hull was penetrated, but details of location and extent not reported
- Hull not penetrated

Note that one incident may have resulted in more than one penatration or damage to more than one area of the bottom (center, port or starboard wings)

FIGURE 2-5. LONGITUDINAL LOCATION AND EXTENT OF DAMAGE FOR 220 VESSEL ACCIDENTS
(IMCO Damage Cards)

The lines shown indicate only the longitudinal extent of the damage and whether it occurred on the side or bottom. The analysis and evaluation of this study concluded:

1. No area of the ship is immune from damage. However, the forward half of the ship appears to be slightly more vulnerable to an accident.
2. The midship half of the bottom appears to be slightly more prone to penetration and grounding than either the forward or aft areas.
3. Wing tanks of conventional width sustain approximately two-thirds of the total bottom damage in groundings. Penetration in the wing tank from grounding occurs at a ratio of three to one, compared to penetration in center tanks.
4. Bottom damages are generally long, but penetrations are generally short.
5. Side damages and penetrations are generally short (the majority of data supporting this conclusion are from rammings).

2.3.2.3 Location and Extent Analysis for Tank Barges

The analysis of damage to tank barges is based on a compilation of over 700 special damage survey reports submitted to Coast Guard Headquarters by field inspection units. The damages reported were observed during scheduled inspections and special examinations (i.e., following an accident). Figure 2-6 shows a distribution of damage location along the barge by type of damage. This graph shows that 30 percent of all incidents occur within the first 10 percent of barge length. The damage in this first 10 percent of length can be broken down further as follows:

Damage	Percent
Cracks or fractures	9.5
Holed	9
Wasted through	0.5
No hull penetration	11

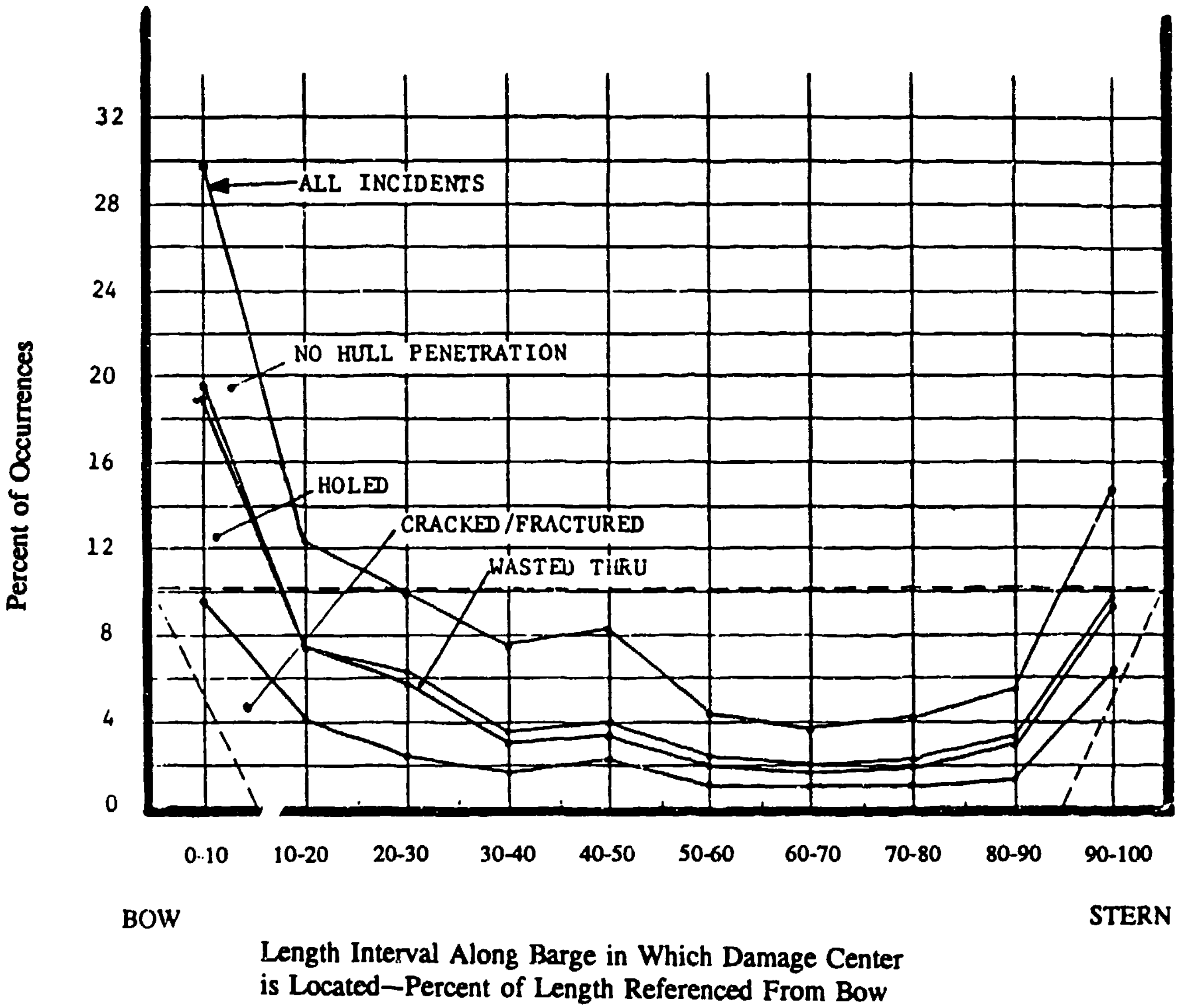


FIGURE 2-6. GRAPH SHOWING DISTRIBUTION OF DAMAGE INCIDENT LOCATION ALONG BARGE BY TYPE OF DAMAGE

Figure 2-7 shows the percentage of damage occurrence by area. Analysis of barge damage indicates that side ruptures are approximately twice as common as bottom ruptures.

Comparing damage to tank barges with larger vessels leads to the following general conclusions:

1. Tank barges are much more likely to sustain side damage than large vessels (over 35,000 dwt). Side damage may occur more often because barge side shell scantlings are less for barges than for a comparable ship hull form.

2. Barge damage tends to be more localized on the forward end of the vessel than it is for large vessels.

2.3.3 Oil Outflow Analysis for Grounding and Collision

In a study performed for the Coast Guard that was aimed at controlling oil released from damaged tankers and barges, outflow calculations were performed for a variety of vessel collision and grounding events. For collisions, holes of various theoretical sizes were modelled. The holes caused by collision were assumed to be at the waterline, the location resulting in the largest volume of oil being released from the tanker. Grounding damage was also modelled for a variety of vessel types and vessel speeds. The grounding events analyzed resulted in very rapid outflow of oil due to the theoretical assumptions that were made. For holes of the sizes analyzed in the collision flow analysis, the initial outflows (driven by the hydrostatic head of the oil and gas within a tank) would not be significantly different for holes generated by groundings so long as there was no plugging of the hole by the bottom. Theoretically, outflow of oil for groundings will cease after the rapid outflow is complete since there is no driving force to move the oil to the outside of the vessel once the hydrostatic heads are equalized between the cargo tank and the sea. Events such as vessel listing, wave action, and tidal change may cause the release or "seepage" of oil to be sustained for extended periods following a grounding, so the continued presence of oil must be expected during subsequent damage assessment performance.

For each of the collision scenarios analyzed, the damage was assumed to penetrate two cargo tanks of nominal size. Table 2-5 illustrates that the time to zero discharge can vary considerably as a function of vessel type and hole size. The time to "complete" discharge of two cargo tanks for the different vessels varies from between 2.75 hours to 139 hours. It can be

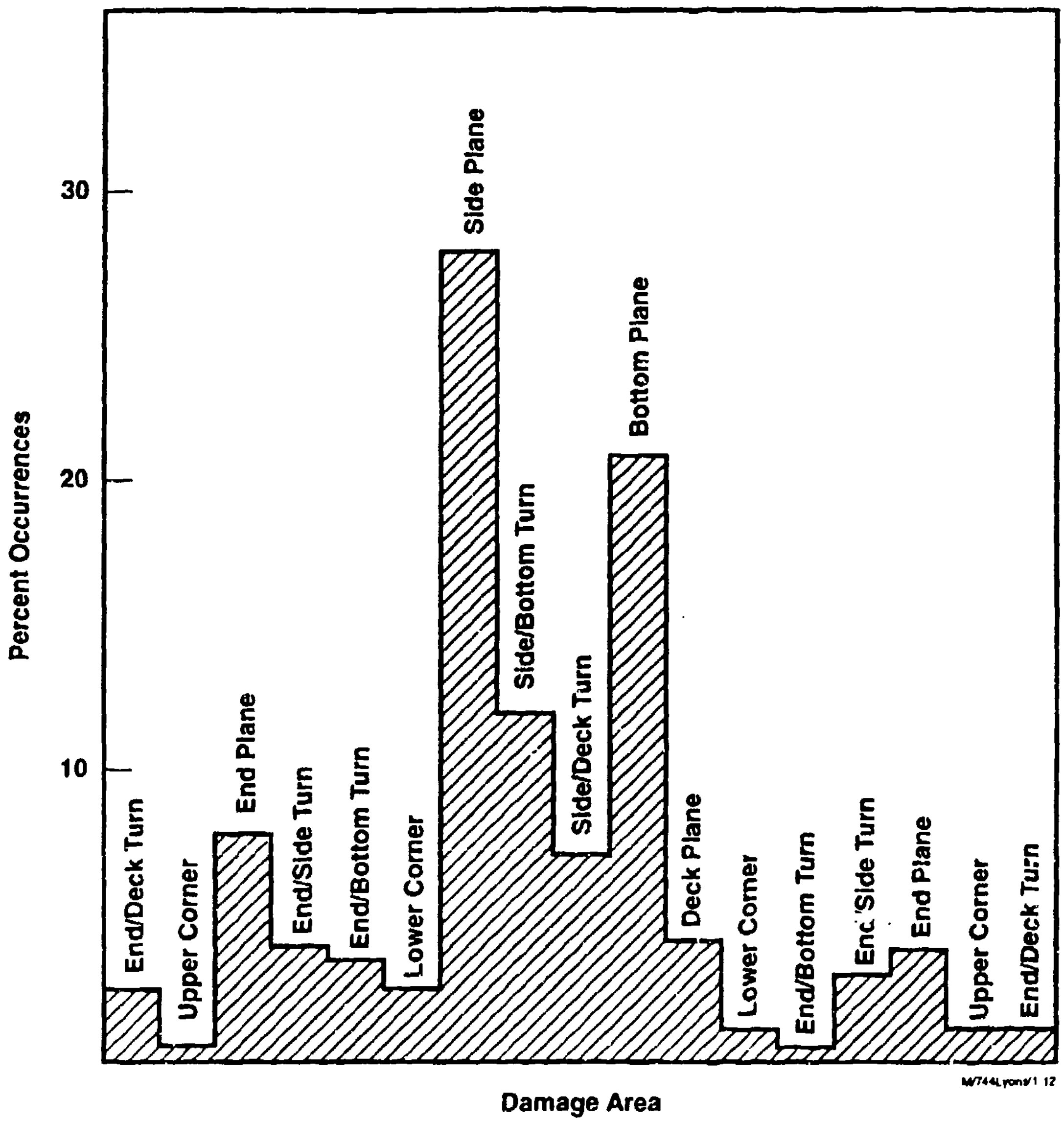


FIGURE 2-7. FREQUENCY OF DAMAGE IN MAJOR BARGE AREAS

concluded from this information that, for large vessels, hydrostatically driven flow will probably not be present during the damage assessment process, but gravity flow or "seepage" conditions will probably exist for those cases where the casualty has resulted in the rupture of a cargo tank.

TABLE 2-5. OIL DISCHARGE CHARACTERIZATION FOR VESSEL COLLISION DAMAGE

VESSEL SIZE	HOLE SIZE	RAPID OUTFLOW	COMPLETE DISCHARGE
(dwt)	(ft^2)	(hr)	(hr)
34,000	2	0.5	17.6
	8	0.16	5.2
89,700	2	1.2	53.5
	8	0.3	13.8
	50	0.05	2.75
225,000	2	4.1	139
	8	0.8	39.8
	50	0.13	7.5

2.3.4 Area Coverage Requirements

Based on analysis of the Coast Guard Standard Operating Procedures (SOPs) and Coast Guard personnel responsible for performing the damage assessment, it is generally necessary to complete a damage assessment and determine a vessel's status within 24 hours of being called to the casualty site. The damage assessment system must be able to provide the area coverage required to ensure that the damage is properly characterized. If it is assumed that the damage inspection system can be transported to the site and readied for use in an 8-hour period, the system will have 16 hours to complete the assessment. If 16 hours ᐧ allotted to completing the inspection, Table 2-6 shows the required area coverage rates for three representative vessels. The coverage rates are based on nominal length, beam, and draft dimensions for vessels of each class analyzed. The coastal barge is assumed to have dimensions of 400 x 70 x 18 feet, the 80,000 dwt tanker is assumed to have dimensions of 728 x 138 x 50 feet, and the 225,000 dwt tanker is assumed to have dimensions of 1094 x 144 x 70 feet.

TABLE 2-6. AREA COVERAGE REQUIREMENTS* (SQUARE FEET PER HOUR)

INSPECTION LOCATION	COASTAL BARGE	80,000 DWT TANKER	225,000 DWT TANKER
Total Vessel	2650	10,820	19,440
Sides Only	900	4,560	9,580
Bottom Only	1725	6, 250	9,855
Bottom and 25% of Sides	1975	7,390	12,250

The table collects the area coverage rates into subcategories of areas that may be inspected singularly (i.e., the bottom only in the case of a grounding on a relatively flat bottom). As noted in the previous discussion of damage location, bottom damage is generally not localized which may necessitate a complete bottom survey. On the other hand, side damage is often localized, (as in the case of vessel ramming), which may significantly reduce the total inspection area requirements. It can be seen from this table that the area coverage varies significantly as a function of the inspection requirements and the size of the vessel. If grounding is assumed to present the worse case area coverage scenario, and it is also assumed that the bottom and 25 percent of the sides must be inspected, then the inspection system should be able to cover 12,250 square feet per hour if the inspection is to be completed in 16 hours.

2.4 Coast Guard Strike Team Casualty Decision Analysis Summary

The Coast Guard Strike Teams go through a decision logic/analysis process when a damage assessment is required. For the purpose of this analysis, response team members are assumed to be Coast Guard Strike Team Members although this is not always the case. The following sequence of events and time frames summarize the likely flow of events that would be experienced during the damage assessment process. The timing and sequencing of events associated with a particular accident will be unique, therefore this listing is provided as an example only.

* Area coverage requirements are based on performing the inspection in 16 hours.

2 Hours After Incident

1. Incident begins with voice call from ship or agent stating:
   a. I am in trouble
   b. I am leaking oil
   c. Location of vessel.

4 Hours After Incident

2. OSC/MSO initiates the following:
   a. Search MSIS for vessel statistics
   b. Identify/locate owner
   c. Send response team to location if accessible
   d. Notify authorities.

6-10 Hours After Incident

3. Response team reports:
   a. Presence of oil in water
   b. Extent of vessel damage
   c. Response being taken by crew
   d. Draft readings.

12-24 Hours After Incident

4. MSO assesses incident based on available information:
   a. Ship's registry
   b. Vessel size and capacity
   c. Verbal narrative of the event
   d. Site review and analysis (i.e., aground, collision)
   e. Verification of location
   f. Identification of responsible parties
   g. Damage extent/size
   h. Damage location
   i. Stability information
   j. Stress concentrations
   k. Cargo amounts and location
   l. Ballast amounts and location
   m. Light ship data (i.e., fuel, water)
   n. Ships power status
   o. Visual ship structural damage
   p. Crew condition
   q. Cargo condition and damage
   r. Vessel and cargo documentation
   s. Draft readings
   t. Trim and list
   u. Tank soundings

5. A decision is made by the OSC regarding what to do with the ship:
   a. Remain as is
   b. Tow to sea
   c. Destroy
   e. Lighten or transfer ballast

2.5 Functional Flow Block Diagram

The Functional Flow Block Diagram (FFBD) (see Appendix A) has been put together from information provided by the Coast Guard describing the kinds of activities, their sequencing, and their relative importance during the early stages of a response to an at-sea oil spill. The purposes of the FFBD are to help the analysts see how the inspection system should be fitted into the overall spill response process and to provide insight into the true needs of the system.

We have used a technique called IDEF modeling to construct a flow-oriented hierarchical decomposition of an U/W Inspection Mission, from the perspective of the Federal On-Scene Coordinator (FOSC). An explanation of the modeling process is provided at the beginning of the Appendix. The following comments address a few of the conclusions which we have drawn from the diagrams.

A quick-response team is usually dispatched to the casualty site very early. If a very small, simple inspection system could be developed for fly-away use by this response crew, there might be significant advantages, perhaps even obviating the need for a larger, more comprehensive system. Generally, unless the inspection system can provide useful information within about 24 hours (in order to provide input for emergency oil outflow control or response action where breakup/sinking may be eminent), most of the time urgency has been dissipated and any subsequent inspection will be focussed more on damage assessment for the purpose of salvage, towing, or dry docking. This dichotomy suggests that rather different design philosophies might be applied for the design of a fly-away quick response inspection system vs. a "time-late" damage assessment system.

The opportunity should not be overlooked for connecting u/w damage assessment images directly, in real time, to shore-based analysis centers where various experts could interpret the raw data directly. For example, a satellite hook-up between the casualty site, the Coast Guard command headquarters, the ship owners, the ship builders, and the spill response parties could, if orchestrated correctly, result in early and correct decisions regarding lightering, counterflooding, firefighting, salvage and towing, and the like.

The handling equipment for the u/w system-whether vehicle, towed body or AUV- may be different than the equipment needed to deploy, position and recover any auxiliary u/w apparatus, such as transponders. For maximum time efficiency, one would not like to have to convert from one to the other many times in the middle of an operation.

The inspection system is presently conceived to be a means of gathering information on the status of the underwater hull damage. But it may be important to include, either on the vehicle, or as an adjunct capability, the ability to perform certain ancillary functions, such as soundings or detailed bottom mapping close to the hull and determining the oil/water/gas levels in tanks.

In planning the logistical support for this equipment, it seems prudent to include provision for the use of the gear for training with Coast Guard spill-response teams.

2.6 Summary of Inspection System Performance Requirements

The information collected from the Coast Guard Survey was melded with data from previous reports, to derive the system performance requirements shown in Table 2-7. Minimum and maximum performance levels are given. The minimum performance level is based on being able to accomplish the mission in the "moderate" operating environment listed in Table 2-1 and on meeting the minimum performance requirement desired by the system user. The maximum performance level is based on being able to accomplish the mission in the "severe" operating environment listed in Table 2-2 and on meeting the maximum performance requirement desired by the system users. It should be noted that in some cases the operating valves have been adjusted to a more stringent level than those found in Tables 2-1 and 2-2 to be consistent with what input from the survey (i.e., current speeds of 3 knots are likely in a severe environment, but does not show up in the averaged valve listed in Table 2-2).

TABLE 2-7. SYSTEM OPERATING REQUIREMENTS

MISSION FACTOR	MINIMUM REQUIREMENT	MAXIMUM REQUIREMENT
Wave Height (H_s)	4.5 ft	9 ft
Current Speed	1 kn	3 kn
Water Visibility	7 ft	3 ft
Wind Speed	11 kn	20 kn
Oil Presence	Surface only	25% oil/water mix
Ice Presence	None	25% cover
Hazardous Threats	None	Toxic chemical/fire
Hole Size (diameter)	10 in	3 in
Crack Length (1/4 in width)	10 in	3 in
Accuracy	± 3 ft	± 1 ft
Inspection Area	Bottom and 25% of Sides (12,250 ft^2/hr)	Complete vessel (19,440 ft^2/hr)
Manning Availability	4 men	2 men

3.0 SUBSYSTEM EVALUATION METHODOLOGY AND TECHNOLOGY OVERVIEWS

The underwater inspection system being investigated here consists of three major elements:

- The underwater delivery platform (i.e., ROV, AUV)
- The navigation subsystem
- The inspection sensor subsystem

This study is involved prir ʰ the assessment of potential implementations of these subsystems and secondarily with npatibility with the support platform and the launch and recovery systems that must be intert. ᴊe inspection system. The subsystems are interrelated and are, themselves, composed of lower level subsystems.

3.1 Multifactor Evaluation Process (MFEP)

3.1.1 Description

System evaluation can be effectively performed using a computer-based, Multi-Factor Evaluation Process (MFEP), for evaluating the proposed damage assessment systems and subsystems. The MFEF has been useful on other projects as a tool for trade-off studies in the early stages of design. It allows for extending the number, richness, and depth of detail of the criteria used in evaluation. It operates on the premise that comparative analyses should be done using numerically measurable quantities, if possible, and that a reasonable consensus may be reached among those charged with the evaluation as to the relative importance of the various categories established for evaluation. Figure 3.1 shows the MFEP that was performed for the underwater vehicle systems (in this case the ROV). The weighting or relative importance of the various primary evaluation levels (i.e., ' ^ Area Coverage Attributes) can be found in the first weighting column (Level 1) designated WT. These primary evaluation categories are further broken oown into subcategories or lower levels which are again weighted as a function of how important their contribution is to the grading of the primary evaluation category. The computer program normalizes the weights such that the "System Level Summary Rating" is scaled between 0 and 1.

U/W VEHICLE DELIVERY SYSTEM: ROV	Levels / Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. AREA COVERAGE ATTRIBUTES		50	175						
1.1. Traverse Rate	kts.		50	0	0.5	1.25	5	H	5
1.2. Max. Endurance	hrs.		50	0	0	16	24	H	24
1.3. Accessibility	-		75	100					
1.3.1. Vertical Areas	%			25	0	85	100	H	100
1.3.2. Horizontal Areas	%			75	0	85	100	H	100
2.0. POSITION KEEPING		75	90						
2.1. Wave Height Effects	ft.		30	0	0	4.5	9	H	4.5
2.2. Current Effects	kts.		60	0	0	2.5	4	H	2
3.0. COMMAND AND CONTROL AND LOGISTICS		75	90						
3.1. Portability and Handling	-		30	0	1	5	9	H	7
3.2. Human Factors Considerations	-		60	0	1	5	9	H	4
4.0. ON-SCENE OPERATIONAL ATTRIBUTES		50	100						
4.1. Launch and Recovery			50	140					
4.1.1. Wave Height Effects	ft.			70	0	4.5	9	H	4.5
4.1.2. Current Effects	kts.			50	0	2.5	4	H	2
4.1.3. Ice Cover Effects	%			20	0	25	75	H	50
4.2. Surface Condition Degradation			50	180					
4.2.1. Ice Coverage Effects	%			30	0	50	75	H	25
4.2.2. Oil Coverage Effects	%			90	0	50	100	H	25
4.2.3. Hazmat/fire Effects	-			60	1	5	9	H	6
5.0. RELATIVE RELIABILITY		50	0		1	5	9	H	8
SYSTEM LEVEL SUMMARY RATING		300							0.61

NOTES:

1.1. Under nominal conditions, and for nominal performance.

1.2. Max. time between Launch and mandated recovery (e.g., maintenance, battery recharge etc.)

1.3. Can conduct satisfactory inspection up to the max. % of specified surface condition.

2.0. System maintains position within acceptable tolerance, up to max. specified level of wave height or current.

3.1. Relative ease of dock side load out, set-up and handling on a wide variety of platforms.

3.2. Relative ease of use of system in terms of simplicity, efficiency, training, inherent safety etc.

4.1. Risk of damage/loss is 10% at the specified level of the effect.

4.2. Performance is degraded by 25% in the coverage specified.

5.0. Engineering estimate of relative reliability of delivery system.

TYPICAL EVALUATION GRAPH

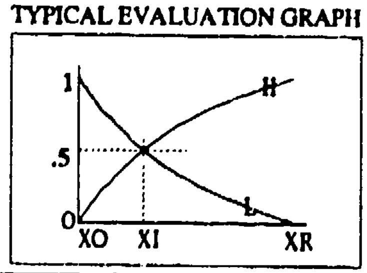


FIGURE 3.1. SAMPLE MFEP EVALUATION

To be effective, the process demands that we establish categories for which a numerical measure can be assessed, either by direct measurement, calculation, or estimation based on consensus of those skilled in the general technology. For each of these secondary categories, four numbers must be preset: a minimum expected value (X0), the maximum expected value (XR), a "point of indifference" (XI), and a weighting number (WT). A "bias" must also be assigned for each parameter, (e.g., "L" means low values are better than high values).

As an example, consider *Current Effects* under *Launch and Recovery* (see Figure 3-2). As indicated in Note 4.1 of Figure 3-1, the current at which the risk of damage or loss to the system during launch or recovery is to be no greater than 10 percent. We might assign the following values to establish the framework against which all candidate systems would be evaluated for this attribute:

- X0 = 0 kn - the lowest value of current of interest
- XR = 4 kn - the highest value of current conceivable for operation
- XI = 2.5 kn - "point of indifference" - if the system can operate at this level, and have a chance of damage/loss no greater than 10 percent, we would judge it "marginally acceptable."

Bias = H for "High" - for this attribute, high scores are best.

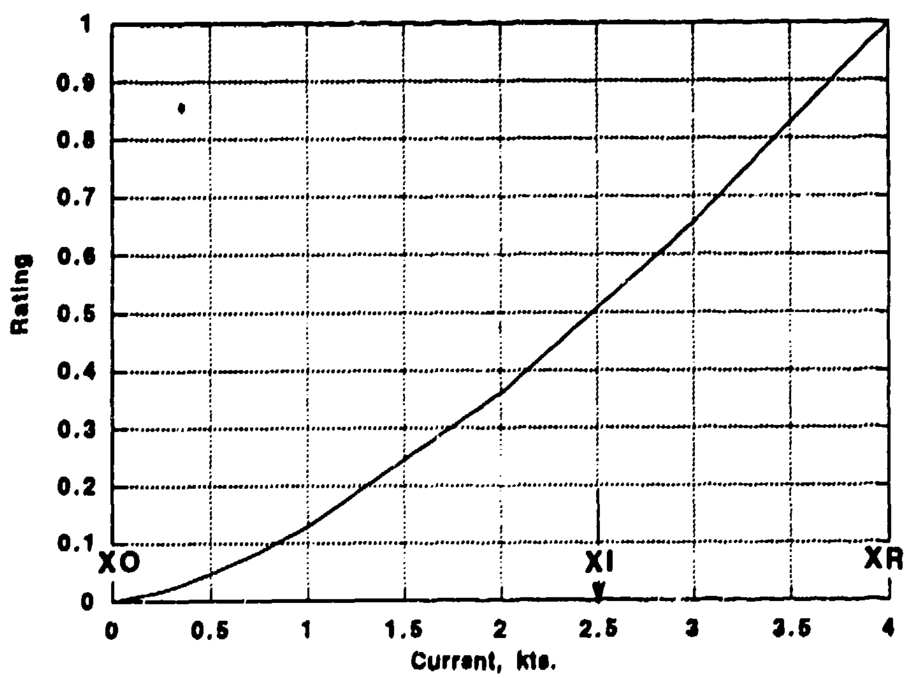


FIGURE 3-2. SAMPLE SCORING CURVE FOR CURRENT EFFECTS

An assumption implicit in the use of MFEP is that the evaluation of each attribute must be made independently of all other such evaluations, i.e., a linearity assumption. As in many engineering problems, such linearity is impossible to guarantee. In particular, the method provides insight into the key differences among the candidates and highlights those attributes which will not be discriminators. It allows for sensitivity analyses to be explored—to envision how capabilities not yet invented might compare with existing systems—and it provides a systematic way of collecting and evaluating the results of more-detailed technical trade studies in a common format.

3.1.2 Critical Factors and Weighting

As explained above, the critical factors are those attributes which capture the most useful information about the systems under study. To be most useful, they should be quantifiable so that relative capabilities can be ranked unambiguously (e.g., a higher search rate for the same resolution should always be preferred). Some important characteristics, such as "ease of use" and "interpretability," may be difficult or impossible to quantify directly. These type of attributes are evaluated on the basis of a scale from 1 to 9, where competing concepts are scored on a purely relative basis.

3.1.3 Performance Rating Curves

The MFEP worksheets used in the evaluation of underwater vehicle and sensor systems, along with the performance rating curves and system scores, are contained in Appendix C. The rating curves and weighting factors were derived from the Coast Guard questionnaire and meetings held with the Coast Guard and Volpe National Transportation Systems Center.

3.2 Vehicle System Overview

The vast differences between underwater vehicles make classification somewhat difficult. The unwritten rules governing the categorization of remotely operated undersea vehicles are based upon operating conditions including power source, propulsion scheme, human intervention, and communication/data links. The designed purpose also is used in categorizing these vehicles. Not surprisingly, characteristics often overlap. In these cases, the vehicles can be categorized as "hybrid" or "specialized" vehicles.

All of the vehicles evaluated herein for the damage assessment of ships are unmanned and remotely operated or autonomous in nature. No vehicles requiring human divers for operation are included in this analysis because the desired scenario is to eliminate placement of divers in the water.

3.2.1 Technology Review

3.2.1.1 Free-Swimming Remotely Operated Vehicles

A free-swimming remotely operated vehicle (ROV) is a submersible controlled from a remote location through a tether. The tether delivers power to the vehicle and allows communications both to and from the vehicle. A surface control console provides an interface between the operator and the vehicle. The control console usually has provisions for monitoring vehicle status information (e.g., depth, heading, faults); contains sonar, video, and other sensor displays; and has hand controllers operating commands to the vehicle (e.g., propulsion, lighting, camera pan and tilt). ROVs are typically propelled by hydraulic or electric motors that drive propellers that generate thrust. The major subsystems generally associated with an ROV system are shown in Figure 3-3. Some method of deployment and retrieval is needed if the system is too heavy to be lifted by one or two people, and a tether management system is generally used to pay tether in and out as required.

The submersible portion of an ROV consists of many subsystems. These subsystems may include structural elements for mounting and protecting system components, thrusters, electric power conversion and distribution networks, microprocessors for command and control, navigation

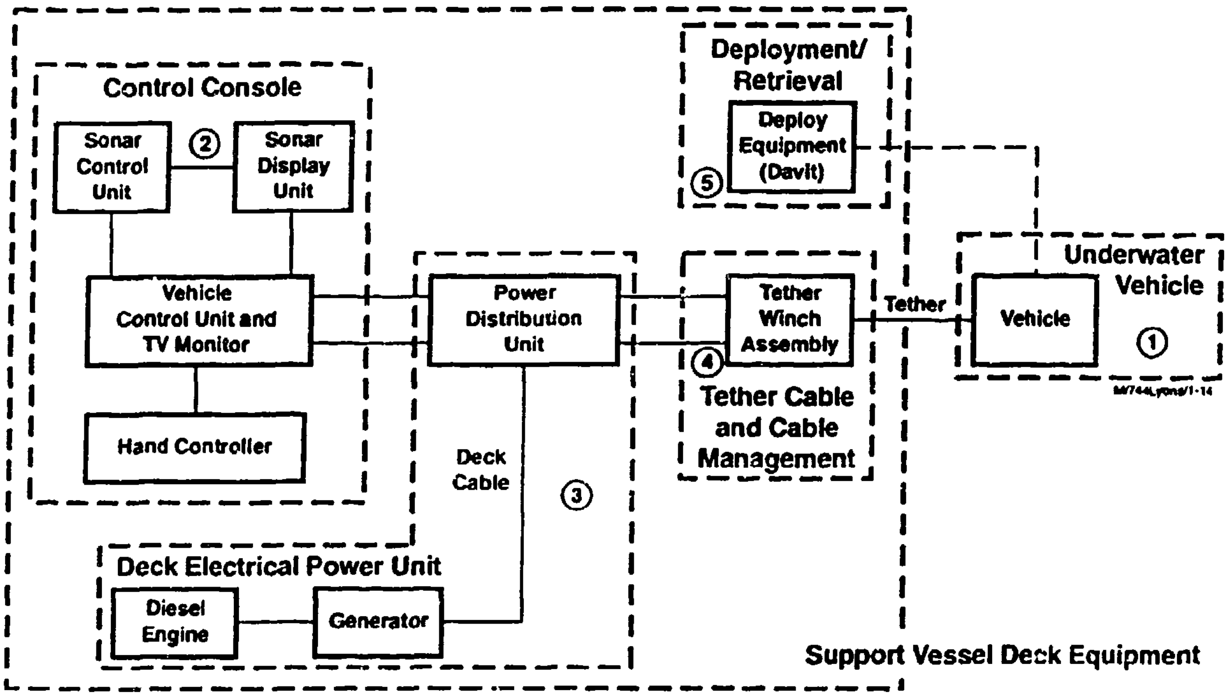


FIGURE 3-3. MAJOR ROV SUBSYSTEMS
(Billet, 1985)

systems, manipulators, and auxiliary sensors and inspection devices. The buoyancy is usually adjusted to make the vehicle a few pounds positive by adding buoyant material such as syntactic foam.

Performance capabilities and designs of ROVs vary widely as a function of the mission requirements that must be met. ROVs are usually designed to have capabilities for carrying out specific tasks such as work, observation, or inspection. Some of the operational variables that have impacts on the system design include depth, current, sea state, level of complexity of a specific work or inspection task, and the local operating environment (e.g., bottom, near structures, water column). Figures 3-4 and 3-5 illustrate two different remotely operated vehicle systems designed to perform subsea tasks. Smaller vehicles that consist of a video camera, small thrusters, and possibly a small, simple manipulator are representative of a class of commercially available systems that are referred to as low-cost ROVs (LCROVs). These vehicles usually have a limited payload capacity and are able to perform only the simplest of tasks. The performance, level of complexity, and cost of an ROV system depends greatly on the functional requirements imposed on the system design. A survey of ROVs is included in Appendix D. Included in this survey are vehicle characteristics, including weight, power requirements, propeller horsepower, maximum speed, and operating depth. The "average" vehicle is approximately 90 x 53 x 47 inches, weighs about 1,000 pounds, and has a depth rating of about 3,000 feet. The principal subsystems of a ROV system are discussed below. Sensors for damage assessment are not addressed here as they will be covered in following sections.

The source of surface-supplied power for an ROV is either the ship's power or a dedicated generator. Electrical power requirements vary significantly, primarily as a function of the designed operating depth and propulsive power requirements of the ROV. The most commonly used power for an ROV system is 220/240 vac at 60 Hz, but their requirements vary widely as seen in Appendix D.

3.2.1.1.1 Propulsion

Thrusters provide positioning capabilities for the ROV. The design and propulsive power output of the thruster is guided by factors such as operating depth, lateral excursion distance, vehicle size, and operating environment (e.g,, high current). Thrusters usually consist of voltage-controlled ac motors, hydraulic motors, or dc motors driving a ducted propeller. Thruster

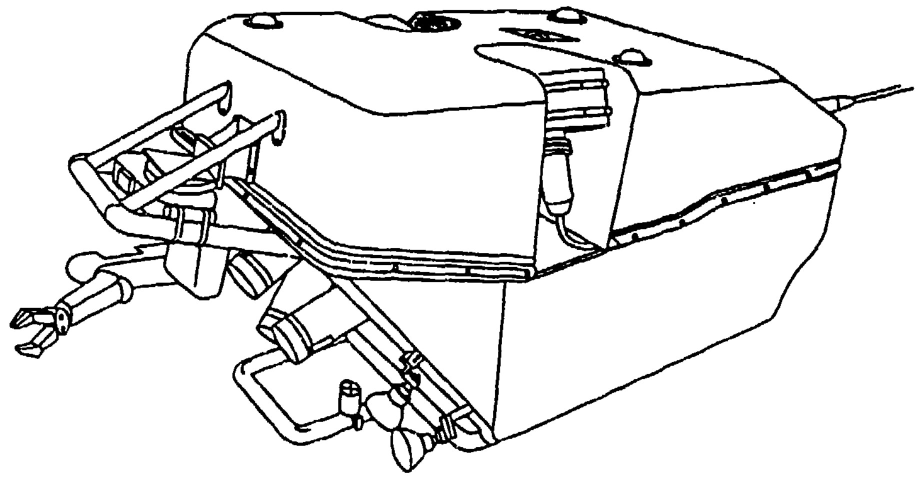


FIGURE 3-4. *JASON* REMOTELY OPERATED VEHICLE

Operating depth	6,000 m (19,680 ft)
Dimensions (l x w x h)	2.1 x 1 x 1 m
Weight in air	1088 kg (2400 lb)
Speed (max surface)	1 kn
Propulsion	7 thrusters
Instrumentation	Side scan sonar, forward
Navigation	Scanning sonar, video cameras, still cameras
	Navigation transducers, manipulator, attitude sensor
	Gyrocompass, magnetic compass
	Pressure sensor, altimeter, long baseline positioning system

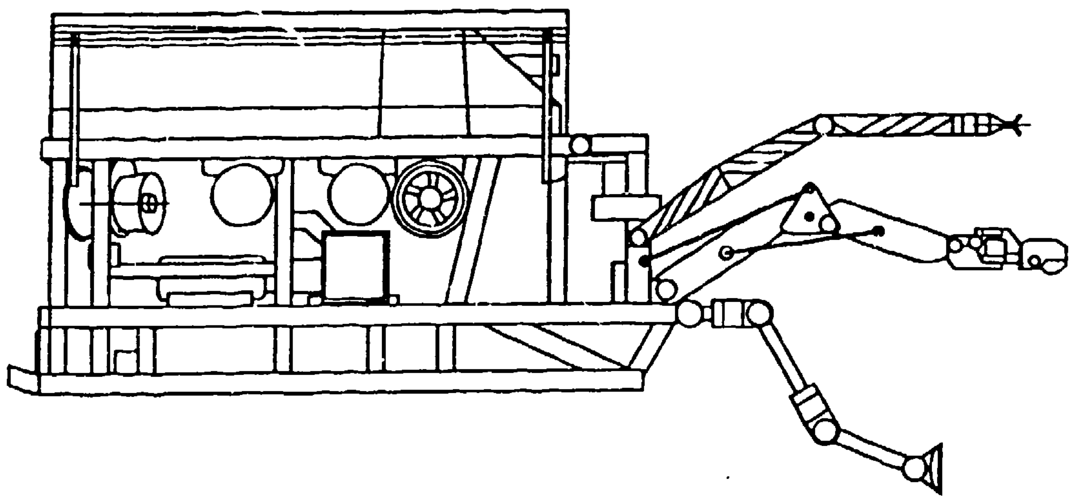


FIGURE 3-5. *CHALLENGER* REMOTELY OPERATED VEHICLE

Operating depth	1525 m (5000 ft)
Dimensions	2.43 x 1.1 x 1.37 m
Weight in air	1450 kg (3200 lb)
Propulsion	Two longitudinal, 1 lateral, 1 vertical thruster - capable of delivering 4201 bf each
Instrumentation	Video camera, forward looking sonar, manipulator
Navigation	Gyrocompass, acoustic transducers

horsepower ranges from fractional for small systems to over 100 hp for large, heavy work systems. Brushless motors are considered to be the current state of the art in drive motor technology. Conventional brushes have been replaced by a rotor position sensor and electronic switching. Efficiency as high as 95 percent is not uncommon, and the arcing and wear problems associated with brushes are eliminated. For deep water applications, a pressure-balanced oil filled (PBOF) housing is desirable to prevent seal wear and leakage of water into the housing, but for shallow water applications a 1-atmosphere housing is adequate to protect the motor. Figure 3-6 depicts a state-of-the-art dc-brushless-motor-powered thruster.

Nearly all free-swimming ROVs have three-dimensional maneuvering capability. The maximum speed is usually between 2 and 3 knots in the forward direction. Many manufacturers report the ability to operate in currents of 1 to 2 knots, but factors such as the amount of tether paid out, tether dimensions and weight, current profile, and vehicle/tether aspect to the current will have significant impacts on operability. For most ROVs, the forward speed exceeds the lateral and vertical speeds due to the difference in the area presented and the propulsive force generated.

Maintaining an ROV's position in even moderate sea states presents a significant operational problem. The surface environment is an area that is generally thought of as being unsuitable for operations. Due to surface swell and the resultant vertical surges, it is usually recommended that the near-surface area be passed through as quickly as possible to reach a safe working depth. A simple analysis of the effects of waves on vehicle positioning was performed to determine if typical vehicles would be able to maintain position in the near-surface environment. The water particle velocities were calculated for increasing depths below the free surface as a function of various sea state conditions. These calculations were carried out for both deep water waves and shallow water waves. For the shallow water wave scenario, a depth of 40 feet was assumed, which is a likely depth of operation for grounding events. The assumed wave conditions for the various sea states are listed in Table 3-1. Figure 3-7 shows the minimum operating depth at which a vehicle capable of a specified velocity can stably operate. For example, a vehicle that has a 1/2-knot maximum speed capability in each of the x,y, and z directions would have to operate 10 feet below the still waterline if positional stability was required in 5-foot seas. Any depth above 10 feet would result in vehicle motion which could not be fully compensated for by thrusters. Most vehicles have lateral (side to side) and vertical speed capabilities of about 1/2-knot, so the 1/2-knot operational curve would apply in most cases since the vehicle would be able to orient itself to make use of its maximum speed (2 to 3 knots) in only one direction. For waves in a shallow-water environment,

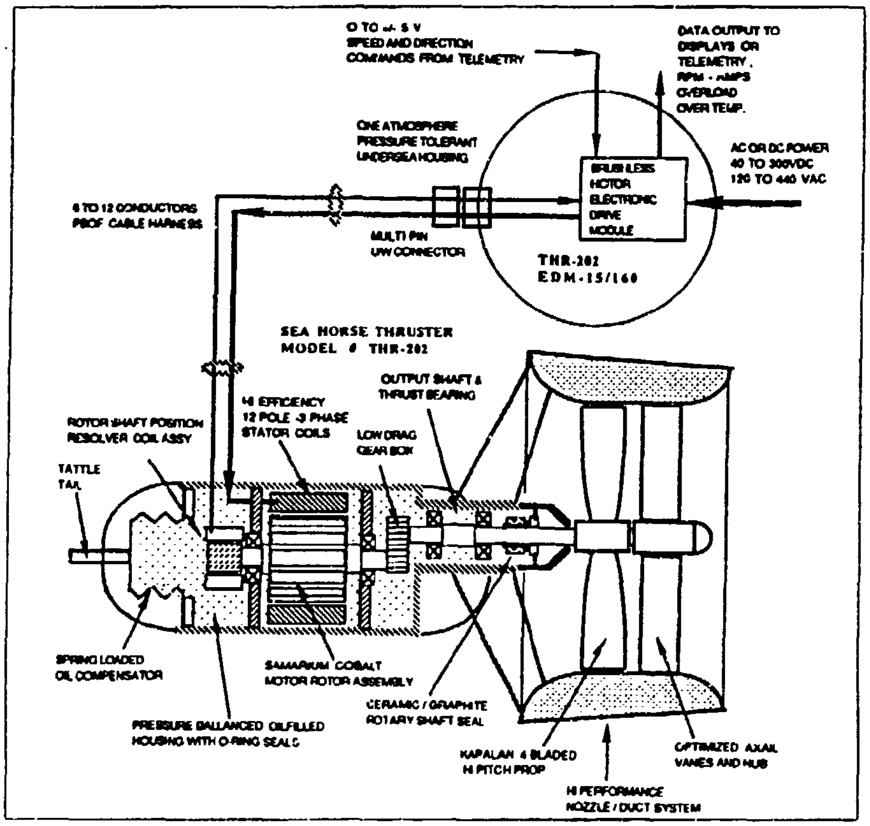


FIGURE 3-6. STATE-OF-THE-ART DC-BRUSHLESS-MOTOR CONFIGURATION
(Deep Sea Systems International, Inc.)

TABLE 3-1. WAVE CHARACTERISTICS FOR VARIOUS SEA STATES

SEA STATE	WAVE HT (H 1/3)	WAVE LENGTH	PERIOD	MINIMUM OPERATING DEPTH (FEET) VS. ROV SPEED CAPABILITY	
		(feet)	(seconds)	1/2 knot	1 knot
2	2.2	25	3	4.03	1.26
3	4.6	52	5	10.32	4.53
4	6.9	79	7	16.35	7.66
5	10	114	8	28.00	15.42
6	18	205	12	56.36	33.71
7	37	422	15	149.26	102.71

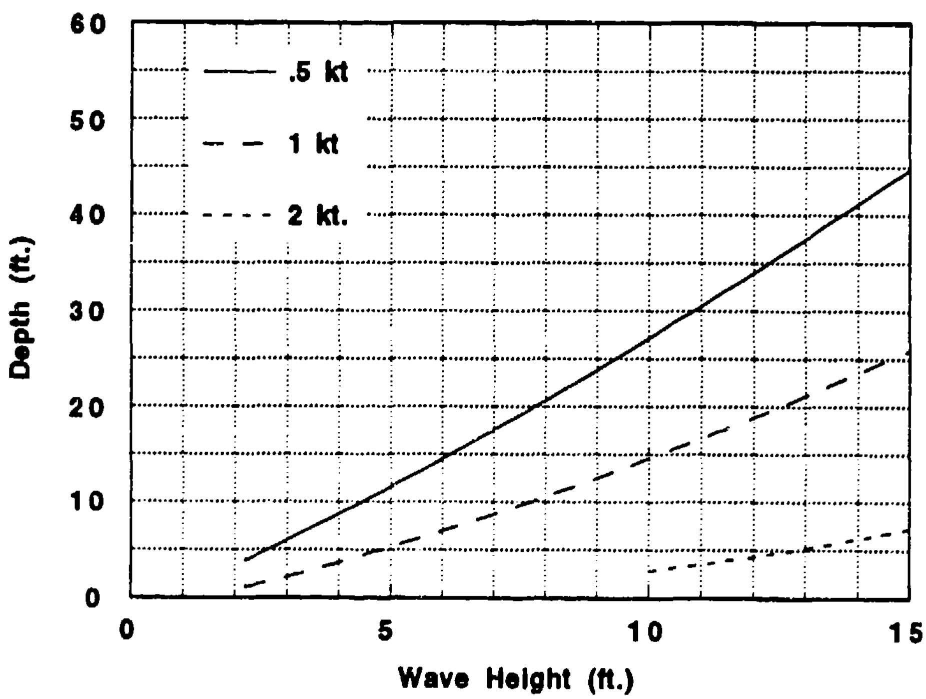


FIGURE 3-7. MINIMUM OPERATING DEPTH FOR VEHICLES WITH GIVEN THREE AXIS SPEED CAPABILITY

the vertical component of water motion decreases as the bottom is approached, but the lateral water motion is greater at a given depth than for an equivalent deep-water wave. Therefore, the ROV has a more limited position-keeping ability in the shallow-water environment than in a deep-water wave of similar characteristics. This analysis did not consider the boundary layer effects on wave motion caused by the presence of the ship itself.

3.2.1.1.2 Navigation

Several navigation techniques and systems are available for underwater vehicles. These include visual sighting, acoustic position location, doppler sonar, inertial navigation systems, and integrated navigation systems. (Often, several navigation subsystems are integrated to enhance navigation capabilities.) The suitability of specific systems often depends on factors such as the particular application, environment, accuracy requirements, water depth, and terrain.

Visual Navigation. Visual navigation is possible if the vehicle is being operated in a known environment with adequate marking (e.g., pipeline field or offshore structure). This technique assumes some degree of underwater visibility along with recognizable features at known locations.

Acoustic Navigation. Acoustic navigational systems can generally be categorized with regard to how the acoustic elements of the system are located. The systems are generally described as either bottom-oriented or surface-oriented; and long-baseline, short-baseline, or ultra-short baseline. The type of navigational system is generally driven by the ROV operational requirements (i.e., positional accuracy, traverse range, depth).

Bottom-oriented systems employ bottom-mounted reference points called acoustic transponders, which simultaneously provide three or more ranges to the vehicle. These ranges are then used to triangulate the position of the ROV in relation to a reference position.

Surface-oriented systems provide position fixes of the submerged vehicle relative to a surface position, generally the surface support ship. The systems are usually able to generate range and bearing information from the fixed surface location to the underwater vehicle.

Long-baseline systems are bottom-oriented systems that require deploying several accurately calibrated transponders on the sea floor. These systems require a large amount of subsea hardware, lengthy calibration, and a skilled operator to produce valid data.

Short-baseline systems consist of a subsea transponder beacon and an array of at least three hydrophones mounted in an orthogonal array on a vessel. ROV position is calculated on the basis of pulse arrival angle and time at the receiving array.

The ultra-short baseline system is the most widely used technology for ROV navigation. A single sub-sea transponder is used in conjunction with a multi-element hydrophone mounted on the support vessel. Arrival time and phase angle are measured for each element of the hydrophone, and this information is used in conjunction with vertical separation information to derive a vehicle's position. Inclinometers are typically included in the system design to account for phase difference errors generated by ship movement.

Dead Reckoning. Underwater vehicles can also be navigated using dead-reckoning techniques. Doppler sonar can be used to measure the speed of a vehicle in relation to a non-moving reference (e.g., a hull or the seafloor). The doppler shift of a signal transmitted at a fixed angle is translated into vehicle motion. Dead-reckoning systems generally contain a heading sensor and a speed sensor. The speed is resolved into the axes of the coordinate system and then integrated to obtain position. One inherent problem with dead-reckoning systems is that small errors in speed or heading cause the positional error to grow linearly with time. The advantage of dead-reckoning is that the system is self-contained and requires no external signals. Accurate measurement of the velocity requires that the beam width in a given direction be as small as possible. Errors of doppler sonar navigation are generated by speed of sound variations, pitch and roll errors, stationary drift (null velocity errors), and transducer misalignment. State-of-the-art commercial doppler navigation systems weigh approximately 60 pounds and have a total volume of 2 cubic feet. The best system accuracy, excluding speed-of-sound errors and attitude bias errors, is 0.25 percent of the distance. The vehicle would therefore accumulate 0.25 feet of positional error for every 100 feet of distance travelled.

Inertial Navigation. Inertial navigation systems double integrate accelerations to produce position. Like a Doppler navigation system, an inertial navigation system is a self-contained unit. The systems that are size compatible with underwater vehicles include the Ring Laser Gyro (RLG), and the Fiber Optic Gyro (FOG). These gyros are inherently rugged, small in size, have fast warmup periods, and have the potential for accuracies that are as good as the best inertial systems currently available. Optical gyros measure the relative path length difference between optical waves propagating in opposite directions (usually around a ring) induced by rotation of the ring about its axis. Error rates for these systems are on the order of 1 percent of the distance travelled (i.e., 1-foot error for 100 feet travelled).

3.2.1.1.3 Command, Control, and Display

Station-keeping refers to an ROV's ability to maintain position at a particular spot in the water column or to maintain a constant altitude or depth as it is traversing from one location to another. The data display and controls required to operate an ROV range from simple to sophisticated. For some LCROVs, the only display present is often a single video image; more-complex systems often display multiple sonar system outputs, multiple video images (including 3D representations), depth, heading, speed, temperature, attitude, leak detection, and hydraulics system status. The complexity of the displays can usually be correlated with the complexity of the task being performed. More-difficult tasks require a higher degree of "telepresence" that allows an operator to more capably perform a task by an improved sense of the working environment.

An ROV's control system may be as simple as a proportional joystick to control heading, forward/reverse movement, and up/down movement. More-complex systems may incorporate proportional joystick controls, automatic heading and depth control, TV pan and tilt, TV camera focus, switching for lights, manipulator controls, and sonar system and camera control. Figure 3-8 is a block diagram of the typical interfacing that occurs between an ROV and the control and display systems.

Enhancing the command and control interface between an operator and the ROV allows increasingly complex tasks to be performed. Supervisory control is a vehicle/manipulator control technique that is increasingly being used to allow carefully controlled, coordinated movements of both vehicle and manipulator systems. Supervisory control allows the operator to issue high-level commands that the vehicle's controlling systems will then carry out. This allows an operator to offload portions of a control task to a computer while maintaining control of the overall system operation. An example of high-level control would be to command the ROV to inspect a ship's hull. The controlling system could be used to maintain the vehicle at a fixed depth, heading, and standoff

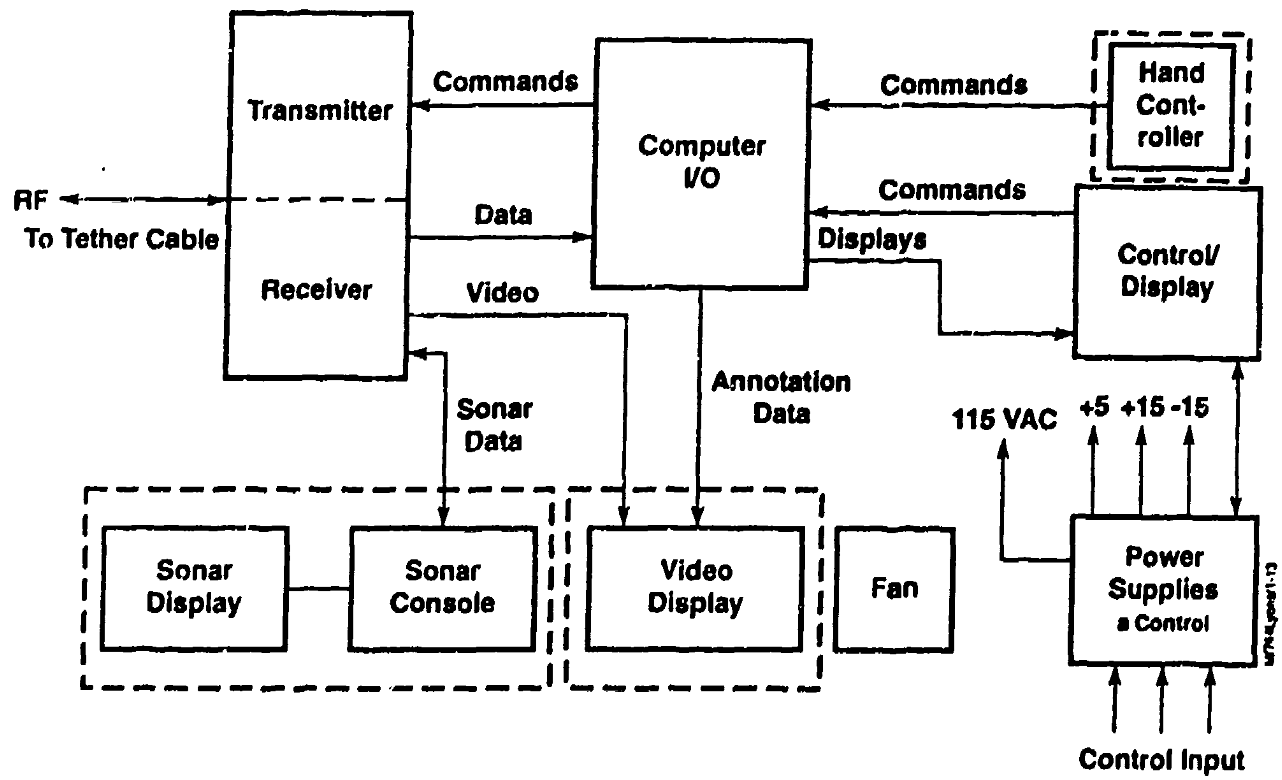


FIGURE 3-8. CONTROL PANEL FUNCTIONAL BLOCK DIAGRAM
(*Billet, 1985*)

while the operator simply controls the traverse speed. An inspection or search task could be greatly simplified by constraining a vehicle's motions so the operator can focus on the inspection rather than vehicle positioning. The overall performance of a system can be improved and otherwise impossible tasks can be performed with the implementation of supervisory control techniques.

3.2.1.1.4 Deck Handling/Tether Management

Deck-handling equipment is required when the vehicle system is too heavy to be manually placed into the water. Tether management systems to pay out and retrieve the vehicle tether as required. Heavy compensation systems may be incorporated into the deck handling equipment if tether loading due to system weight or wave action are significant. The design of deck handling equipment is a function of the vehicle weight, the configuration of the load that must be lifted, and the on-deck mobility required. The configurations for deck handling equipment range from simple davits that are temporarily installed to large A-Frame structures that are fixed in place. Most commonly, a boom is used. To prevent damage to the vehicle if the ship is rolling, the length of the boom is equal to or exceeds the ship's freeboard. Launching over the side is generally preferred to prevent entangling the umbilical with the ship's screws. To minimize loading the umbilical, many vehicles are launched and recovered by a line other than the umbilical. Tether management systems generally consist of powered drum or reel on which the tether is wound and unwound as required. A level wind mechanism is often incorporated into the takeup system design to allow the tether to be wound evenly on the reel. Figure 3-9 illustrates a configuration of deck handling and tether management systems commonly used in ROV operations. Although Sea State 4 is usually considered the safe limit to avoid damaging the vehicle or the launch and recovery system, operations are often carried out in higher sea states.

3.2.1.2 Autonomous Undersea Vehicles (AUV)

Autonomous Undersea Vehicles (AUV) are self-powered and operate without a physical connection to the vehicle operator. Maneuverability is generally three-dimensional, and the data collected is stored on board the vehicle. Untethered vehicles may operate according to a pre-programmed schedule, or they may receive course and depth change commands or data acquisition commands from the surface via an acoustic link. Within the past two years, the U.S. Navy has

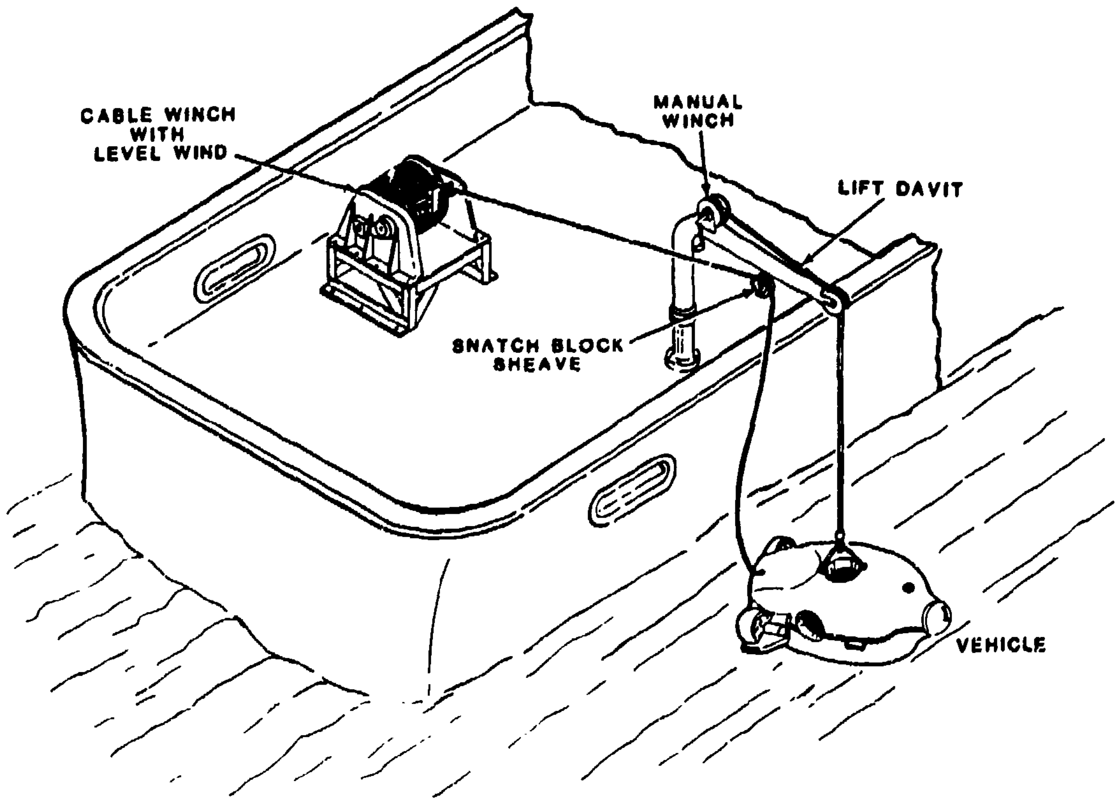


FIGURE 3-9. TYPICAL LAUNCH AND RECOVERY SYSTEM
(*Billet, 1985*)

funded development of several of these vehicles, calling them Untethered, Unmanned Vehicles (UUV). The acronym UUV is often used synonymously with the acronym AUV.

Past and prospective missions for AUVs include oceanographic water column, benthic, and under-ice surveys, inspecting and servicing underwater structures, and a range of fishery and military related applications.

The basic functional systems of AUVs and their surface controls are summarized in Figure 3-10. It is important to note that links are generally acoustic (tetherless), but they may be established through fiber-optic cable, in which case information only (no power) is transmitted to and from the vehicle.

Vehicle size and configuration vary greatly among AUVs, depending on the design goals and application. Despite differences in overall configuration and size, many subsystems are common among AUVs. These include hull shape and structure, propulsion, power generation, emergency backup, control and mission planning, communications, and sensor arrays.

3.2.1.2.1 Hull and Structure

Hull and structure configurations for AUVs vary depending upon application. For example, vehicle weights range from 20 pounds to 140 tons. In general, AUVs used for inspection are equal in size to or larger than ROVs designed for the same purpose. AUVs are larger because they must carry their own energy source, usually batteries. AUV characteristics for systems either designed or being built are summarized in Appendix D.

Most AUVs have a sleek, stream-lined outer shell, often made of composite materials. The design goal is to achieve laminar flow over the length of the vehicle. This torpedo shape results from the fact that self-contained energy sources are relatively bulky and inefficient. As a result, a low hydrodynamic drag coefficient will minimize the power loss for propulsion, which translates into extended mission times. One problem associated with the torpedo body style is that the vehicle is essentially unidirectional. Cross currents could make hovering very difficult for an AUV near the side of a ship. Depending on sensor mounting, it may be necessary for the vehicle to maintain position at an angle not parallel to the current in order to take accurate measurements, readings, or pictures.

Beneath the outer fairing, is a structural steel or aluminum frame that provides support and mounting for the subsystems. Some vehicles, especially testbeds (those used for subsystem

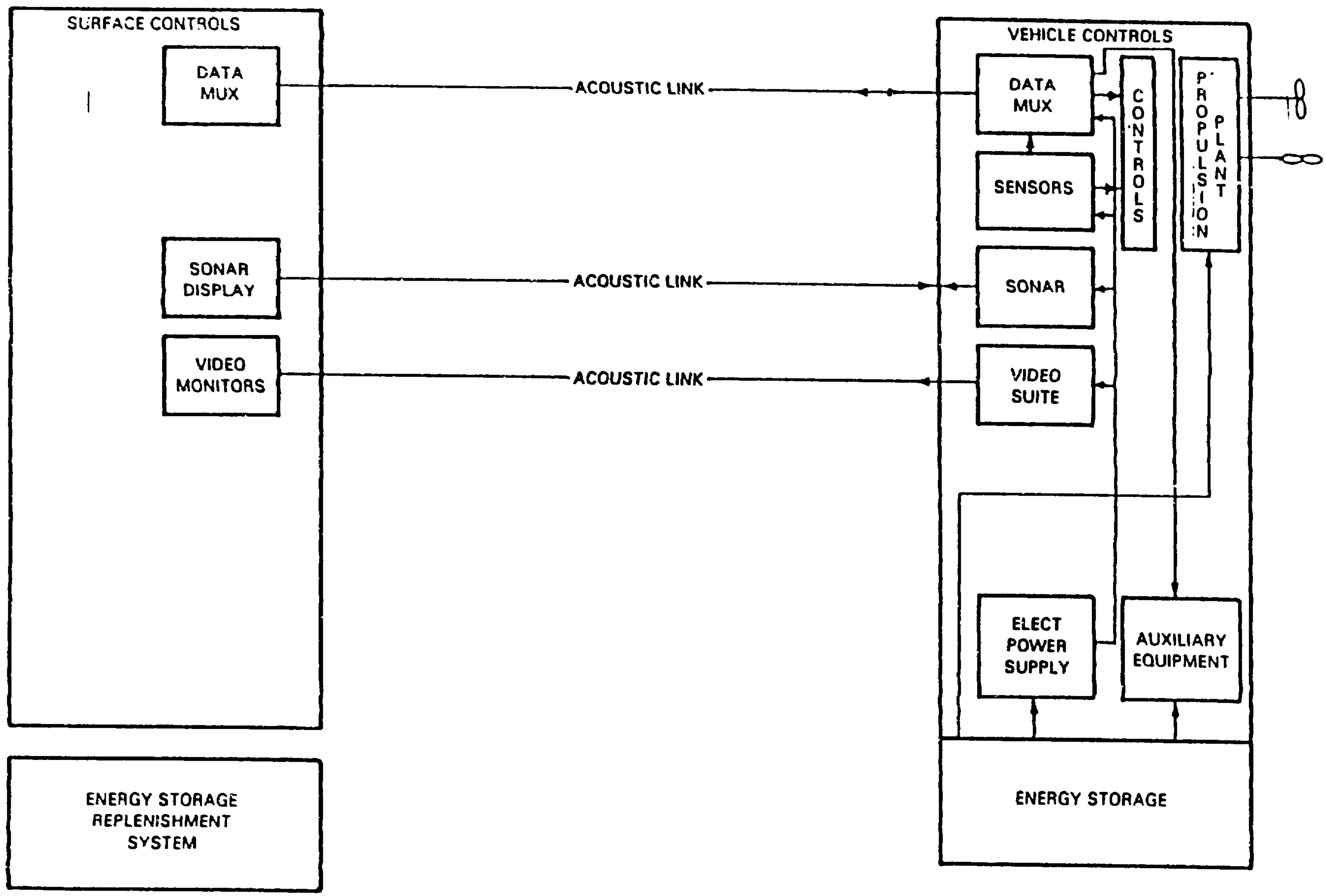


FIGURE 3-10. UNTETHERED ROV SYSTEM FUNCTIONAL DIAGRAM
(G.M. Stenovec, 1985)

testing rather than for single purpose missions), tend to be modular in construction. Center sections can be added or removed to accommodate larger payloads. AUVs not intended for long distance travel typically do not incorporate the hydrodynamic shells.

Parts of the vessel remain watertight while the rest of the vehicle is free-flooded. The batteries, payload, and electronics are typically subsystems that are kept dry at all times. The dry sections or pressure housings vary in size and construction from vehicle to vehicle. One vehicle, the ***Odyssey***, shown in Figure 3-11, incorporates three 17 inch diameter glass spheres that have been pressure tested to 21,980 feet. They are actually a pair of matching hemispheres with mating edges ground to a close tolerance.

3.2.1.2.2 Propulsion Systems

Multiple thrusters or channelled props are almost the exclusive means of propulsion for swimming AUVs. More than 95 percent of the AUVs investigated used either single or multiple props or thrusters. These are generally driven by brushless dc motors. In fact, the greatest factor governing mission duration is the vehicle speed and water currents. High water currents significantly reduce the mission duration of AUVs because more propulsion energy must be used to maintain position.

3.2.1.2.3 Power Generating Systems

Although anaerobic engines and fuel cells are proposed sources of power for future AUV applications, the most common form of power supply for AUVs is onboard batteries. Batteries are the most logical choice for AUV power because the vehicle must be self contained and operate continuously underwater. Currently, several different types of batteries are used. They include lead acid, silver-zinc, lithium, and other chemical types. Their frequency of use in AUVs is roughly 40, 20, 10 percent for lead acid, silver-zinc, and lithium batteries, respectively. Engineering tradeoffs

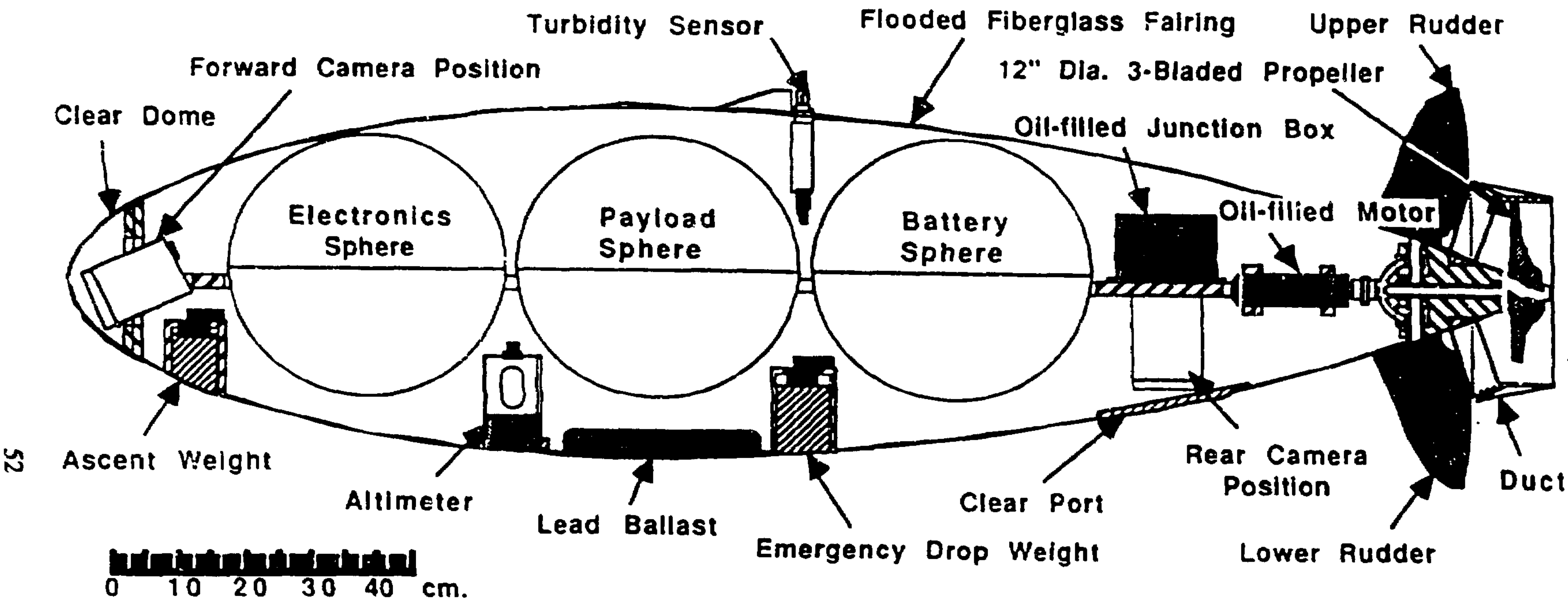


FIGURE 3-11. GENERAL ARRANGEMENT OF *ODYSSEY*
(J.G. Bellingham et. al., 1992)

must be made during battery selection. One tradeoff is the required mission duration, which is a function of the power requirements of the vehicle subsystems. The main battery specification that dictates endurance vs. size and weight is known as the "energy density."

In practice, the choice of battery technology depends on the specific circumstances of the mission. Criteria for selecting battery systems include not only the critical issue of energy density, but also such considerations as power density, safety of operation, and economy of use. Figures 3-12 and 3-13 display some of the characteristics of battery types and a typical AUV application. Note that for a given chemistry of battery, the energy density is a function of discharge rate. This effect is especially pronounced with alkaline batteries.

3.2.1.2.4 Emergency Systems

Depending upon the mission, operating an AUV carries a relatively high risk of vehicle loss. Two possible failure modes are: (1) the vehicle's navigation system may fail, resulting in the vehicle's surfacing miles from the expected recovery point, and (2) power failure may occur and the vehicle may never surface. Several vehicles are equipped with pingers. Pingers provide a direction for the recovery vessel to head to locate the surfaced AUV.

Because most vehicles are slightly positively buoyant, a certain amount of power is required to keep them below surface level, and they will automatically float to the surface upon total power loss. Some vehicles incorporate drop weights to maintain neutral buoyancy. These weights are automatically released upon power outage to make the vehicle positively buoyant and allow it to float to the surface (e.g., *Odyssey*). In addition, backup emergency power supplies are not uncommon.

3.2.1.2.5 Control/Programming

Because AUVs have low data transmission rates, real-time control in not permissible. As a result, the vehicle has to have a high level of onboard intelligence, including built-in obstacle avoidance and emergency situation control programs. The vehicle must also be able to follow a preplanned mission that describes not only intended travel path but also the corresponding depths and the types of information to be gathered. It is also expected that the intelligent vehicle should be able to "understand" images as well as to learn from previous experiences.

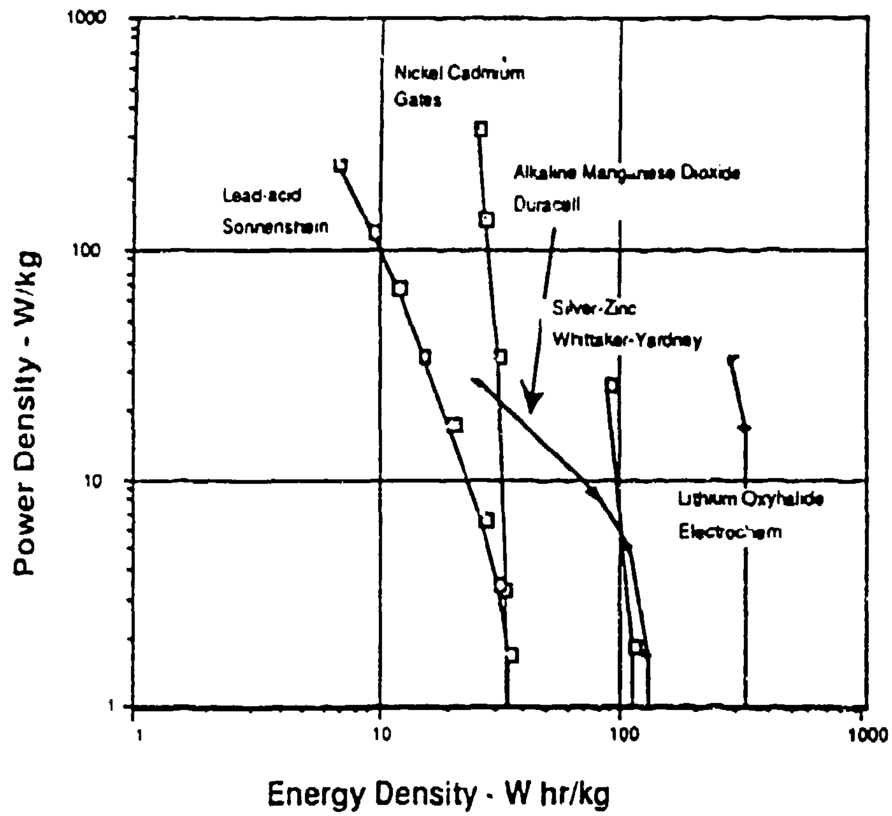


FIGURE 3-12. POWER DENSITY AS A FUNCTION OF ENERGY DENSITY FOR VARIOUS BATTERY CHEMISTRIES
(J.G. Bellingham, et. al., 1992)

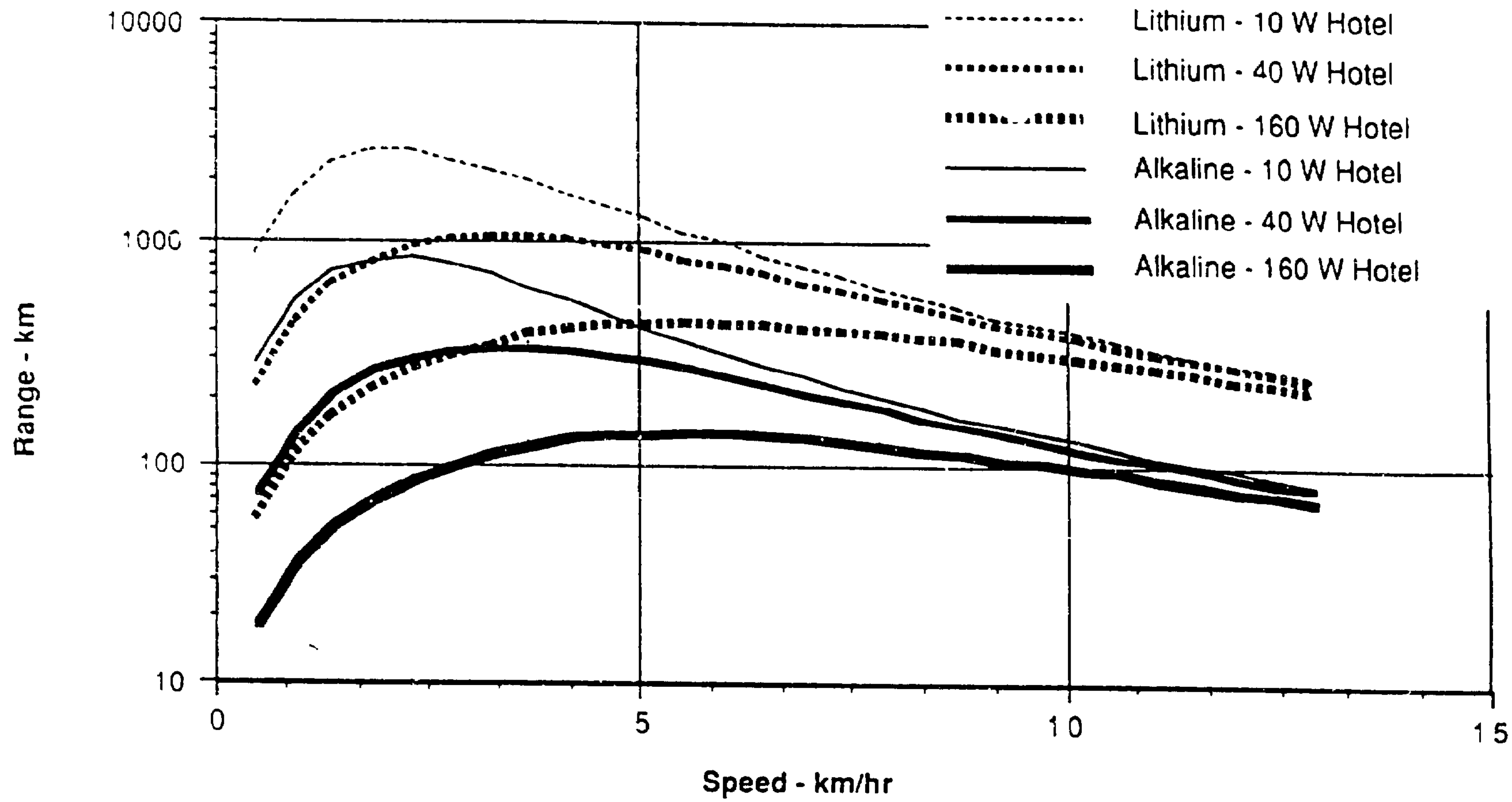


FIGURE 3-13. RANGE AS A FUNCTION OF SPEED FOR DIFFERENT HOTEL LOADS FOR *ODYSSEY* FOR 50 KG OF ALKALINE-MANGANESE DIOXIDE BATTERIES AND LITHIUM BATTERIES
(J.G. Bellingham, et. al., 1992)

AUV designers have taken several approaches to creating this artificial intelligence. The various programming architectures and control approaches include blackboard, knowledge-based, situation, sliding, layered, and neural networks. All of these variations have their strengths and weaknesses suited to AUV, but virtually all have the same purpose: to gather, interpret, record inputs from the various sensors, make necessary decisions, and send the correct stimulus to the thrusters and other output devices. The goal is to accomplish this in the shortest amount of time with the least amount of mission preplanning. One additional problem that must be addressed is upgrading or adding new sensors. The system must be able to adapt to these changes without total reprogramming.

Several of the approaches attempt to teach the AUV several situations. Various sensors can be used to recognize the characteristics of a known situation, and the AUV can respond with the best suitable sensor outputs. Others, such as the layered control architecture, address the functions of the vehicle hierarchically. For example, obstacle avoidance would be the lowest level, or have the highest priority. A higher-level layer would follow the mission path. If a conflict arises, the lower level would take over. This prevents two simultaneous situations from trying to move the vehicle in opposite directions at the same time. New layers can be added without modifying the existing layers. Figures 3-14 and 3-15 show the basic strategies of AUV control and layer control hierarchy.

The application of autonomous control to ship damage assessment might be as follows, with the goal-oriented behaviors programmed into the vehicle intelligence:

- Find the wall with sonar, and approach it to inspection distance
- Move along the wall (right or left) while maintaining separation
- Descend/ascend while facing the wall and maintaining separation
- Hold position relative to wall.

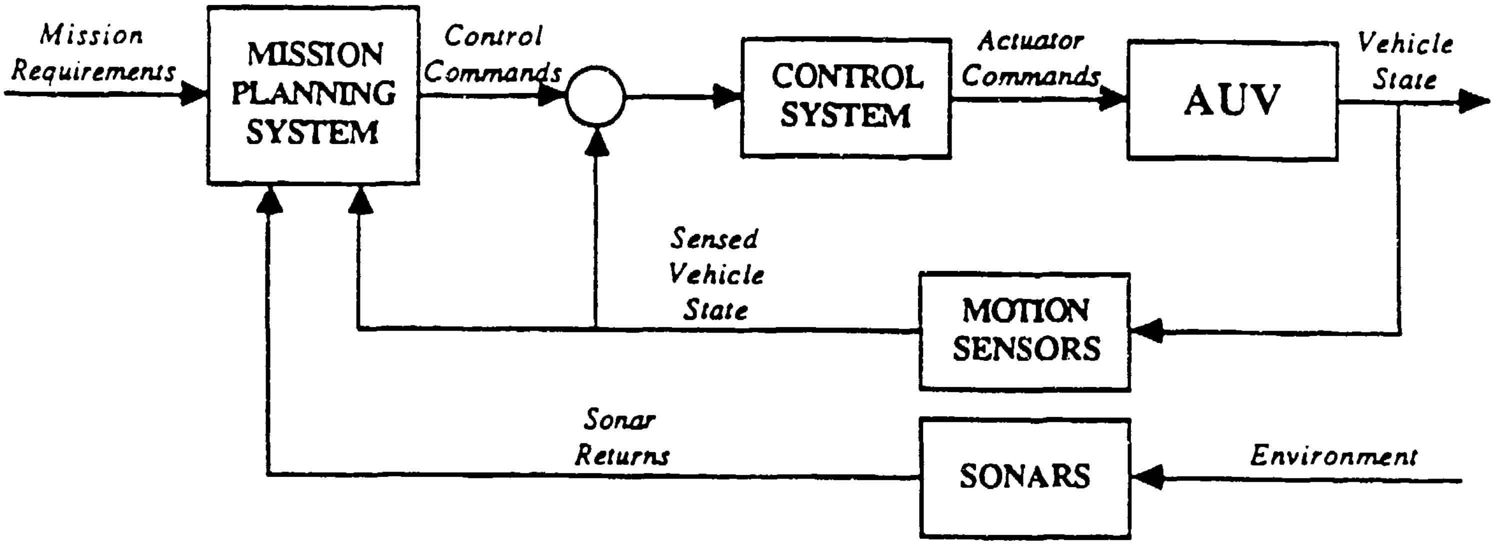


FIGURE 3-14. FUNCTIONAL CONTROL BLOCK DIAGRAM FOR AUV
(J. Loch, et. al., 1989)

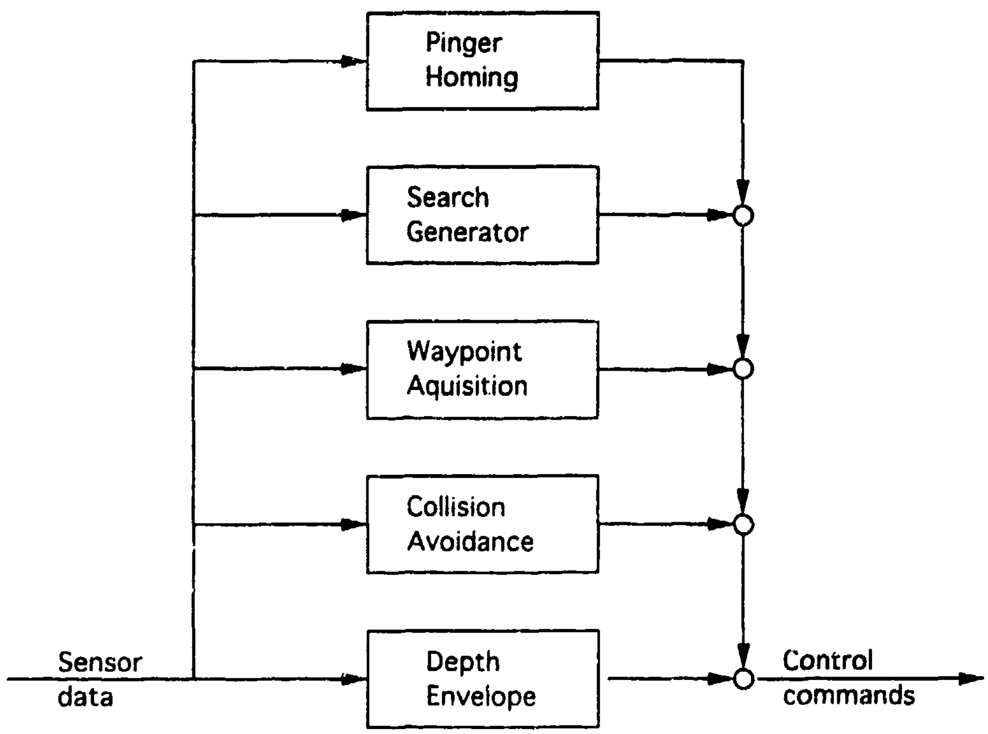


FIGURE 3-15. EXAMPLE OF AUV LAYERED CONTROL HIERARCHY
(J.G. Bellingham, T.R. Consi, 1990)

Drawing from this simple pool of behaviors, an operator could concentrate on the inspection while the vehicle could handle the piloting and navigation functions.

As explained, AUVs are typically information gatherers. This information is often stored on magnetic tape or within the computer's memory for later retrieval and analysis. Optical disks results in much more compact storage.

3.2.1.2.6 Communications

By definition, an autonomous vehicle does not communicate with the "control station" while in operation. Most vehicles record data or collect samples from the mission; information is gathered only upon completion of the mission. In practice, some amount of communication takes place during the mission. This permits the operator/monitor to change the preplanned course if needed.

Establishing a bi-directional communication channel between an AUV and an operator provides four important capabilities for vehicle operations:

1. Mission data can be recovered and evaluated in near real-time.
2. Performance and condition of the vehicle can be monitored.
3. Mission profiles can be modified to respond to new data or to changes in the vehicle condition.
4. Information relevant to vehicle operations can be obtained by the operator and can be communicated to the vehicle.

It has long been recognized that the acoustic channel is the only feasible alternative for underwater communications over any appreciable distances. The severe attenuation of electromagnetic energy propagating through water forces the use of acoustic methods, yet working with the acoustic channel has proven to be difficult.

At present, acoustic communication systems are commercially available with capabilities attractive for AUV operations. However, the relatively low bandwidth of acoustic communication technology (usually less than 5,000 bits/second over several kilometers), coupled with the time delay intrinsic in acoustic propagation, prevent more immediate control in the style of an ROV. The roundtrip communication delay (about 1.3 seconds for every kilometer of separation) prevent an operator from responding instantaneously to urgent circumstances, such as an impending collision. Real-time control of the vehicle will, therefore, be the domain of the onboard computer system, while the human operator will command the vehicle in a supervisory fashion.

Low data transmission rate is the major shortcoming of acoustic communication links compared with radio frequencies. Two reasons are responsible for the lower transmission rates. First, the carrier frequency is relatively low (i.e., 3000 Hz for acoustic vs. 100 MHz for radio). Information is typically encoded into the carrier frequency by either amplitude modulation or frequency modulation. Upon receiving the encoded signal, the useful information must be extracted. This extraction process filters out the lower frequency information. As a result, not as much information can be "loaded" into the lower acoustic carrier frequency per unit time. The second reason is transmission rate in the medium. The speed of sound through water is significantly slower than the speed of electromagnetic radiation in air, as in the case of radio transmissions. The result is that it takes much longer to send the same amount of information in water than it does in air.

Video requires a relatively large amount of data transmission for imaging purposes. Current acoustic data transmission rates are on the order of 1200 bits/second. Acoustic transmission rates of 5000 bits/second are currently being developed and it is foreseeable that future systems will be able to transmit and receive data on the order of 20,000 bits/second. The 1200 bit/second system used on the AUVS Vehicle is able to produce and transmit a high resolution black and white image via acoustic link every 90 seconds.

Despite the title of Autonomous (Untethered) Unmanned Vehicles, several of these vehicles have the ability to operate with a single fiber optic cable link to the mother ship for fast and accurate data/video transmission. Unlike an ROV, this type of umbilical is not used to supply power to the vehicle. As a result, the umbilical is typically smaller in size, hence minimizing the effects of hydrodynamic drag on the vehicle.

3.2.1.2.7 Instrumentation

AUVs incorporate a wide range of instrumentation, depending on the specific mission requirements. Each AUV sensor array is different, but many sensors are common to most AUVs.

They include:

TV cameras
Still cameras
Lights
Echo sounders
Inclinometer (pitch/roll) sensors
Depth (pressure) gages
Sonar (side scan, forward look, down look)
Laser (optical) vision systems
Temperature sensors
Force, vibration, and strain gages
Compasses
Rate gyroscopes
Magnetometers
Transponders, pingers
Altitude sensors
Velocimeter
Salinity sensors
Hydrophones
Various power tools
Manipulators

The number and type of sensors are mission-specific. The only sensors required by AUVs are those used for navigation and obstacle avoidance.

One of the most important functions on an AUV is navigation. If the navigation system were to fail, the mission would likely fail also. In addition, after a 6-hour mission, the vehicle may surface miles away from its intended location, making retrieval difficult and untimely if not impossible. The navigation schemes that can be implemented on AUV platforms are similar to those used on ROVs discussed in previous sections.

In the near future, researchers plan to fit the AUV (Sea Squirt) with either temperature or chemical sensors. They will then have the AUV follow a temperature or chemical gradient to its source. The ability to locate the source of a chemical gradient would allow the AUV to automatically locate the source of an oil leak (e.g., hull damage) on a ship. Thus need to hunt for the source would be eliminated.

3.2.1.2.8 Deployment and Recovery

Deployment methods for AUVs are highly vehicle-specific depending mainly on the size of the vehicle. The massive size of some AUVs makes launch and recovery possible only from a specially designed vessel. One example is the MUST vehicle, which weighs 19,500 pounds. Launching the MUST takes about 10 minutes, while recovery takes approximately 30 minutes. In contrast, SEA SQUIRT weighs only 62 pounds and can be lowered into the water by one man. Most AUVs have some sort of preferred launch and recovery system, often including a winch and loading ramp or an over-deck hoist.

3.2.1.2.9 Summary

Existing needs and availability will undoubtedly spur further applications for small, low-cost AUVs. Continuous pollution monitoring of lakes, rivers, estuaries, and bays will be possible with such vehicles. Fleets of affordable vehicles could be deployed to track and observe a variety of extended phenomena in the open ocean, such as algal blooms, chemical plumes caused by undersea vents, and deep ocean vortices. AUVs could provide oceanographers with a synoptic view of the ocean below its surface. There is a need for additional advancements in intelligent system concepts, sensors, three-dimensional imaging, map building, and integrated sensing and control. Power systems, control and vehicle dynamics, and system architecture have evolved to the point where they are capable of supporting limited AUV applications, but they cannot be considered mature.

The practicality of using AUVs for damage assessment and hull inspection should be closely analyzed. The AUV, tetherless and self-powered with basic decision-making abilities, appears very attractive. The reliability, maintainability, and cost of AUVs designed for use as a damage assessment system are not available since most existing AUVs are either in conceptual stages of design or are single prototype systems. AUVs have much to offer industry and military users, but the technologies require advancement for use in damage assessment, especially in the area of increased data transmission to provide the operator with an improved sense of telepresence. Relatively low acoustic transmission rates will significantly reduce the allowable traverse rate if a complete hull inspection is required. The specifications and layout for two representative vehicles are included in Tables 3-2 and 3-3, and in Figures 3-16 and 3-17.

TABLE 3-2. *SEA SQUIRT* OPERATING SPECIFICATIONS

Vehicle Name	SEA SQUIRT
Classification	AUV (autonomous, untethered ROV)
Manufacturer	MIT Sea Grant and Draper Laboratory Cambridge, Massachusetts, USA
Design Purpose	Testbed for autonomous vehicles
Size (LxDia.)	2.82' x 0.72'
Weight in air	62 lbs
Operating Speed	2 - 3 knots
Buoyancy Control	Vertical thruster is used to change or maintain depth
Structure	Cylindrical shaped vessel with two protruding side-mounted thrusters
Power Requirements	Ag-Zn batteries, 16 amp-hrs at 24V, with ten hour duration envisioned depending on thruster consumption.
Propulsion	Three DC brush type thrusters, two side mounted for forward thrust and one through-hull for vertical thrust. Each thruster develops a static thrust of approximately 6.6 lbs.
Instrumentation	Fluxgate compass, pressure transducer, Datamarine LX-50 speed transducer, pitch/roll sensor, yaw rate gyro, Datamarine LX-100 depth sounder. A Mesotech 807 sonar is used for obstacle avoidance.
Navigation	Compass and an acoustic positioning system.
Shipboard Components	Personal computer and tether (to load software)
Operating/Maintenance Crew	One
Status	Currently undergoing a test program.

TABLE 3-3. XP-21 OPERATING SPECIFICATIONS

Vehicle Name	XP-21
Classification	AUV (autonomous, untethered ROV)
Manufacturer	Applied Remote Technologies San Diego, CA USA
Design Purpose	To provide a modular undersea platform for rapid prototyping, test, and demonstration of new AUV and ROV concepts.
Size (LxDia.)	16' x 21"
Weight in air	1200 lbs
Operating Speed	0 - 5 knots
Buoyancy Control	Depth is dynamically controlled by elevators. Payload is 250-400 lbs depending on modular configuration.
Structure	Torpedo-sized vehicle for compatibility with existing handling equipment. Modular design allow addition of center sections increasing overall length up to 28.4 ft.
Power Requirements	Two 120 VDC lead acid battery packs (total weight of 564 lbs). Mission duration up to 12 hours depending on thruster requirements (speed).
Propulsion	Two stern-mounted thrusters and two lateral thrusters (one forward, one aft).
Instrumentation	Fitted for each mission. Typically include fiber optic cable acoustic sensor array, optical sensors, magnetic sensors, laser doppler systems, etc..
Navigation	Provided for specific missions. Typically are sonar based transponders, pingers, and doppler systems which permit the vehicle to hover (position) relative to ocean floor or any large flat surface.
Shipboard Components	To fit mission requirements.
Operating/Maintenance Crew	Unknown
Status	Operational, launched 1988

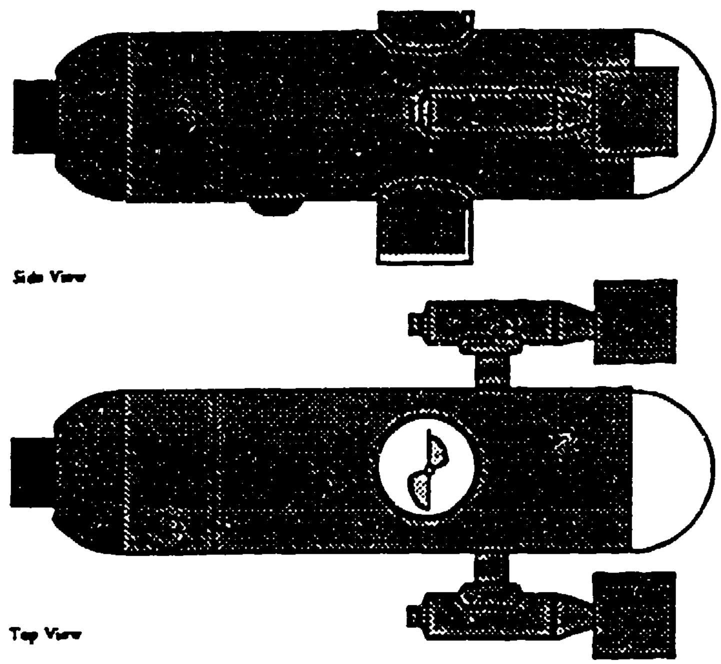


FIGURE 3-16. TYPICAL SMALL AUV CONFIGURATION (*SEA SQUIRT*) (*MIT Sea Grant*)

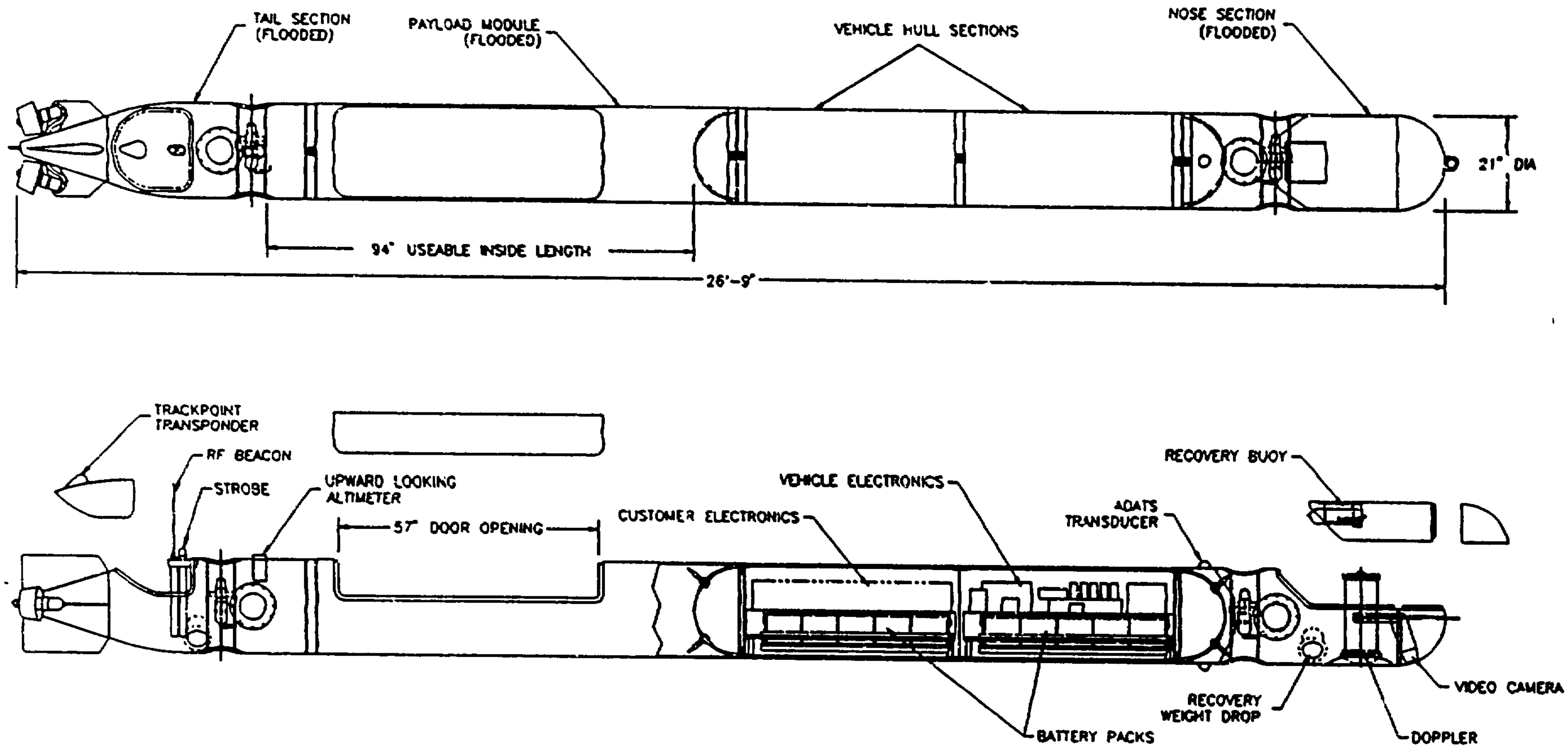


FIGURE 3-17. *XP-21B* OPERATING CONFIGURATION (APPLIED REMOTE TECHNOLOGY)

3.2.1.3 Towed Vehicles

Towed vehicles are generally pulled by a ship or other surface vehicle via a cable. Lateral and/or vertical motion is typically achieved by use of rudder fins or powered thrusters. The depth of tow is also a classification boundary. Vehicles are labeled mid-water or bottom based upon their configuration and application. The scope of this paper discusses only mid-water towed vehicles due to the anticipated application to ship hull inspection. Generally, bottom towed vehicles are those used for pipeline/cable operations on the ocean floor. The enormous size of these vehicles (several tons negatively buoyant) would create considerable problems for transportation and deployment.

Mid-water towed vehicles are propelled and are generally powered by a surface ship via a cable. TV cameras (real-time or slow-scan) and still photography cameras are generally carried. Mid-water towed vehicles are designed to operate in the water column, but they may have the capability to make contact with the bottom for sampling purposes. This type of system usually consists of a submersible vehicle, tow cable and umbilical, handling system, winch, and control/display station. The inclusion of video capabilities generally differentiates these systems from the multitude of towed instrument packages.

Construction of the vehicle is either open metallic framework or closed fairing for reduced hydrodynamic drag. The average vehicle weight is about 3,000 pounds. Depth capabilities range from 650 feet to 20,000 feet. Towing speed ranges up to 14 knots, but this is highly dependent on mission requirements. Slower speeds are used when towing close to the bottom. Typical vehicle power requirements are 60 Hz, 115 Vac.

The umbilical is usually electromechanical, providing the vehicle with power, a data link to the control station, and the tow cable connection to the surface ship for vehicle propulsion. These systems have very limited maneuverability. The vehicle, itself, generally has no propulsive devises, although some systems may incorporate techniques which allow limited positioning capabilities (e.g., rudders to establish offset with the tow ship).

Typical instrumentation often includes some combination of the following: CCTV, still camera, sub-bottom profiler, side-scan sonar, obstacle avoidance sonar, directional hydrophone, nephelometer, conductivity meter, temperature and depth sensors, vehicle altitude indicator, sound velocimeter. Some vehicles are incorporating advanced transponder systems for precise navigation, as well as feedback loops from the obstacle avoidance sonar in order to lessen the probability of vehicle damage by collision.

Towed ROVs are generally employed in bottom search or survey-type missions. Several systems are used by the industrial sector in assessing seafloor mineral deposits. Military tasks include search and identification of objects on the bottom, *in situ* monitoring of munitions and hazardous material dumps, bottom surveys, cable route surveys, and seafloor mapping. Research needs have fostered the development of towed ROVs in the academic community, supported primarily with government funds. Missions include seafloor mapping and surveying, micro-bathymetry, high-resolution sub-bottom profiling, and water analysis. No vehicles of this type have manipulators.

In any towed system, problems may be encountered due to surface vessel heave. Various approaches have been taken in attempts to solve this problem in towed ROVs. The winching systems can be designed to include accumulators, or the tow cable itself may incorporate a depressor. Alternatively, the vehicle may have dynamic control planes coupled with an automatic altitude-keeping device.

The instrument packages vary depending upon the required task of the vehicle. In general, many of the same sensors used on AUVs are incorporated on towed vehicles. The umbilical provides both a means for propulsion and real-time data transmission, eliminating the need for on-board energy systems and vehicle intelligence.

Despite the advanced instrument arrays and data-gathering capabilities, towed vehicles, by nature of their configuration, seem to be less likely candidates for damage assessment of ship hulls. Because a towed vehicle must be in constant forward motion, the vehicle could not be backed up to focus on a point of interest. Instead, another separate pass by the surface towing vessel would be necessary. Also, inspection of the bottom side of a ship hull would be difficult due to the method used to propel the vehicle. Table 3-4 and Figure 3-18 provide information on the MANTA towed vehicle, which is representative of a high-capability vehicle. Appendix D contains information and graphical distributions for the spectrum of towed vehicles.

TABLE 3-4. MANTA OPERATING SPECIFICATIONS

Vehicle Name	MANTA
Classification	Towed, mid-water ROV
Manufacturer	SEA-I Research Canada Ltd. Sidney, BC, Canada
Design Purpose	Surveying, sampling, and documenting the water column, bottom features, and targets of interest
Size (LxWxH)	7.81 x 4.92 x 4.92 feet
Weight in air	1397 pounds
Operating Speed	1 to 5 knots
Structure	Integrated, acoustically transparent, vacuum formed fiberglass molded parts and high density ballast section. Hydrodynamic configuration of main body with aircraft-type vertical stabilizer with elevators and rudder.
Depth Control	Surface supervised, infinitely adjustable, computer-electro-hydraulic system which is adjustable in the following modes: 1) manual; 2) automatic pressure/depth following; 3) descend/ascend at angles of 0 or 45 degrees at 1 degree increments, and 5) undulating paths
Power Requirements	Internal 12-Vdc system
Propulsion	Vehicle is towed by surface ship
Instrumentation	CCTV (low light level, 360 degree pan; 200 degree tilt) with four variable intensity lights. Still camera (35mm) with two slave strobes (vertically mounted). Automatic pressure/depth tracking system (range: 0 to 164 feet). Forward obstacle avoidance system (range: 0 to 164 feet). Emergency ballast jettison system. Bottom referencing sonar (2% accuracy). Emergency locator pinger and lights.
Navigation	Extrapolated from surface position
Shipboard Components	Control system and console, winch system
Support Ship Requirements	Deck space (337 ft^2) for winch system and vehicle. Enclosed space of 3 x 3 ft. of control console plus area for two operators. Communications between bridge, control console and deck. Boom crane with 1980-lb capacity and/or A-frame if not a stern trawler. Power (120 Vdc) optional.
Operating/ Maintenance Crew	Three
Status	Operational, launched 1981.

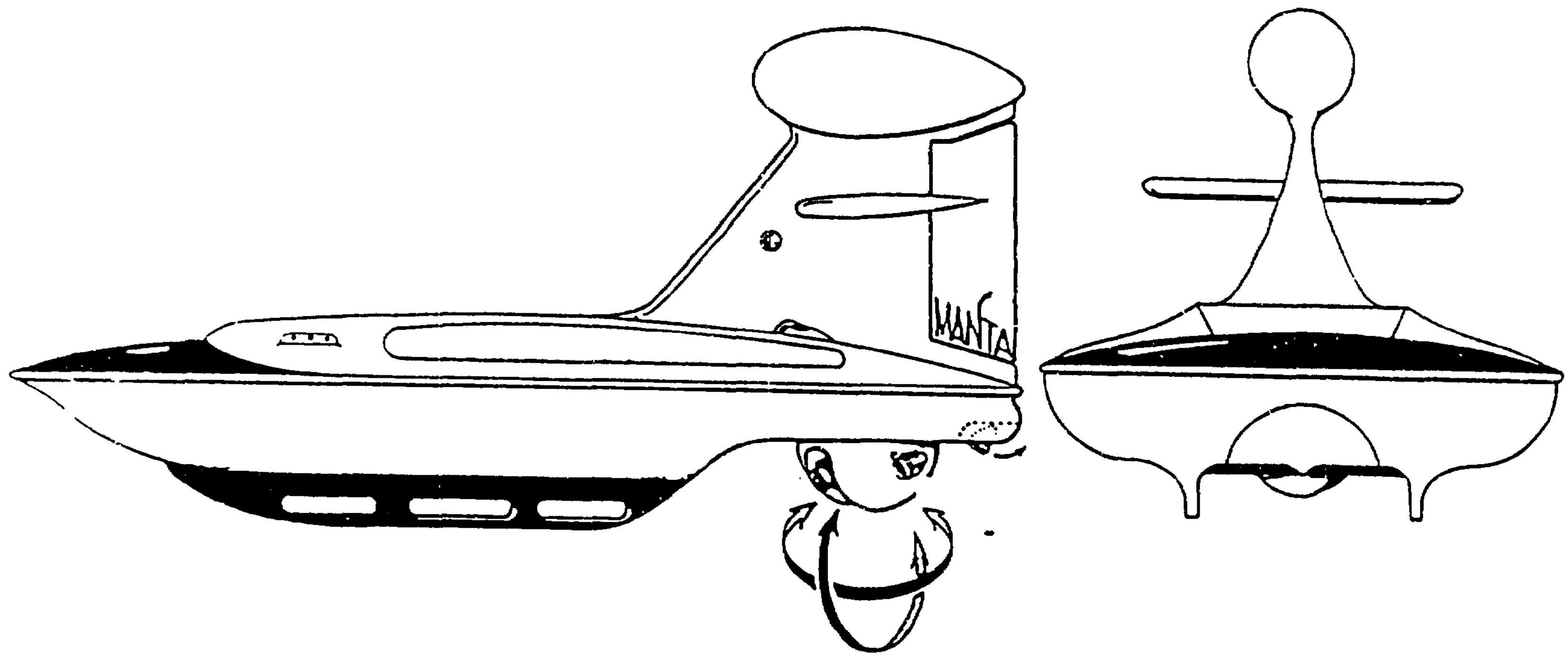


FIGURE 3-18. ***MANTA*** **TOWED VEHICLE**
(SEA-I Research Canada Ltd.)

3.2.1.4 Crawling Vehicles

Bottom Crawling vehicles are propelled by wheels, tracks, or Archimedean screws in contact with the bottom or a similar flat surface. TV cameras and lights are almost always carried. Most are heavy, massive vehicles which may also have the ability to adjust buoyancy to a negative, neutral, or positive condition. They are generally one-of-a-kind and purpose-designed.

Structurally reliant crawling vehicles also obtain power from—and are controlled by—the surface platform. TV cameras and lights are almost always carried on these vehicles as well. Propulsion is obtained through wheels, tracks, magnetic "feet," or push-pull rams in contact with a structure. They may be capable of some mid-water maneuvering capability via thrusters for traveling to and from the structure. All of these vehicles are one-of-a-kind and designed to conduct specific tasks.

Most crawling or structurally reliant vehicles are large and intended to perform tasks such as pipeline burial, but some vehicles are sized such that ship damage assessment might be feasible. These smaller crawlers are typically designed for inspection or hull cleaning. One intrinsic benefit of structurally reliant crawlers is that maintaining a desired standoff distance is very simple, almost regardless of water currents or sea states.

The main design variable to be addressed for a crawler intended to perform ship hull inspection is the method it uses to overcome gravitational and environmental forces and remain in contact with the ship's hull. Several schemes have been addressed. These include magnetism, buoyancy, and thruster power to hold the vehicle fast to the inspection surface.

Crawling, or structurally reliant, vehicles provide some intrinsic benefits over tethered ROVs. First, crawlers are attached to the hull, thus are not as affected by high currents or sea states. Second, position control and standoff distances can be much more accurately maintained due to the constant physical contact of the vehicle with the hull. This makes sensor setup and calibration much easier. Table 3-5 and Figure 3-19 provide information regarding the structurally reliant vehicle ASTROS 200. This vehicle was designed for performing structural inspections.

TABLE 3-5. ASTROS 200 SYSTEM SPECIFICATIONS

Vehicle Name	ASTROS 200
Classification	Crawler/ Structurally Reliant
Manufacturer	Travocean, Marseille, France
Design Purpose	Inspection of platforms, dams, wharfs, pipelines and tunnels
Size (LxWxH)	4.92 x 4.26 x 1.97 feet
Weight in air	286 pounds
Operating Speed	0 to 4 knots
Buoyancy Control	Vehicle is positively buoyant. Depth is controlled by vertical thrusters.
Structure	Cylindrically shaped tubular framework supports and surrounds all components.
Power Requirements	System: 115/230 Vac, single-phase, 50/60 Hz, 3.5 kVA. Winch: 440 Vac, 3-phase, 50/60 Hz, 15 kVA
Propulsion	The vehicle has four thrusters: two forward/reverse, two vertical. The thrusters maneuver the vehicle to the work site. On the bottom of the vehicle are three wheels: two forward and fixed, one aft mounted on a swivel. When the wheels have made contact with the structure, the vertical thrusters hold it against the structure. The vehicle has a 132-lb driving force and traction strength of 1540 lb. The vehicle is said to be capable of operating within a 4-knot current.
Instrumentation	TV camera (for navigation). Two or four 250-W lights. The vehicle is also equipped with the EROS 22 system, which is designed to take stereoscopic color video pictures and, after on-line or off-line processing, to supply 3-dimension measurement data on the object filmed. The EROS 200 system covers a filming field of 200 x 200mm to a precision of ± 1mm in X and Y and ± 2mm in Z directions.
Navigation	By visual sighting on TV
Shipboard Components	Control Cabin, winch/cable handling system (13.12 x 6.56 x 6.56 feet x 1980 lb), umbilical
Status	Operational, launched 1985.

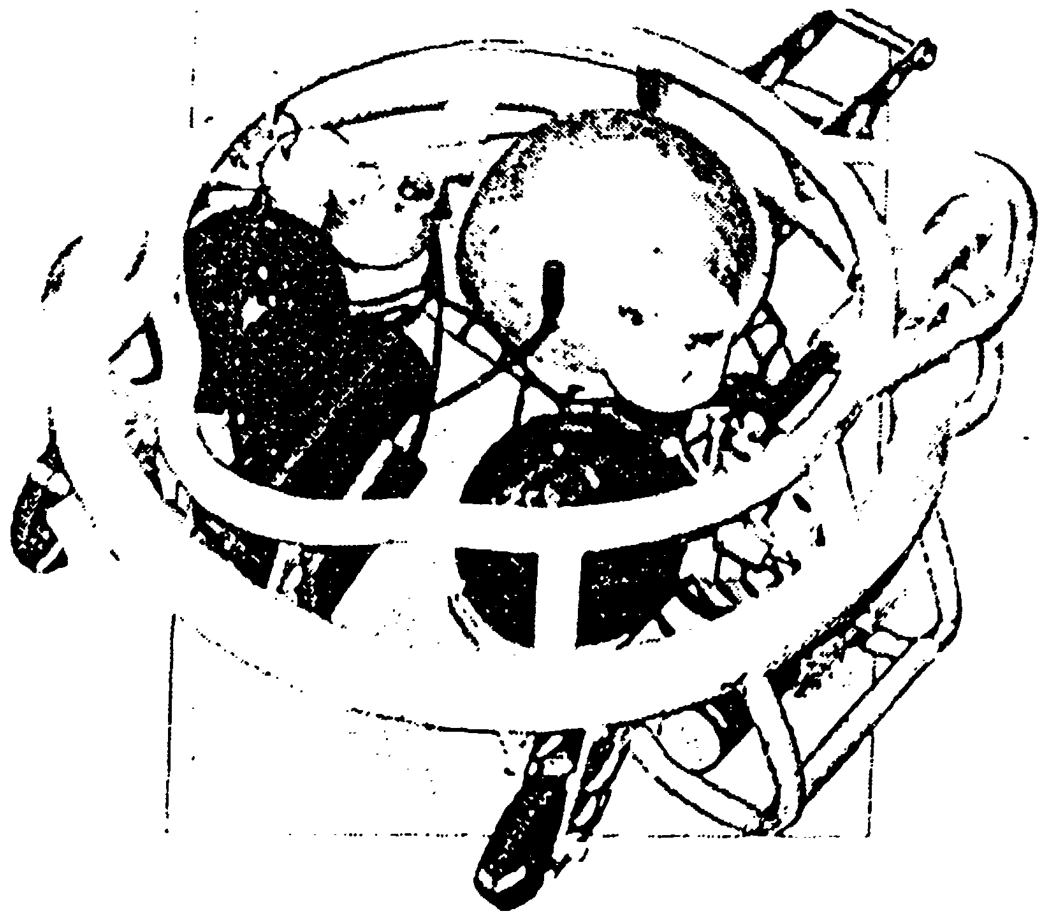


FIGURE 3-19. *ASTROS 200* STRUCTURALLY RELIANT VEHICLE (*Travocean*)

3.2.1.5 Specialized Vehicles (Crawler/Swimmer)

Hybrid vehicles combine features from two of the vehicles previously described. For example, a vehicle might be towed in mid-water until an object of interest is sighted; then it bottoms and operates as a bottom-crawling ROV. The combinations are numerous and there is little, if any, commonality among vehicles in appearance, dimensions, or mode of operation. Due to the vast differences within the hybrid class of vehicles, a breakdown of the subsystems will not be presented, several vehicles will be briefly described.

One specialized vehicle is the AQUAROBOT—a six-legged, articulated, "insect-type" walking machine—which has an operating depth of 50 meters. This vehicle can traverse at a rate of 6.5 m/min on flat ground and can maintain position accuracy of ± 21 cm through a long baseline ultrasonic transponder system. A TV camera with an ultrasonic rangefinding device is mounted at the end of the manipulator. Field tests prove that performance is adequate for practical use.

As outlined in 3.2.1.2.6, AUV communications, radio (electromagnetic) frequencies are not suitable for underwater communication due to severe attenuation. However, two vehicles are known to operate by radio control. By keeping some part of the vehicle above the water surface to send and receive radio signals. These are the DOLPHIN and the SEAS V.

DOLPHIN is essentially an AUV with a mast and an antenna that protrude from the water. The vehicle is powered by a diesel engine, which draws its air supply through the mast. The diesel engine allows extended missions. The major drawback is that the vehicle can go no deeper than the length of the mast, otherwise, the communication link will be broken and the engine will die.

The SEAS V, designed by SubOcean of Sweden, manages to deal with the major problems associated with untethered vehicles. The vehicle is a bottom crawler tethered to a surface buoy directly above the underwater vehicle system. The power system, a conventional fuel engine, is enclosed in the surface buoy. The buoy also contains navigation, communication and dynamic positioning systems. This configuration allows for radio control to and from the vehicle, with the advantages of high data-transmission rates. Interestingly, the fuel for the engine is contained in tanks aboard the subsurface crawling vehicle. The purpose of this system is to detect hydrocarbon leaks in pipelines. The flexible tether permits a wider vehicle depth range than that of the DOLPHIN.

3.2.2 Summary

A wide variety of underwater vehicle systems is available. Most are built to perform specific tasks, such as inspection, trenching, lifting, etc. This allows the vehicle design to be optimized around the task that is to be performed. Appendix D provides a complete breakdown of underwater vehicles by type, along with key features of each vehicle. The graphs provided in the Appendix are intended to show the divers nature of underwater vehicles with regard to length, weight, and speed. Because there is such a great diversity in vehicle characteristics, the MFEP evaluation performed in this report uses "nominal" vehicles, defined as vehicles of the size and shape envisioned as required for carrying the range of sensors available for implementation into a damage assessment system.

3.3 Sensor System Overview

3.3.1 Technology Review

3.3.1.1 Photographic/Video Imaging Systems

Matter excited by the absorption of energy emits some energy in the form of electromagnetic radiation. Regardless of wavelength or frequency, electromagnetic radiation travels through free space at the same speed. The electromagnetic spectrum is a classification system based on wavelength for electromagnetic radiation. The electromagnetic spectrum is shown in Table 3-6. Two basic physical processes are involved in the loss of energy in water. These are absorption and scattering. Light energy is absorbed or scattered by the medium through which it travels. The combined effects of absorption and scattering are referred to as attenuation. The intensity of light is attenuated with distance travelled according to the equation

$$I_r = I_o e^{-ra}$$

where I_r is the intensity of the light after traveling distance r, I_o is the initial intensity of the light, r is the distance of travel of the light, and a is the attenuation coefficient. The transmittance of the energy is the ratio of I_r to I_o.

TABLE 3-6. THE ELECTROMAGNETIC SPECTRUM

ENERGY TYPE	APPROXIMATE WAVELENGTH (m)	CORRESPONDING FREQUENCY (Hz)
Gamma rays	10^{-14} to 10^{-10}	3×10^{18} to 3×10^{22}
X-rays	10^{-12} to 10^{-8}	3×10^{16} to 3×10^{20}
Ultraviolet	10^{-8} to 0.40×10^{-6}	7.5×10^{14} to 3×10^{16}
Visible light	0.40×10^{-6} to 0.70×10^{-6}	4.3×10^{14} to 7.5×10^{14}
Infrared	0.70×10^{-6} to 3×10^{-3}	10^{11} to 4.3×10^{14}
Radar	3×10^{-4} to 1	3×10^{8} to 10^{12}
Radio & TV	10^{-2} to 10^{5}	3×10^{3} to 3×10^{10}
Alternating current	7.5×10^{5} to 1.2×10^{7}	25 to 400

The attenuation of electromagnetic energy in pure water (i.e., no scattering) for different wavelengths of energy is shown in Figure 3-20. The characteristic attenuation length is the distance at which the energy transmittance is equal to 1/e. Since transmittance, T, is equal to e^{-ar}, the characteristic attenuation length, L, when substituted for the distance r, must equal the reciprocal of the attenuation coefficient, a. Thus, if a sample of water has a characteristic attenuation length of 10 meters, then over a travel distance of 10 meters, only 36.7 percent (1/e) of the energy has not been lost due to attenuation. Because the corresponding attenuation coefficient of 0.1 per meter conveys little intuitive measure for the transparency of the water, characteristic attenuation lengths are most often used as a measure of turbidity. Figure 3-20 shows that the water is by far most transparent in the visible portion of the electromagnetic spectrum. Though transparency does increase at very low (radio waves) and very high (X-ray) frequencies, these are not used. The high frequency band is not used, due to the dangerously high energy levels of individual photons.

Figure 3-21 shows the transmission of light in distilled water in the visible portion of the electromagnetic spectrum. The peak of energy transmission occurs at the low wavelength end of the visible range. Transmission is highest for violet light (400 to 420 nanometers) and gradually drops as wavelength increases through blue (460 to 480 nanometers), green (525 to 545 nanometers), yellow (565 to 585 nanometers), orange (590 to 610 nanometers), and red (650 to 670 nanometers). This explains why the blue-green lasers can be used from greater ranges than the red lasers, as will be discussed in a later section.

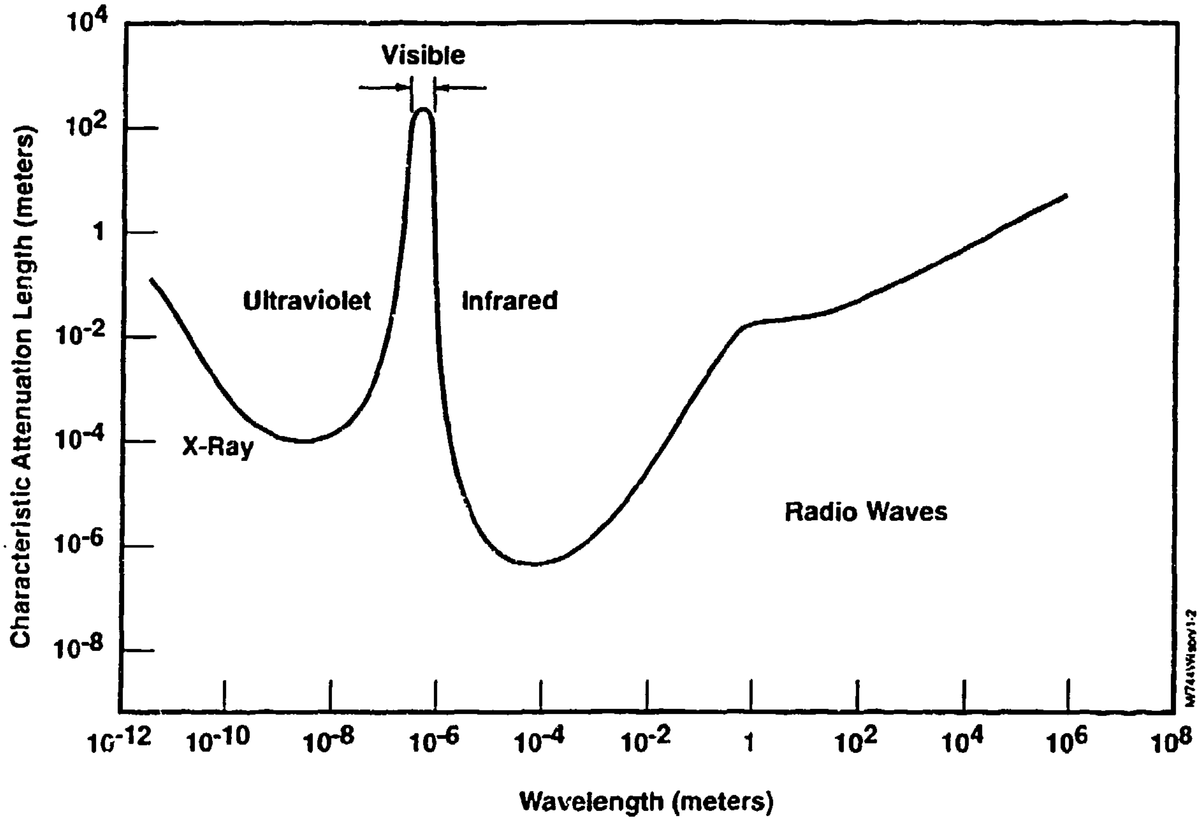


FIGURE 3-20. THE ATTENUATION OF ELECTROMAGNETIC ENERGY IN SEAWATER
(J. Williams, 1970)

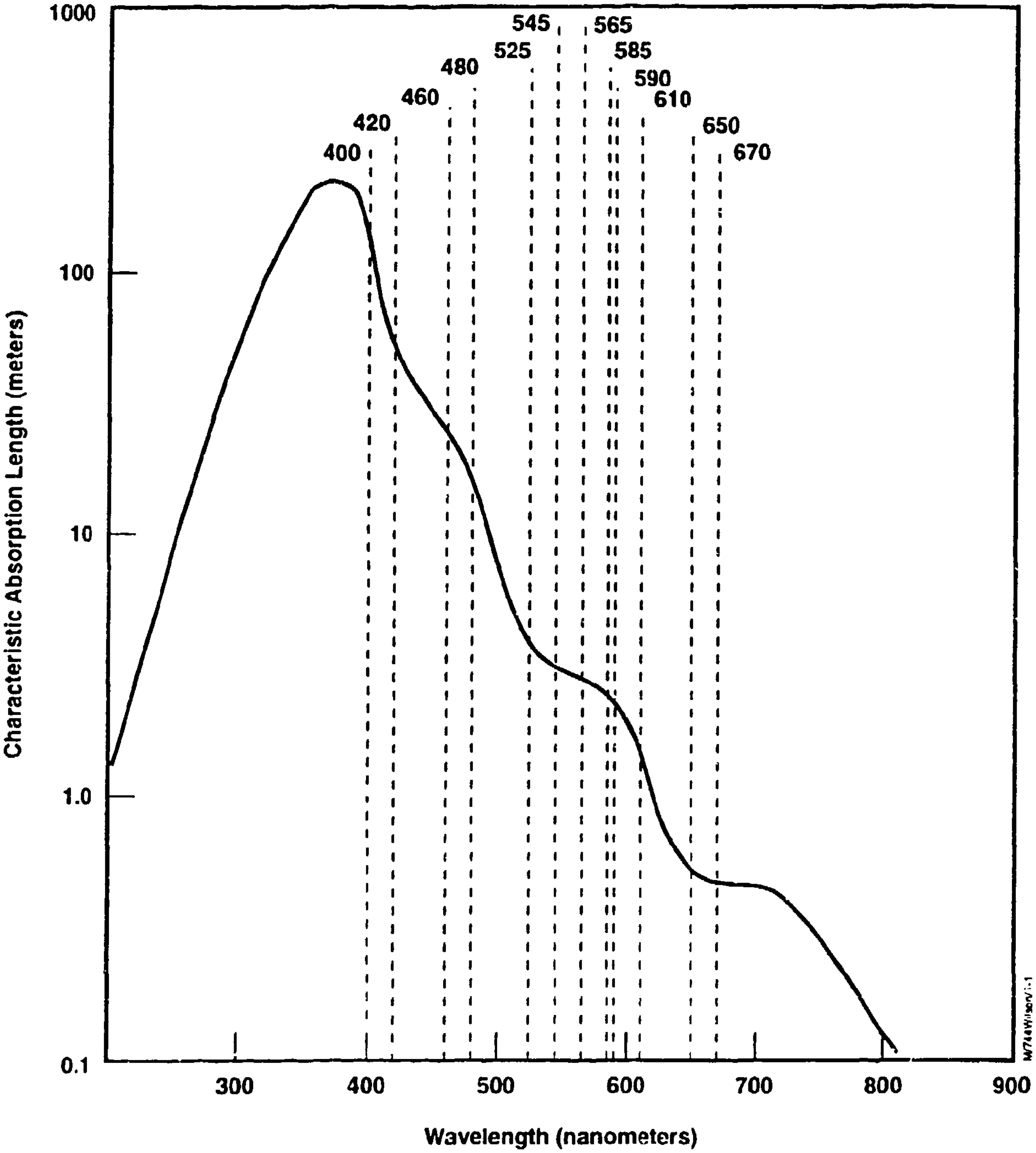


FIGURE 3-21. THE SELECTIVE TRANSMISSION OF LIGHT BY DISTILLED WATER
(J. Williams, 1970)

Scattering is the other basic physical process involved in the loss of energy in water. This loss is due to the many particles suspended in water, which can interfere with the travel of electromagnetic energy. Very simply, scattering can be described as a phenomenon where energy impinging on the particles is absorbed by the particles and then reradiated in many different directions without a change in wavelength. In general, scattering is a greater problem in underwater optical imaging. The effect of turbidity on light attenuation is shown in Figure 3-22a. Figure 3-22b shows how the attenuation length affects the maximum imaging range for a variety of visually oriented sensors. It can be seen that the maximum range achievable for the systems shown is approximately five attenuation lengths. Laser imaging systems will be discussed in greater detail in following sections. It can be seen that the attenuation length (1/extinction coefficient) varies significantly as a function of geographic location and resultant scattering effects. Properly positioned, lights can enhance the image by reducing backscattering effects as shown in Figure 3-23. As can be seen from this figure, if illuminating sources are not properly positioned, light from these sources can be reflected by the particles back to the camera, disturbing exposures and overpowering the more faint light reflecting from the target. Under ambient light conditions, light from the sun does not get reflected back to the camera, due to the position of the sun in the sky. With only ambient light, the image can be improved simply by minimizing the number of particles between the camera and the target by moving the two as close together as possible. Light absorption in water limits the effective range of most imaging systems to 100 meters. Likewise, sunlight can penetrate clear water to only about 100 meters. This is much deeper than necessary for hull damage assessments. In turbid water however, some lighting may be needed. Positioning the lights as shown in Figure 3-23 will prevent light reflected from particles in the camera's field of view from obscuring the light arriving from the more distant target. To arrange the lights as shown in this figure, the lighting must be separated from the camera by an appropriate distance. This distance increases with camera/target standoff, or altitude as shown in Table 3-7. At a standoff of 10 meters and using a 50 mm lens, the camera and lighting should be separated by 7 meters in turbid water. This setup is not possible with a single ROV.

3.3.1.1.1 Television Cameras

Figure 3-24 shows the basic elements of a television camera. These include the lens assembly, the sensor, and the electronics assembly. The lens gathers light from the viewing area and

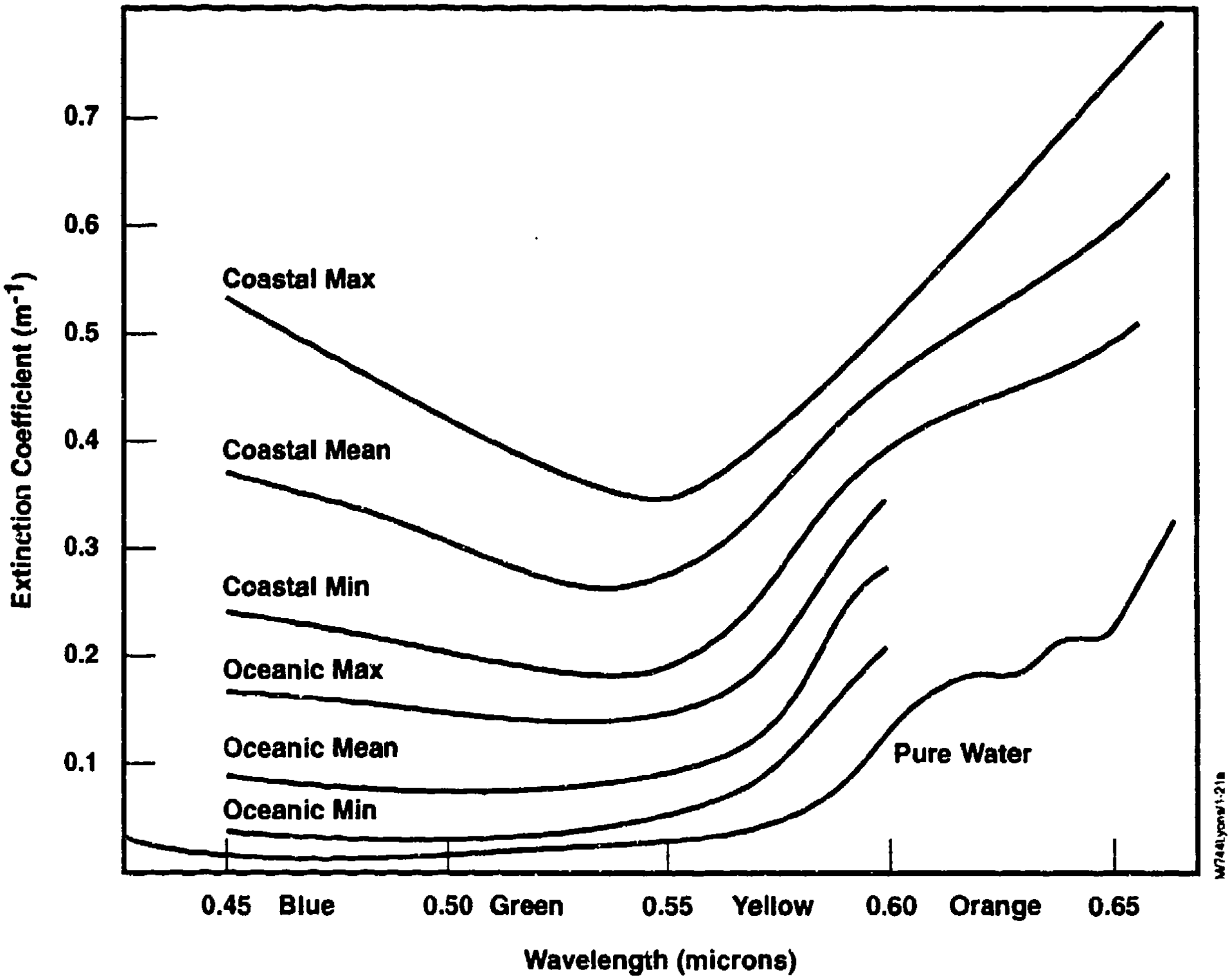


FIGURE 3-22A. EXTINCTION COEFFICIENT OF VISIBLE WAVELENGTHS IN VARIOUS OCEAN ENVIRONMENTS
(Sverdrup, Johnson, and Fleming)

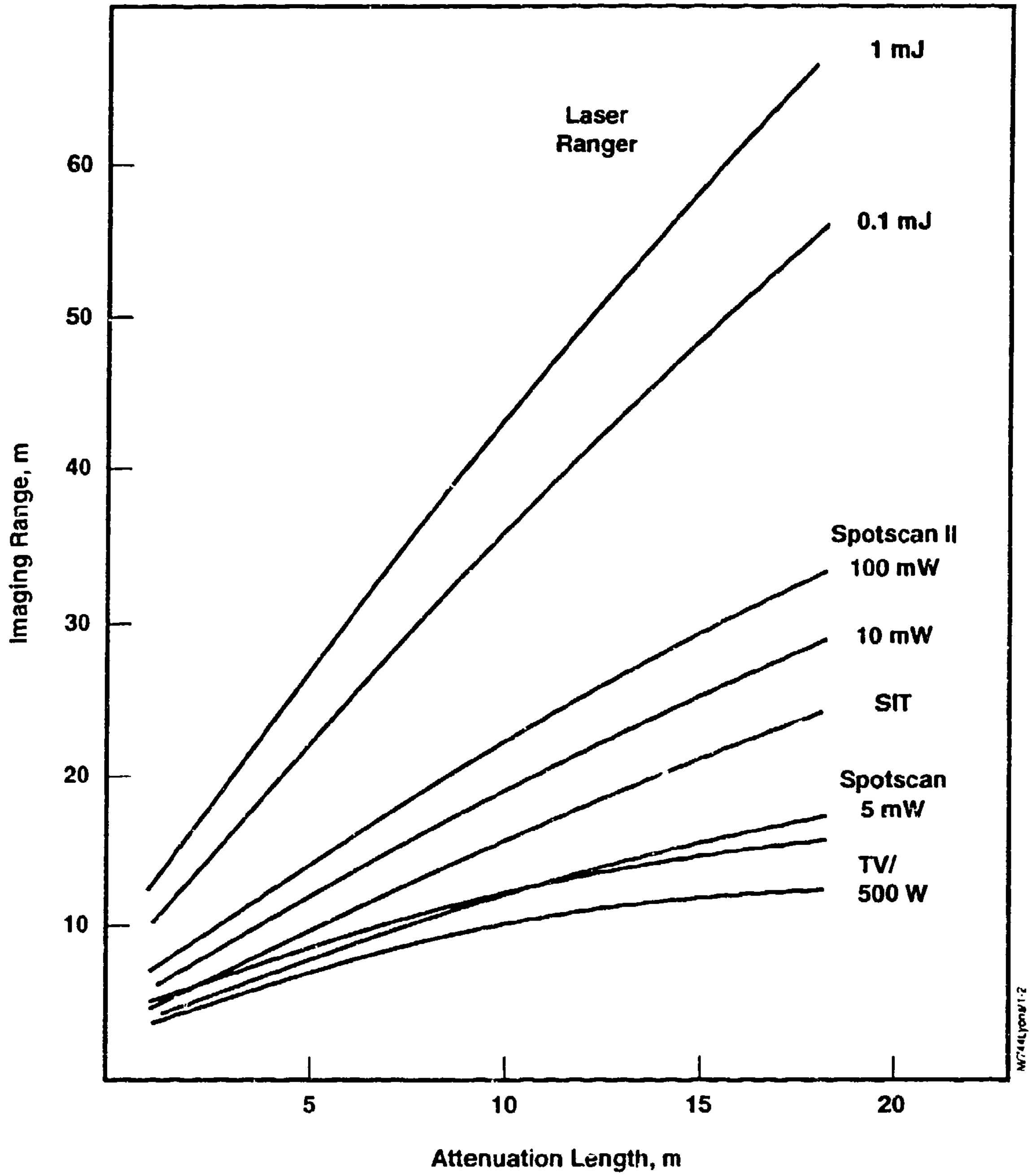


FIGURE 3-22B. IMAGING RANGE VS. ATTENUATION LENGTH FOR VARIOUS IMAGING SYSTEMS (*SEATEX AS*)

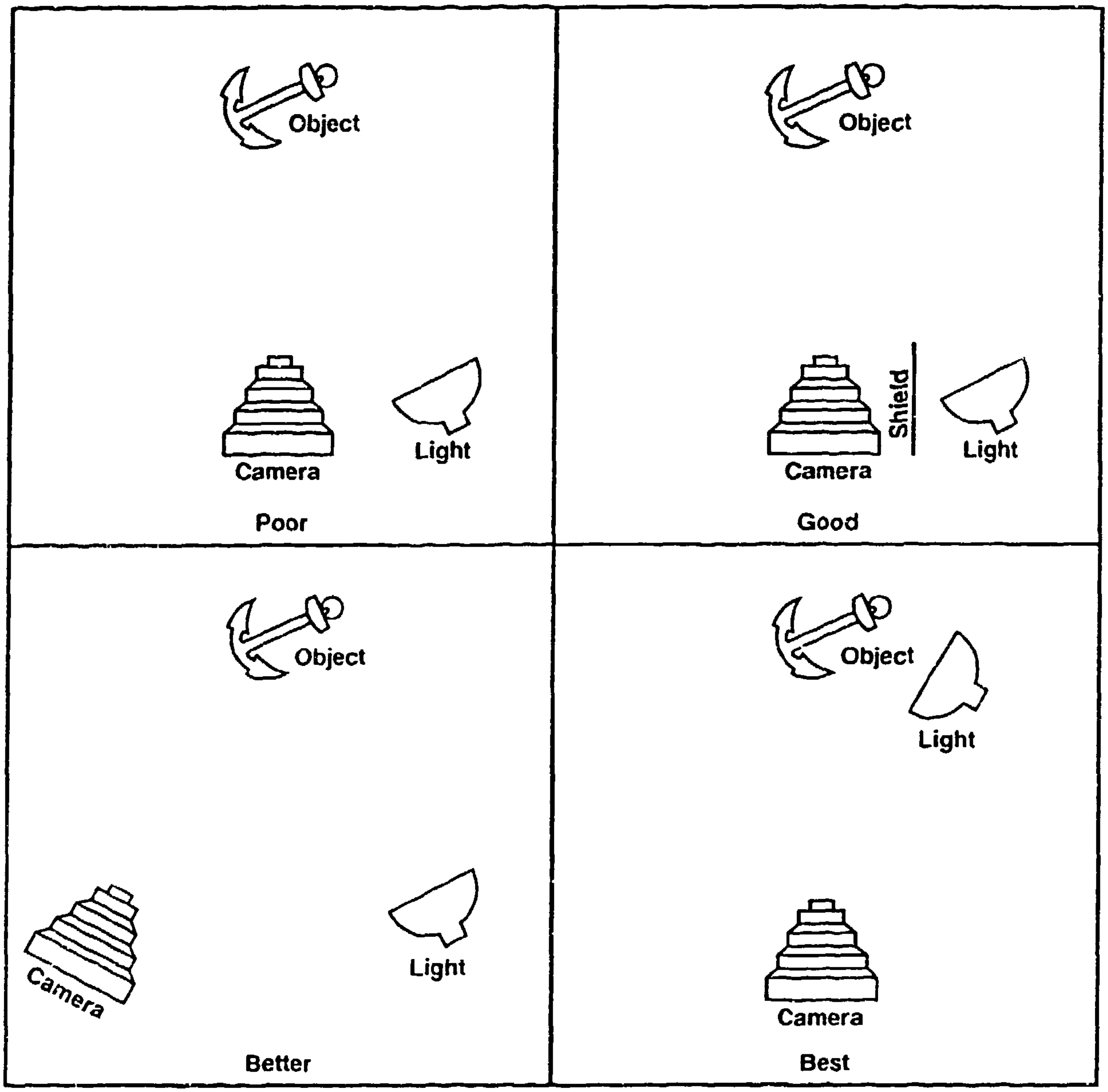


FIGURE 3-23. VARIOUS CAMERA-LIGHT PLACEMENTS FOR THE REDUCING OF BACKSCATTERING EFFECTS
(J. Williams, 1970)

TABLE 3-7. CAMERA LIGHT SEPARATION REQUIREMENTS
(University of New Hampshire, 1990)

	SEPARATION OF CAMERA AND LIGHT SOURCE (meters)		
ALTITUDE (meter)	**50mm LENS 35mm FILM**	**SIT-10mm 16mm TUBE**	**SIT-90mm 16mm TUBE**
1	0.7	0.6	0.2
2	1.5	1.25	0.37
5	3	3.1	0.85
10	7	6.3	2
20	14	12.5	3.7
30	21	19	5.1

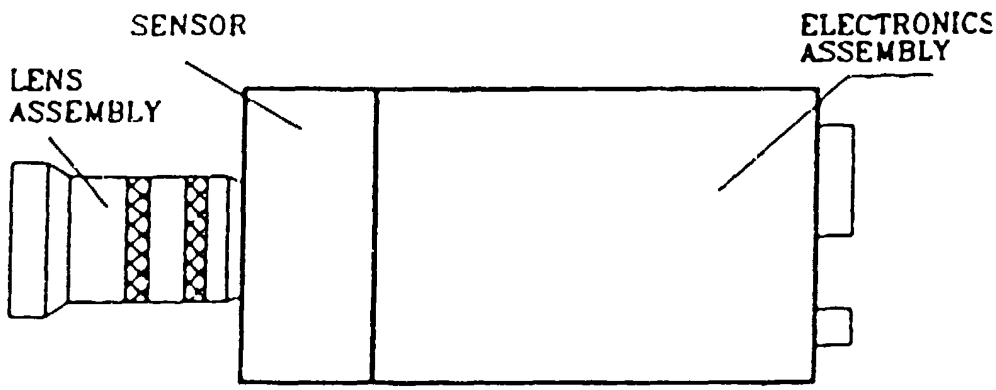


FIGURE 3-24. BASIC ELEMENTS OF A TELEVISION CAMERA

focuses the light on the sensor. The sensor converts the light image received into an electronic image. Finally, the electronics stimulates the sensor, reads the electronic image, and generates an output video signal.

The primary difference between cameras is the sensor. Vacuum tubes were commonly used for many years, but solid-state CCDs (Charge Coupled Device) are now the predominant television sensor. CCD cameras have a number of advantages over tube sensors. Advantages include:

- Insensitivity to damage due to high light levels, including sunlight
- Little geometric picture distortion
- Virtually no image lag (real time video)
- Improved stability and repeatability.

Television cameras that can use a vacuum tube device called an image intensifier operate in extremely low light. The image intensifier is used in conjunction with the sensor. The intensifier receives the low light level image and electronically amplifies the image. A common intensifier is the SIT (Silicon Intensifier Tube), which is typically attached to a vacuum tube. The ISIT (Intensifier Silicon Intensifier Tube) provides even higher sensitivity by using two intensifiers in tandem. Intensifiers are also used in conjunction with CCD sensors, resulting in ICCD (Intensified Charge Coupled Device) cameras.

Television pictures generated from the images collected by the camera sensor are "painted" by an electron beam moving from left to right across the CRT screen. The electron beam paints one horizontal line at a time on the screen. The beam is shut off when it reaches the right side of the screen, then it is rapidly moved to the left side of the screen where it paints the next horizontal line.

The electron beam is deflected from the top of the CRT screen to the bottom, allowing each horizontal line to be painted just below the previous line. A TV field is the picture resulting from 262.5 horizontal lines. Each field of 262.5 horizontal lines takes 1/60 second to be painted. Two sequential fields are interlaced and combine to form a frame. The 262.5 lines of the first field are numbered odd, and this field is called the odd field. The 262.5 lines of the second field are numbered even and the field is referred to as the even field. The odd field lines fall between (are interlaced with) the even field lines when a frame is painted, thus creating a more detailed picture with 525 horizontal lines total. Thus, each frame update of a television camera occurs in 1/30 seconds. Television cameras and video cassette recorders work in this procedure. TV cameras generate an odd field followed by an even field, etc. VCRs record the sequence treating the two fields as a group of repeating signals.

The 525 horizontal-line picture produced by a TV camera is the NTSC standard. It can be related to the vertical resolution of the camera: the height of the field of view of the camera divided by 525 gives the approximate vertical resolution of the image. Color TV cameras have lower vertical resolutions, with the number of horizontal lines generally being between 300 and 325, and they require considerably higher illumination levels than black and white cameras.

For hull damage assessment, video cameras can provide continuous scene updates with excellent resolution, if the standoff is close enough to produce good images despite the effects of absorption and backscatter. At appropriate ranges, the resolution of video cameras will be good enough to identify holes in the hull larger than 3 inches in diameter. For example, using Photosea System's Nighthawk SIT camera, the vertical field of view from a standoff of 10 feet is 17.1 feet. With 525 horizontal lines, the vertical resolution is about 0.4 inches, allowing a 3-inch diameter hole to appear over at least 8 horizontal lines. This would allow the hole to be detected, but the monitor showing the image must be large enough for the viewer to see the hole. On a monitor with a vertical height of only 10 inches, the 3-inch hole will be only 0.15 inch high and would very likely be missed. On a monitor with a vertical height of 20 inches; however, the hole will be 0.3 inch high, improving the chances that it will be detected. Reasonably fine cracks will be identifiable as well, as long as the appropriate-size monitor is used. A shorter standoff will decrease the field of view of the camera, improving the resolution of the image but decreasing the area coverage rate. Most cameras can be used to zoom in on the target to look at small details. This would be useful for obtaining close-in observations of the hull without the need to move closer. The images can also be recorded for permanent files, for future comparisons of the conditions of the hull, or for off-line processing or inspection.

Difficulties will arise in turbid water. As visibility decreases, the usefulness of television cameras will decrease significantly due to attenuation of light. Low-light cameras will help, but in this situation, an acoustic sensor or a laser system may be necessary to perform the damage assessment.

3.3.1.1.2 Still Cameras

Still cameras can be divided into three types: color film, monochrome film, and electronic ICCD. Monochrome still film cameras are best for distinguishing contrast. Contrast detection will be important for performing damage assessment and discriminating among holes, cracks, dents, and non-damage objects such as marine growth and barnacles. With 16,000 gray levels, electronic still cameras are also far superior to television cameras in detecting contrast shifts.

3.3.1.1.3 Comparison of Photographic/Video Imaging Systems

Figure 3-25 shows the effect of standoff on camera resolution. As was the case for contrast shift, the resolution of still cameras is better than that for television cameras. With the highest resolution, black and white film will provide the best capability for detecting fine cracks in hulls in clear water from a reasonable standoff. Figure 3-26 shows the amount of light needed to create a usable image from a given camera/target altitude for various cameras. Color charge coupled device (CCD) cameras require 1,000 watts of lighting for an altitude of 10 meters; monochrome, low-light ICCD, and SIT cameras require little lighting even at an altitude of 20 meters. Low light ICCD and SIT cameras require low-power, continuous illumination; the color CCD TV cameras require higher power continuous illumination, and the still cameras require higher power strobe lighting.

The greater the camera/hull-target standoff, the larger the field of view of the camera and the fewer the number of exposures required to survey the entire area of the hull. The relationship between survey area and number of exposures is shown in Figure 3-27 for various standoffs. For a given survey area such as 10,000 square meters, the number of exposures needed from a standoff of 30 meters is less than 100. At a standoff of only 1 meter, well over 10,000 exposures are needed. Table 3-8 shows key parameters for the different types of television and still cameras discussed previously. The ICCD television and still cameras have the best light sensitivity, followed by the SIT television camera. SIT cameras are not available for color work. The resolutions attainable by the different camera types are not as widely varying as light sensitivity and range. Because of the low-light sensitivity of the ICCD and SIT cameras, however, lower power is required for lighting for the ICCD and SIT cameras than for the other cameras. The primary

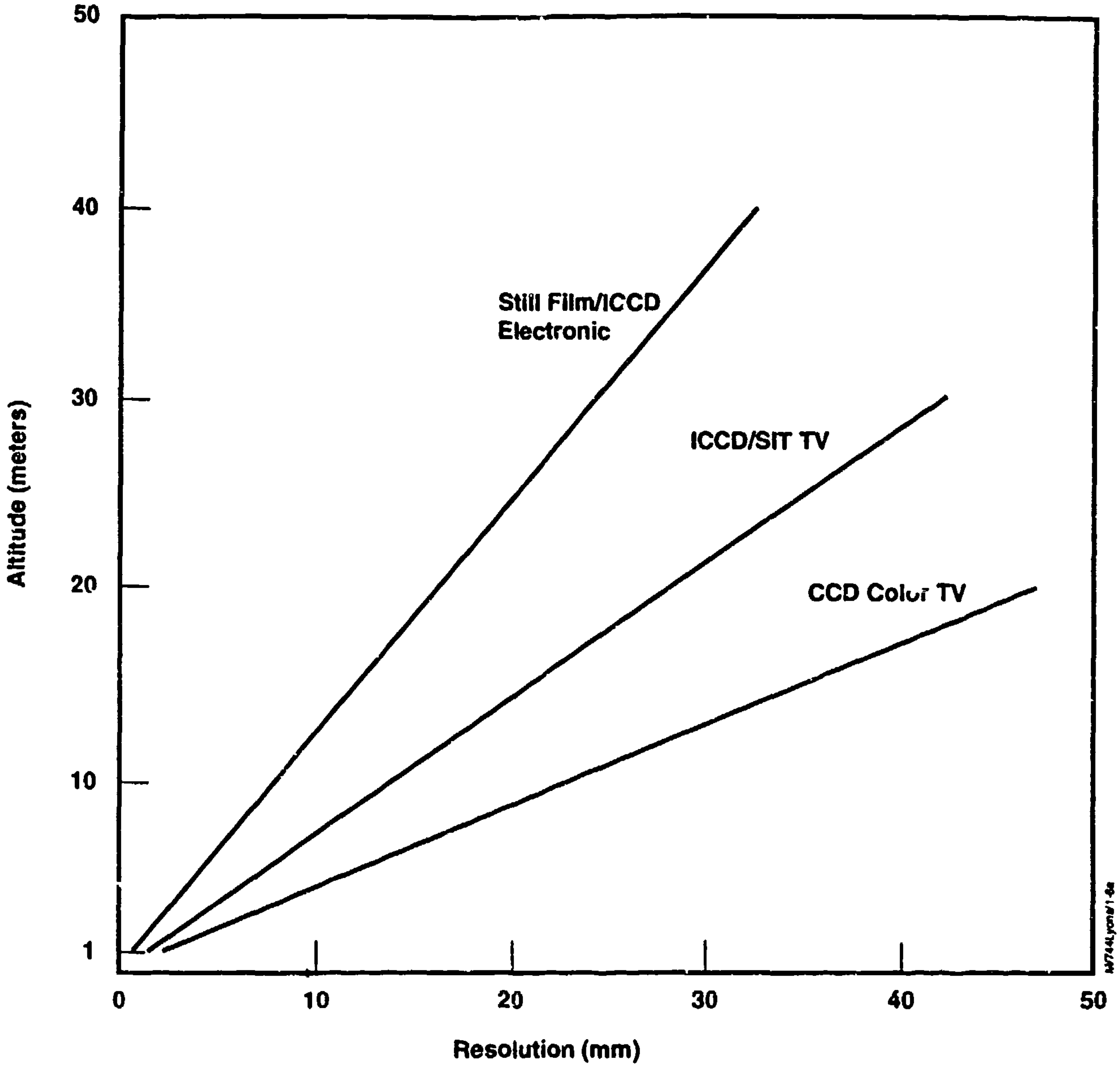


FIGURE 3-25. MINIMUM OBJECT SIZE (RESOLUTION) THAT CAN BE RESOLVED BY CAMERA SYSTEM AT VARYING ALTITUDES ABOVE THE SEA FLOOR IN CLEAR WATER *(University of New Hampshire, 1990)*

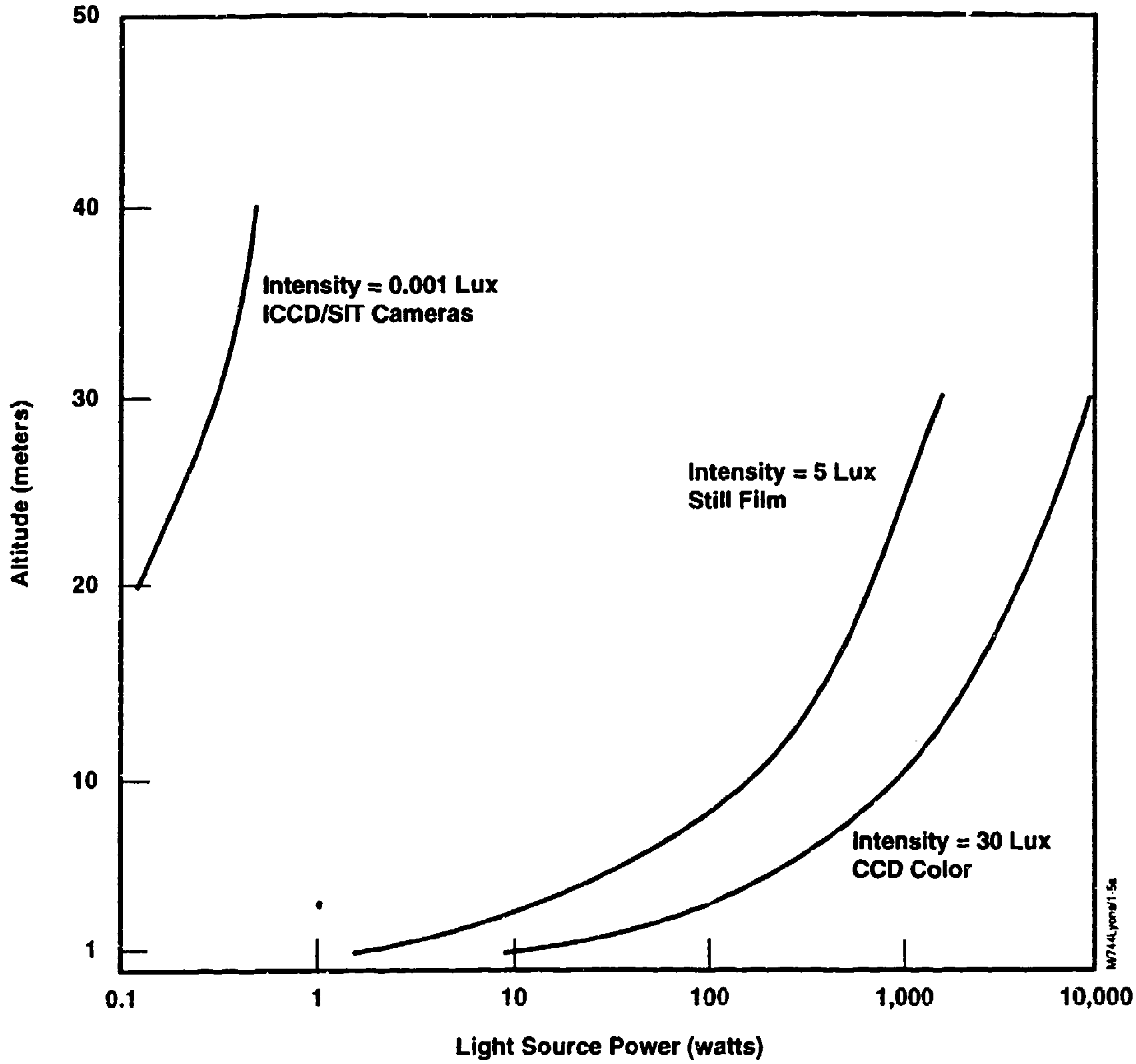


FIGURE 3-26. NECESSARY LIGHT FOR USABLE IMAGE AT GIVEN ALTITUDE ABOVE SEA FLOOR
(University of New Hampshire, 1990)

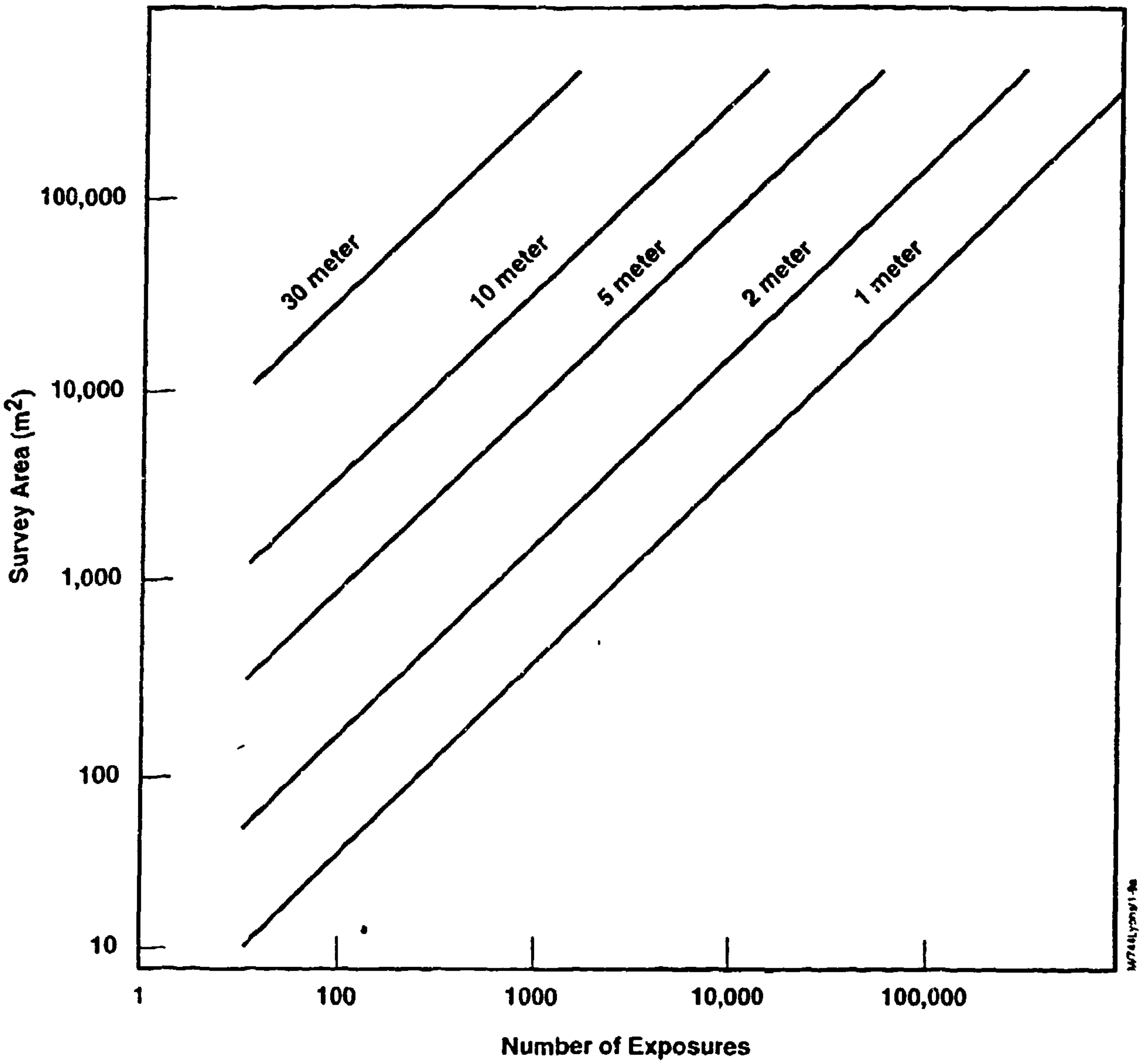


FIGURE 3-27. REQUIRED NUMBER OF EXPOSURE DEPENDING UPON SURVEY AREA AND ALTITUDE ABOVE SEA FLOOR (*University of New Hampshire, 1990*)

TABLE 3-8. KEY PARAMETERS FOR STILL CAMERAS AND VIDEO IMAGING (Blidberg, 1990)

STILL/TV CAMERA SYSTEMS	LIGHT SENSITIVITY (LUX) meters	MIN/MAX ALTITUDE millimeters	RESOLUTION AT MIN/MAX ALTITUDE (WATT)	LIGHT REQUIRED AT MAX. ALTITUDE (WATT)	UPDATE RATE (SEC)	NEED STROBE OR CONTINUOUS LIGHT	MIN/MAX SPEED (CM/SEC)	SENSITIVE TO PITCH OR YAW?
Still Cameras								
Film-Mono	5	1/20	2/20	500	3	S	0/100	Y
-Color	10	1/10	2/20	1000	3	S	0/100	Y
Electronic								
-ICCD	.0001	1/30	2/25	100	5	S	0/100	Y
TV Camera-LO/Light								
-ICCD	.0001	1/30	3/40	100		C	0/300	Y
-SIT	.001	1/30	3/40	100		C	0/300	Y
-CCD	30	1/10	3/25	1000		C	0/300	Y
Color								

advantage of the television cameras over the still cameras is the higher allowable traverse speeds. Thus, the area coverage rate for hull damage assessment using a still camera would be lower than the rate possible using a television camera.

Despite the improvements in resolution and contrast with still cameras, video cameras are preferable for performing hull damage assessment due to their ability to provide real time visual images of the scene. This image can be used to locate and quantify the damage while the damage assessment system is deployed. If a video camera is to be used, the following questions must be answered: should the camera be color or monochrome, what light level will be available, is artificial lighting necessary, and should the sensor be a CCD, an SIT, or an ICCD. Pearpoint Inc. manufactures the P228 Changeover, which incorporates both an advanced low light intensified camera (ICCD with 30 microlux faceplate illumination sensitivity) and a high resolution color camera. The camera can be switched to operate in either mode, eliminating the decision of whether the video camera should be color or monochrome.

3.3.1.1.4 Stereoscopic Video Systems

Stereoscopic effects have been achieved in industry, but with limited success due to high cost and to the fine alignment of the two images needed to create high-quality stereoscopic images. Visual Research Corporation's BTX-3D stereoscopic video systems use two TV cameras to capture two images of a scene from two different perspectives. One field from one camera is followed by a field from the other, so the signal contains two views of a scene in one frame. The video signal is coded such that the even field of the left camera is ignored. The odd field of the left camera is followed by the even field of the right camera. The resulting signal can be viewed on a standard monitor or recorded by any VCR.

Unless the viewer wears special liquid crystal display (LCD) glasses, the picture looks strange because the human brain cannot make sense of two perspectives at the same time. With LCD glasses, the picture acquires depth, allowing the viewer to feel like part of the scene. When the odd field captured by the left camera is being displayed on the monitor, the right part of the glasses is electronically darkened so only the left eye is looking at the picture. The right eye begins to see the even field of the right camera 1/60 seconds later while the left eye view is being electronically darkened. In this fashion, the scene can be viewed as it would be with the viewer's own eyes.

Geometric setup of the two cameras is the most important factor to obtain good stereoscopic images. The cameras should be separated by 62 to 65 millimeters. This short distance matches the interocular distance of the average human eyes. In shooting distant scenes, a better stereo effect can be obtained by increasing the distance between cameras.

Lenses of the same focal length must be used in both cameras, and the cameras must be closely aligned. A coaxial cable between the two cameras is needed to gen-lock (synchronize) the cameras. It is generally good practice to have the lens axes of both cameras exactly parallel. This works for targets greater than 10 feet away from the cameras. Zoom creates problems for stereoscopic viewing systems. The standoff from the target should be held constant.

Many manufacturers of stereoscopic vision systems use two gen-locked cameras. Stereo images can also be produced with a single camera. One approach is to place an optical adapter in front of the lens. Mechanical or electro-optic devices can block the light through parts of the optical path to create field-sequential stereo pairs. Another approach is to use a camera which translates in the depth direction or which uses elements that cyclically change their index of refraction to provide depth information.

Visual Research Corporation's BXT-3D system could be used with low-light cameras to create real time stereo images of the hull of a vessel. Because the scene is updated 30 times per second just as with television cameras, motion of the remote vehicle on which the system is mounted should not prohibit the use of the system. Motion toward and away from the hull will have the greatest impact on the performance of the system, as the focus of the system will be fixed for an appropriate standoff.

The allowable standoff for obtaining a good image with low-light cameras, will be greater than the standoff possible with ordinary television cameras. Stereo images would be extremely useful for detecting dents as well as holes and cracks. The advantage of using the BXT-3D system is its compatibility with standard off-the-shelf components such as cameras and VCRs. Some caution must be taken in selecting a VCR if a stereo image is to be maintained when freezing the video. Most VCRs show only one field in freeze mode, but there are VCRs which will truly show a frame (two fields) in freeze mode.

Camera Alive's NCS2 Non-Contact Video Measurement System also offers some unique capabilities in stereo video. Like the BXT-3D system, the NCS2 system uses two video cameras to create real-time video in color. The NCS2 system also comes with extensive software which allows a number of functions to be performed. The most important of these functions for hull damage assessment would be Measure. The Measure function allows a cursor to be moved over the stereo image to select and measure points, distances, profiles, angles, and surfaces. A stereo CAD overlay can be toggled on and off to indicate the measurements that have been taken, and a DXF file can be created for input into external three-dimensional CAD software packages such as AutoCad. This system would be useful for characterizing the size and shape of all types of damage, including dents, cracks, and holes.

Tecnomare Co. of Italy has developed a TV-trackmeter ranging device that uses stereo TV cameras in real time for visual inspections. This system's range is 1 meter to the visibility limit, with an accuracy of 5 millimeters at a 2 meter standoff.

3.3.1.1.5 Polarization Cameras

Johns Hopkins University Computer Sciences Division is developing a polarization video camera that will provide images based on the polarization characteristics of received light. Polarization of light occurs as a function of the properties of the materials it is being reflected from. Conductive surfaces tend to reflect unpolarized light while dielectrics (e.g., ceramics, rubber) tend to polarize the light significantly. This variation in polarization may provide a useful method for detecting damage accompanied by scraping away of paint (non-conductive surface) and exposing bare metal (conductive surface). The laboratory unit being developed at Johns Hopkins uses twisted nematic liquid crystals for polarizing filters. Voltage applied across these crystals causes them to selectively "filter" the different components of the incoming light as a function of the voltage applied. This scheme eliminates many problems associated with the use of a standard polarizing filter such as alignment errors, difficulty in automating, introduction of optical distortion, etc. The video display for the system will provide the operator with a color representation of the polarization characteristics. The hue/color will depict the orientation of the plane of polarization while the intensity will indicate the degree of polarization (i.e., more polarization results in greater intensity). In the future, high resolution capabilities may be possible by incorporating VLSI Chip technologies directly into the camera head, eliminating the need for video data processing in a SUN™ Workstation.

3.3.1.2 Laser Imaging Systems

Lasers are increasingly being used in the underwater environment either to provide detailed range and positioning data or to overcome the visual range limitations that conventional video imaging systems suffer due to common volume backscatter. For conventional underwater video imaging systems, the practical limit of performance occurs when the spatial contrast of the image being viewed is exceeded by the backscatter noise. For conventional systems the imaging limit is about two attenuation lengths. The concentration of particulate matter is the primary factor which affects the attenuation length. Particulate matter in sea water varies significantly in concentration, size, and composition. The concentration of particulate matter varies from micrograms to tens of milligrams per liter.

Lasers have many features that make them attractive devices for use in underwater imaging. Lasers emit discrete wavelengths and are highly directional (well-collimated). The common volume between the light source and the detector can be significantly reduced, and laser light frequencies can be selected which have low absorption coefficients, thus optimizing the transmission range. For many short- range measuring and imaging applications, relatively low cost lasers are available. Some commonly used low cost lasers and their characteristics are listed in Table 3-9.

Many different techniques have been used to incorporate lasers in underwater systems for observation, inspection, or work. The techniques range from simply using the lasers as "pointers" to more-complex scanning and range-gating systems. Synchronous scanning is one technique which is used to "spatially" reject backscattered light. A highly collimated laser is often scanned across the target and is spatially synchronized with the collecting beam of the imaging system. Thus, the laser illuminates only one resolution point on the target, and the detector senses only the return energy from that point. The small overlap between the laser and sensor minimizes the common volume backscatter. Another technique is range gating, in which a laser pulse is transmitted to the target and the imaging system is time-gated to pick up the reflected light pulse from the object being imaged. This allows all backscattered light to be rejected if it falls outside the gating time period. This technique "temporally" rejects backscattered light. Both of these imaging techniques will be discussed in greater detail in the following sections.

TABLE 3-9. EXAMPLES OF LASER FOR UNDERWATER APPLICATIONS'

LASER TYPE	COLOR & WAVELENGTH (NM)	OUTPUT POWER (MW)	BEAM DIVERGENCE (MRAD)	RELATIVE BEAM INTENSITY	APPROXIMATE COST ($, U.S.)
Helium Neon	Red 633	0.5	1.7	1	400
		7	0.8	60	900
	Green 543	0.2	1.2	0.8	700
		1.5	0.9	11	1,600
Diode	Red 660-680	5	1.6	10	500
Diode Pumped Yag	Green 532	2	1	12	10,000
		80	7	10	25,000

3.3.1.2.1 Lasers for Photographic Size and Range Determination

Underwater lasers are often used to provide an absolute size reference in a photograph. Lasers can be mounted side-by-side to project parallel beams of light into a camera's field of view, so that two spots a known distance apart are projected onto an image. Absolute-size measurements can be made independent of the camera-to-subject range and the focal length of the lens by comparing object or feature size with light spot spacing. If a fixed-focal-length lens is used, the parallel-beam lasers also provide a direct measure of the distance from the camera to the subject by comparing the proportion of the field of view that is spanned to the angular field of view of the camera. Systems have been described for making measurements with four lasers that are insensitive to the attitude and altitude of the vehicle transporting the camera system. The lasers used in this application are typically helium-neon (he-ne), producing either red-orange light (633 nm) or green region light (543.5nm).

Although the efficiency and power output of blue-green lasers are typically one tenth that of comparable-size red devices, the better optical transmission of green light provides for longer range operation.

The parallel-laser beam technique can also be used to measure small-scale features underwater. To obtain beam spacings smaller than the diameter of the laser package, a single laser could be equipped with a beam splitter to obtain the two parallel beams as shown in Figure 3-28. Translational motion of one of the optical elements allows the beam spacing to be varied and the spacing to be displayed. Another method of utilizing lasers for measurement triangulation, is depicted in Figure 3-29.

Seatex has developed a system called Spotrange^{TM}, which uses a laser and a video camera to precisely aim a high-frequency, narrow-beam-width acoustic range finder. The SPOTRANGE laser/acoustic ranging system is operated in conjunction with a computer-controlled video system. A grid overlay generated on the video display can be used to obtain

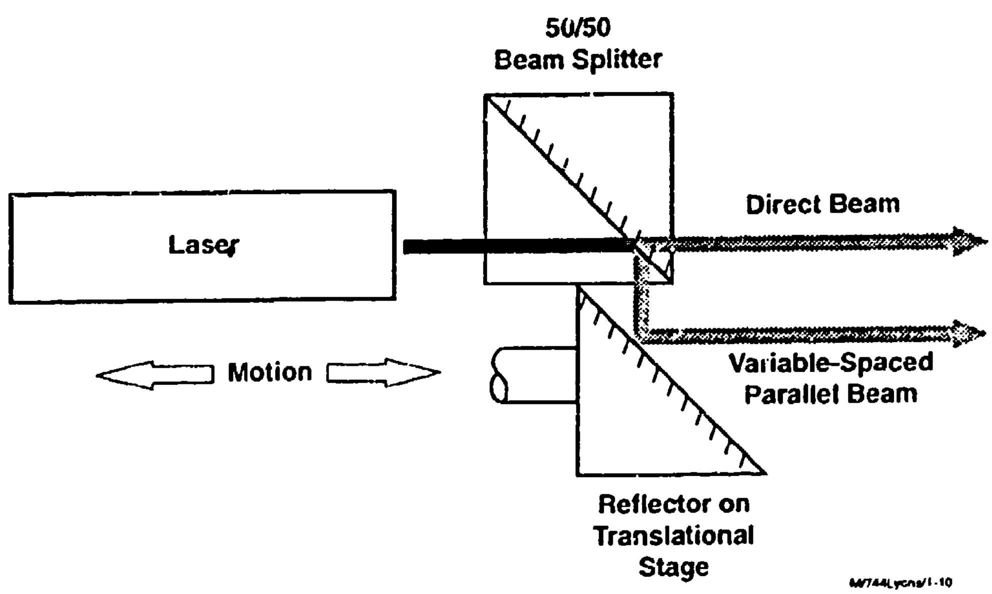
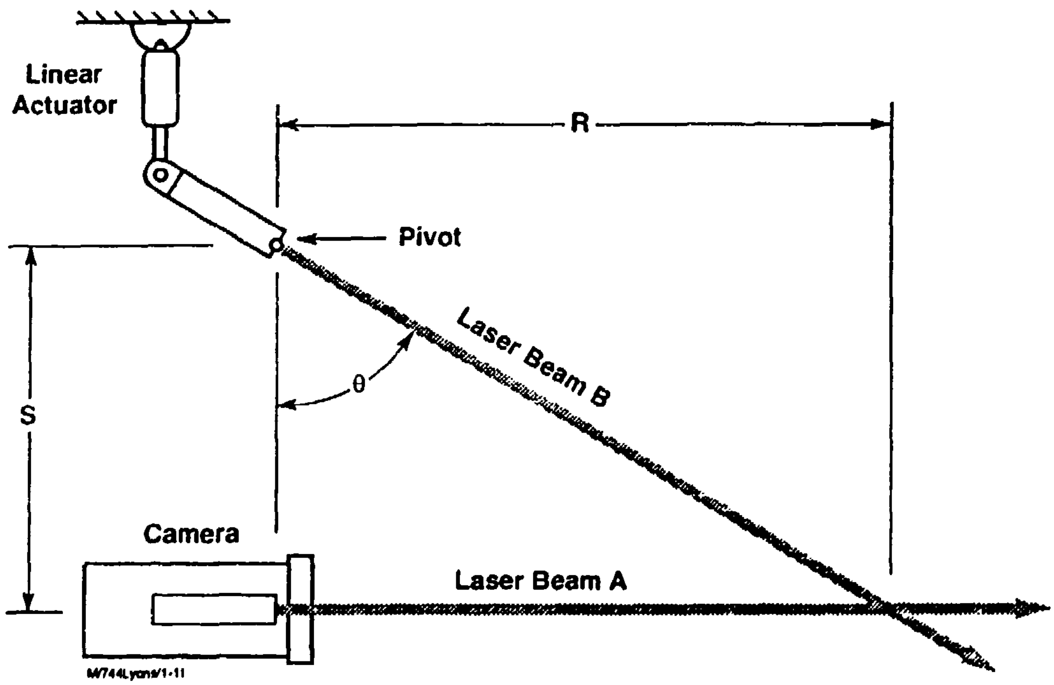


FIGURE 3-28. A PROPOSED METHOD OF PROVIDING ADJUSTABLE AND CLOSELY-SPACED PARALLEL LASER BEAMS FOR SMALL-SCALE INSPECTION AND MEASUREMENT TASKS (*Tusting and Davis, 1992*)



$R = S \cdot \tan\theta$

FIGURE 3-29. AN APPLICATION OF LASERS AND TRIANGULATION TO MEASURING THE DISTANCE FROM THE CAMERA TO A TARGET
(*Tusting, 1990*)

differential range measurements. The positional-measurement accuracy of the system is limited by the beam width of the acoustic transducers, which is 1.5 to 2 degrees. This commerciall; available system can be supplied with either red or green lasers and an acoustic ranger operating frequency of 1 MHz or 2 MHz. The maximum operating range for the 1 MHz system is 100 feet, and the maximum operating range for the 2 MHz system is 33 feet. The specifications for these systems are listed in Table 3-10.

3.3.1.2.2 Scanning Lasers for Two-Dimensional and Three-Dimensional Mapping

Synchronous Scanning Systems. The Naval Civil Engineering Laboratory and Harbor Branch Oceanographic Institution are currently developing a scanning laser imaging system that is able to generate three-dimensional maps. The system is designed to have a 1-mm-depth resolution at a standoff of 1 to 2 meters with a field of view of 40 degrees. The system uses a lateral-effect photo-diode that detects the position of the reflected laser dot on its surface to 1 part in 1,000 or better. Coupling this information with the known scan angle of the laser allows the range to the target to be triangulated. The scanning mirrors move in the x and y directions to cover the full 40-degree field of view. The information obtained from the imaging device is stored and processed to allow a 3D relief map of the scanned area to be generated. The system is able to detect features occupying an angular field of 0.05 degrees or greater. The system was designed to optimize resolution at the expense of range. But it is adaptable such that other desired operational capabilities could be obtained (e.g. increase speed of acquisition with decreased resolution, increase range with decreased resolution). Figure 3-30 shows conceptually how the NCEL/Harbor Branch system operates, and Table 3-11 summarizes the design specifications. Although designed for operating in the 3D mode, the system could be reconfigured to operate as a 2D flyby system. The developers expect that the standoff distance could be increased significantly (up to 6 attenuation lengths) if the system is designed specifically for flyby operations, but resolutions would be reduced from the current specifications.

Seatex builds the Spotscan™ system, which also uses a scanned laser beam to generate two-dimensional or three-dimensional profiles. The mapping is performed using a two-axis optical scanning arrangement (scanning mirror) and a camera/detector combination. In the measurement mode, the system is able to generate a 3D picture (40-degree by 30-degree field of view) in 3 seconds by continuously triangulating the position of the laser spot as it is scanned over a

TABLE 3-10. SPOTRANGE™ SPECIFICATIONS

RANGER	SR01R red	SR01G green	SR02 red	SR02G green
Acoustic				
Frequency (MHz)	1.0	1.0	2.0	2.0
Range, max/min (m)	30/0.2	30/0.2	10/0.2	10/0.2
Resolution (mm)	1	1	1	1
Beam width (deg)	1.5	1.5	2	2
Repetition rate, (Hz)	10	10	10	10
Laser pointer				
Wavelength (nm)	633	532	670	532
Power (mW)	1.5	5	3	2
Visible range (m)				
(b/w CCD)	2-5	8-10	1.5-2	7-9
Beam width (deg)	<0.1	<0.1	<0.1	<0.1
Dimensions/power				
Diameter (mm)	100	100	50	59
Length (mm)	390	489	80	235
Depth rating (m)	1000	500	1000	1000
Power supply (V/A)	24/1.0	24/0.75	24/0.5	24/0.75

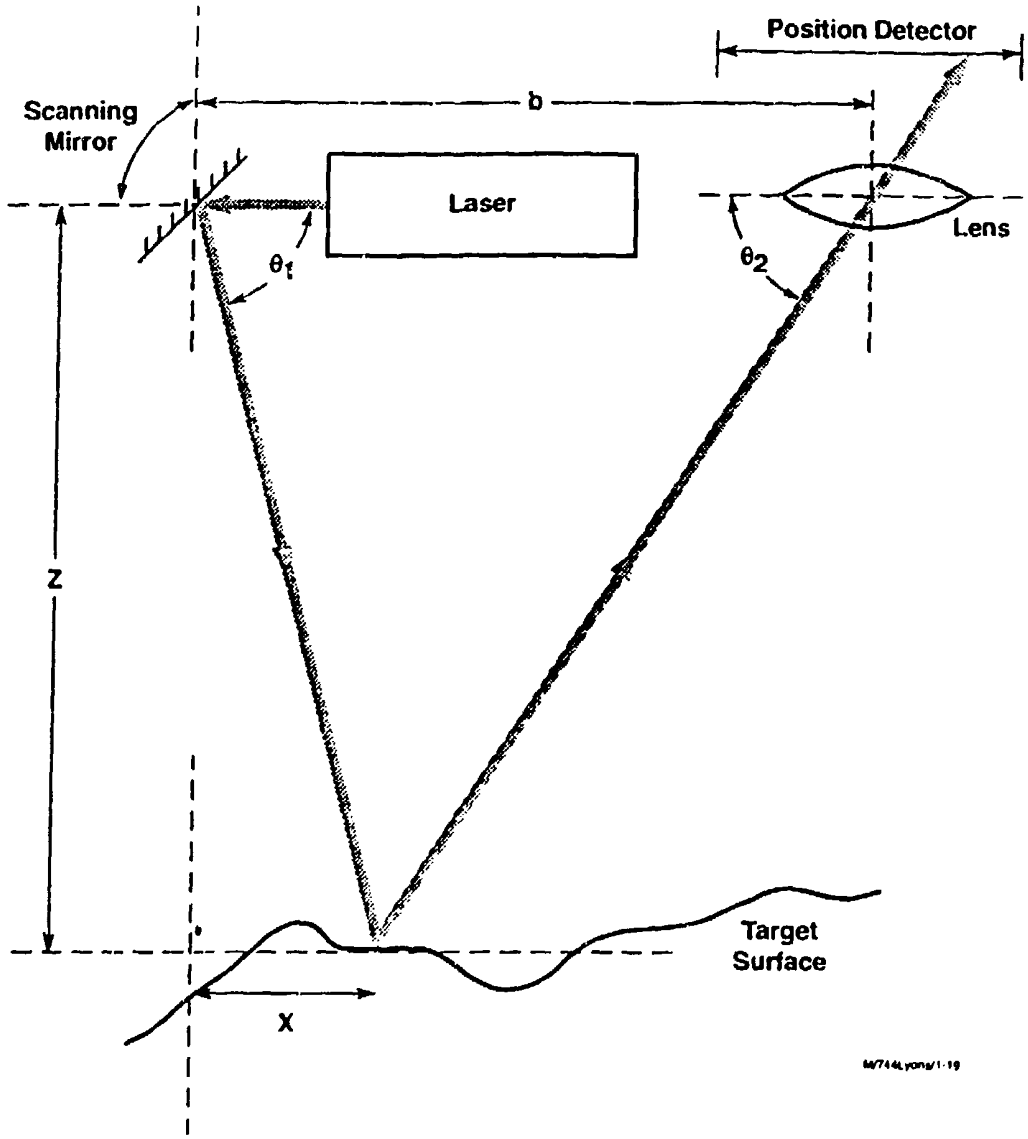


FIGURE 3-30. NCEL/HB01 3D IMAGING SYSTEM—PRINCIPLE OF OPERATION

TABLE 3-11. NCEL 3-D SURFACE MAPPING SYSTEM DESIGN SPECIFICATIONS

Range of operation	0.5 - 2.5 meters
Depth resolution	< 1 mm @ 1 m standoff
Lateral resolution	3 mm @ 1 m standoff
Frame acquisition time	4 seconds
Max. operating depth	3000 feet

target area. The 2D "flying" scanning system produces cross-sectional information as the scanner is flown over an area of interest. The laser/detector of the 2D system scans one axis, and the vehicle provides the perpendicular motion required for image generation. The system software provides scaling, automatic focussing, backscatter reduction, and contrast enhancement. The specifications for the Spotscan 2D and 3D systems are found in Table 3-12. The 3D system has undergone prototype testing but has not been developed to commercial standards: the 2D system is commercially available. The Spotscan system uses a frequency doubled Nd:YAG diode pumped laser with output power of 15 mW. The system is able to image to a distance of approximately two attenuation lengths.

Light Detection and Ranging (LIDAR). Seatex is currently developing a subsea laser radar system for 3D imaging that will be commercially available in 1993. The subsea laser system operates by gathering target range information as the laser is scanned over a target area by a pan-and-tilt mechanism. The prototype system uses a diode-pumped Nd:YAG laser which emits light at a wavelength of 532 nm. The pulse energy is 6.5 μJ at a 1-kHz pulse repetition frequency. The beam has a 5-mm radius and a beam divergence of less than 1 mrad. The outgoing laser light pulse triggers a timing device (range counter), which is stopped when the reflected return pulse reaches the detector. This operating scheme is similar to that used in conventional radar systems and is generally referred to as Light Detection and Ranging (LIDAR). Depending on the required resolution and the standoff range, 3D frame acquisition times vary between 0.5 seconds and 30 seconds. The maximum range of the system is between 20 and 50 meters, depending on the target diffusivity. In laboratory tests, the system was able to measure distances in the 5 to 20-meter range for diffuse targets, and up to 50 meters using a non-diffusive target (corner reflector). The system field of view is 40 degrees by 40 degrees.

TABLE 3-12. SPOTSCAN™ SPECIFICATIONS

SCANNER SPECIFICATIONS		
Laser	Frequency doubled Nd:YAG, diode-pumped	
Wavelength	532 nm (Green)	
Output power	15 mW	
Metric resolution	Depth (2)	0.5 mm at 1-m range 12.5 mm at 5-m range 50.0 mm at 10-m range
	Horiz (XY)	3.0 mm at 1-m range 15.0 mm at 5-m range 30.0 mm at 10-m range
Maximum imaging range	Depends on water quality. Typical ranges for North Sea water (5-m attenuation length) is 8 to 12 meters. In clearer waters, range could be doubled.	
Field of view	40 degrees x 30 degrees	
Frame resolution	240 x 180 (H X V)	
Frame acquisition time (full frame)	3 seconds	

3.3.1.2.3 Laser Scanning and Illumination Systems for Image Enhancement

Laser Line Scan. Laser line scan systems that operate similarly to the synchronous scanning systems described above have been developed. The line scan systems use higher powered laser systems that allow effective viewing ranges approximately five times greater than conventional camera and light systems. Westinghouse has manufactured and tested a system that can be towed at an altitude of 10 to 120 feet, producing a swath width between 10 and 120 feet. For this system, the illumination beam and detector field of view are synchronized onto a common volume of space between a minimum and maximum depth of field. When an object intersects the common volume of the laser beam and the detector field of view, light is reflected onto the detector surface as depicted in Figure 3-31. The sensor must be moved past the object to be imaged, and the rotational speed of the scanner is adjusted to obtain a waterfall video display (similar to the manner in which a side scan

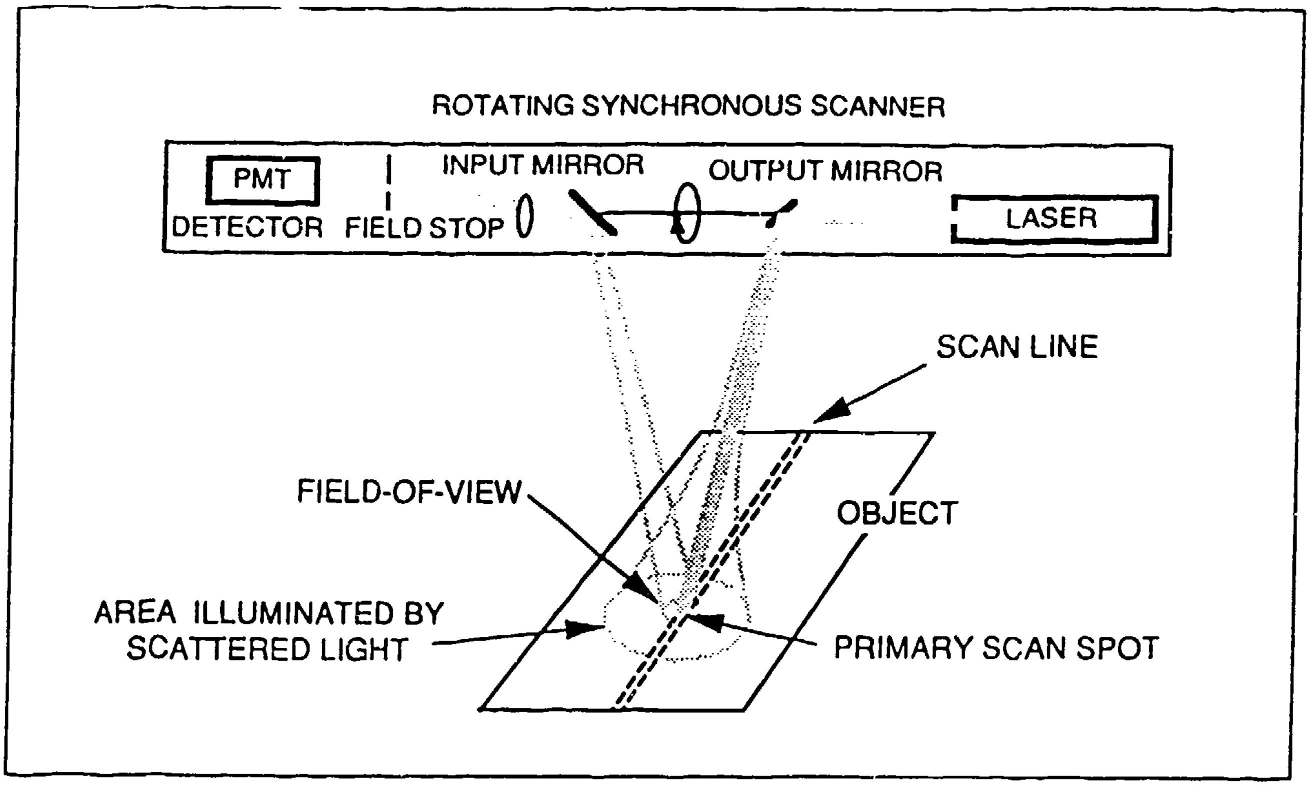


FIGURE 3-31. SYNCHRONOUS SCAN CONCEPTUAL DIAGRAM (*Westinghouse*)

sonar display is generated). Currently the sensors are incorporated into a towed vehicle to provide stability for the system. The specifications for this laser line scan system are in Table 3-13.

TABLE 3-13. LASER LINE SCAN SURVEY SYSTEM SPECIFICATIONS

Vehicle length	80 inches
Vehicle weight	300 pounds (air)/170 pounds (water)
Vehicle type	Towed, passive
Survey speed	2 to 6 knots
Swath angle	70 ° (standard mode)
Survey depth	6,000 feet
Data recording	Standard VHS tape (digital optional)
Data display	Standard video monitor
Resolution	2048 pixels/line
Display format	1024 x 1024 lines

Laser Raster Scan. Lawrence Livermore National Laboratory has developed an underwater laser imaging system (UWLIS) that operates by means of synchronous scanning in two dimensions. It is the first synchronous scanning system of its kind with the capability of achieving real-time scanning rates. The scanning assembly features torque-driven mirrors that enable laser scan rates of 30 frames per second. The system incorporates a special photomultiplier known as an image dissector tube (IDT). The IDT allows the instantaneous field of view to be synchronized with the laser scanner drive signals so that the laser spot at the target plane is always within the field of view. The result is that imagery can be produced over a total field of view of 18 degrees. Although the field of view for this system is smaller than for single-line scanners, the real-time capability is a strong advantage. The raster scan pattern removes the restriction of having to move the platform in a controlled manner in order to generate an image. The ultimate range of the UWLIS is expected to be between 6 and 7 attenuation lengths. According to tests run on moving targets, an 8-frame running average (7.5 frames/second) is the projected maximum that could be used from a moving ROV without experiencing blurring of the video image. The UWLIS system uses a continuous-wave argon-ion laser with an optical output of 7 watts and an input requirement of 10 kW (less than 0.1 percent conversion efficiency). It is expected that within the next few years, smaller, more-efficient laser light sources will be available that will make this system ROV-deployable. This capability will be available with the development of diode-pumped frequency-doubled solid-state Nd:YAG lasers.

Scripps Institution of Oceanography has developed a system that also uses a raster scanning laser to produce high-quality images through turbid waters by collecting time-encoded reflected light from a laser-illuminated target area. The laser works in conjunction with a remote receiver that collects both scattered and unscattered light that varies in intensity in accordance with the reflectance of the minute spot being illuminated. The received signal is known as a time varying intensity (TVI) signal. The laser scanner can be moved freely about the field of interest unencumbered by cables, and real-time images are received for viewing by an operator monitoring the image display at a remote location. Figure 3-32 diagrams the basic components of this laser scanning system. For image generation, the laser scanner portion of this system is positioned within a few meters of the target by a diver or ROV. The laser sends out a synchronizing pulse to the receiver unit and then "paints" the scene. At any instant, the flux detected by the distant receiver is proportional to the reflectance of a particular spot in the scene. This system makes use of a 6-mW helium-neon laser (632.8 nm wavelength) to scan the target. Laboratory and field tests have been performed with this system with good imaging results. The field testing indicates that the scanning unit must be located within 3 to 4 attenuation lengths of the target to produce useable images, but the receiving unit can be placed much farther away (15 to 20 attenuation lengths) and still produce good quality images of an illuminated scene. The experimental TVI system requires 0.5 to 2 seconds to scan a scene. The field of view (scan angle) is adjustable from 3 to 18 degrees. To prevent image distortion, there must be little relative motion between the scanner and the target during the scan. The system basically requires that the receiver be located in or near the line-of-sight of the object being scanned.

Laser-Illuminated Range-Gated ICCD Camera System. A range-gated underwater imaging system is one that employs a temporal, or tir ıdent scheme to provide target imaging.

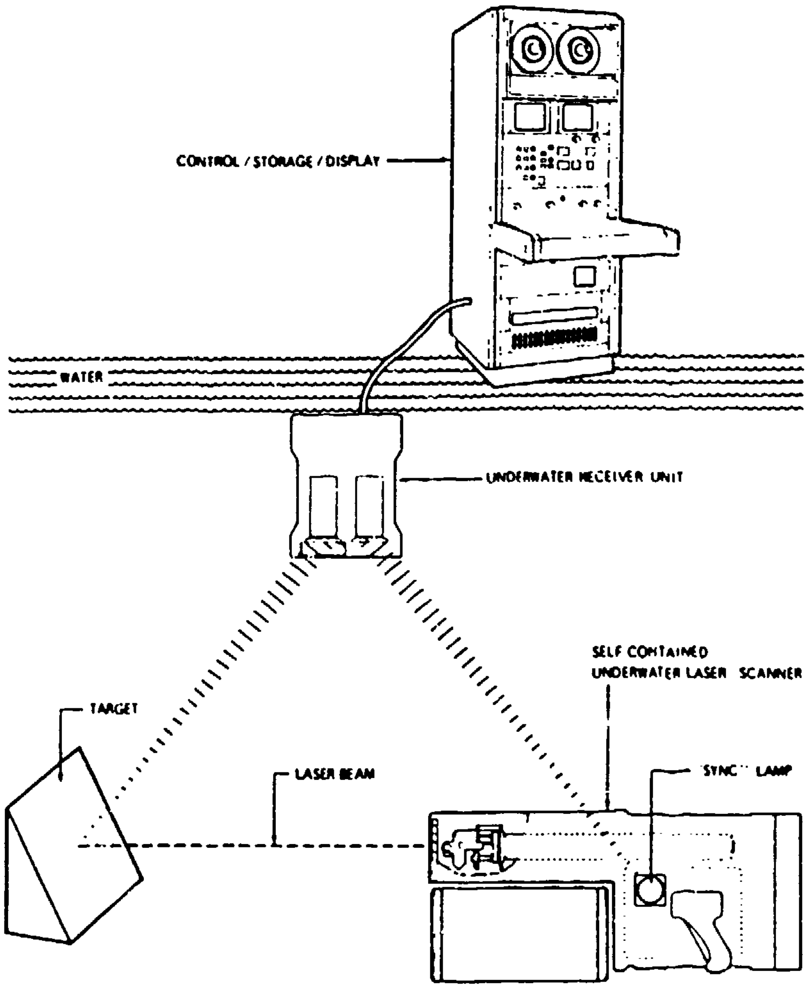


FIGURE 3-32. EXPERIMENTAL TVI IMAGING SYSTEM
(*Austin, et. al., 1991*)

The basic concept of operation for a laser-illuminated range-gated imaging system is depicted in Figures 3-33 and 3-34. The illumination technique is employed to minimize backscatter noise, thereby allowing imaging to occur at increased attenuation lengths. Figure 3-33 illustrates how light intensity returning to a receiver varies as a function of time after the emission of a short illumination pulse. Curve A shows that for a transmitted pulse of laser light, a receiver will collect mainly noise. If, however, the receiver is left off until just before receiving a return pulse and then turned off after receiving it as shown in Curve B, the signal-to-noise ratio is significantly increased.
Figure 3-34 illustrates the technique in the distance domain. This figure shows that, if the illumination pulse width and receiver gate width are matched and the timing is properly sequenced, the light return Curve B of Figure 3-33 can be achieved.

Sensitive ICCD cameras that can be gated down to 5 nanoseconds are now commercially available. High peak power lasers are capable of delivering pulses of comparable width in the blue/green spectral region. Sparta Laser Systems Laboratory has developed a system which uses a frequency-doubled Nd:YAG laser that can generate pulses down to 7 ns in width containing up to 200 mJ of energy at 532 nm. The system operates at 30 Hz. A range-gated system does not impose restrictions on platform stability, because the full frame acquisition time is less than 10 ns and the relative motion between a target and the sensor delivery platform during that time period would be negligible. This system is reported to be very insensitive to background ambient light and to back lighting because the receiver is on for such a short time that the light from these sources is insignificant compared with the high peak laser power received during the gating period. Additional image enhancement of the target area has been achieved in laboratory tests by adding polarization filters, which make use of differences between a target and background depolarization characteristics.

Video Moire Imaging. Interferometric techniques can offer improvements in range resolution as compared to other structured lighting techniques. Video moire imaging makes use of the interference patterns generated by two spatial gratings to provide real-time range information. Harbor Branch Oceanographic Institution and Florida Institute of Technology have developed a laboratory moire imaging system that effectively demonstrates the feasibility of using a moire contouring system to generate surface contours. The laboratory system uses an argon-ion laser operated at either 488 or 514 nm wavelength and from 5 to 100 mW output power, depending on the size and illumination needs of the target. The grating pattern is generated by inputting the laser beam into an interferometer which produces vertical straight line patterns with spacing that can be varied by

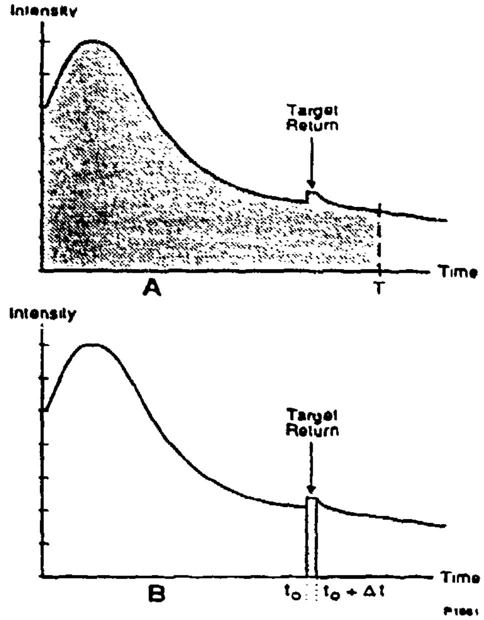


FIGURE 3-33. SIGNAL-TO-NOISE-RATIO IMPROVEMENT THROUGH RANGE GATING
(Sparta Laser Systems Laboratory)

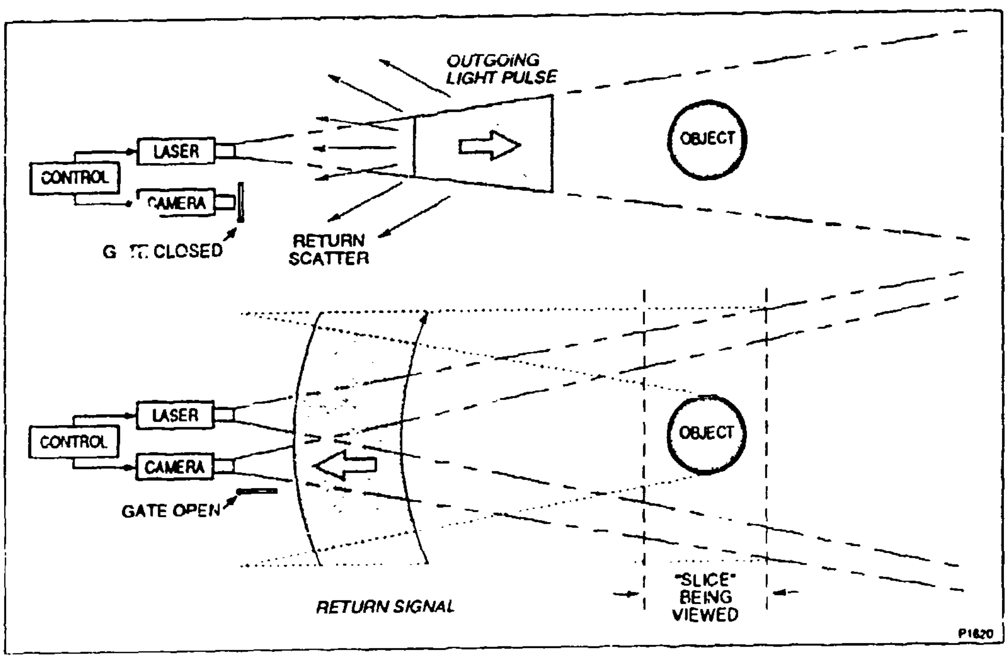


FIGURE 3-34. THEORY OF OPERATION FOR A LASER RANGE-GATED IMAGING SYSTEM
(Sparta Laser Systems Laboratory)

the operator through positioning an integral mirror. A projection zoom lens is placed in the interferometer output beam to expand or condense the area of illumination. The grating pattern splits after it leaves the zoom lens, with a portion being projected onto a reference target and a portion being projected onto a distorted target as shown in Figure 3-35. The projected images are individually viewed through reference and target video cameras. The image projected on the undistorted target is used as a "filter" for the image being received from the distorted target. In effect, the deviations between the reference surface and the target area are made visible through this filtration technique. The moire patterns generated make a distorted or damaged area easier to recognize by creating topographic contour lines on the object being imaged. Figures 3-36 and 3-37 show how effectively the moire imaging technique establishes depth information on objects that may be difficult to analyze using conventional lighting methods.

3.3.1.2.4 Laser Safety

Personnel safety is an important consideration for laser systems. The human eye is the organ most sensitive to the laser, with the retina being the primary site of damage for wavelengths between 390 and 1,500 nm. Depending on the wavelength, exposure time and power level limits existed (typically measured in Joules/cm^2). Laser light can pass through the air-sea interface, being refracted according to Snell's law, which describes the relationship between the angle of incidence and angle of refraction of the laser light. The amount of laser light that reaches a person above the waterline is a function of the attenuation of light in both the water and air through which it is passing. Personnel protection should be provided for any system that generates sufficient laser energy to be of concern. Examples of protection methods that could be incorporated are tilt sensors, which switch off the laser if it is transmitting above a given angle, or float switches, which turn off the laser if it is removed from the water.

3.3.1.3 Sonar Systems

Because of the ocean's relative opacity to electromagnetic energy, sonar commonly has been used in undersea imaging, surveying, and mapping applications. Despite the widespread applications of sonar in the ocean, acoustic techniques for underwater use are less advanced than

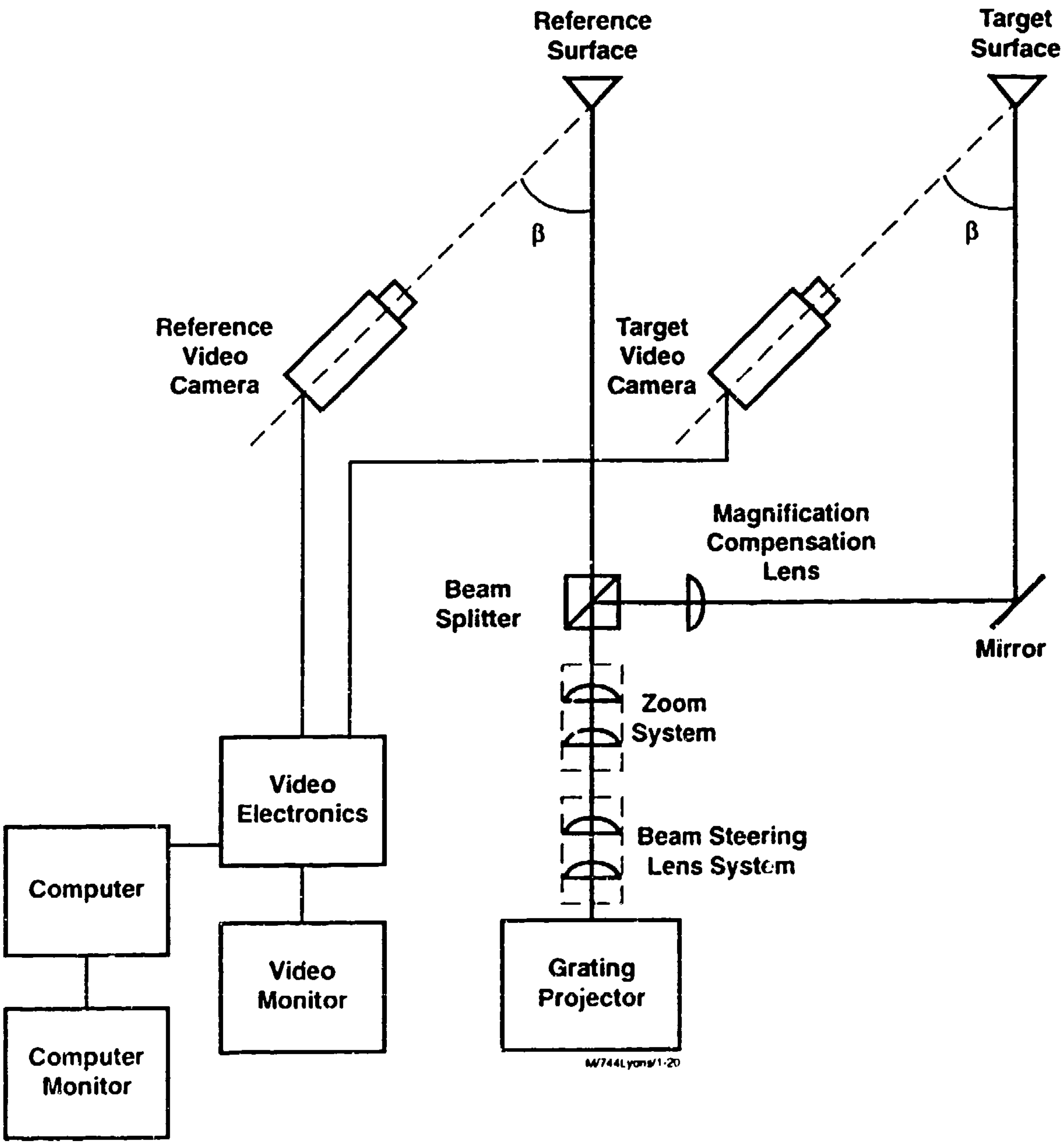


FIGURE 3-35. SET-UP FOR TWO-CAMERA PROJECTION MOIRE

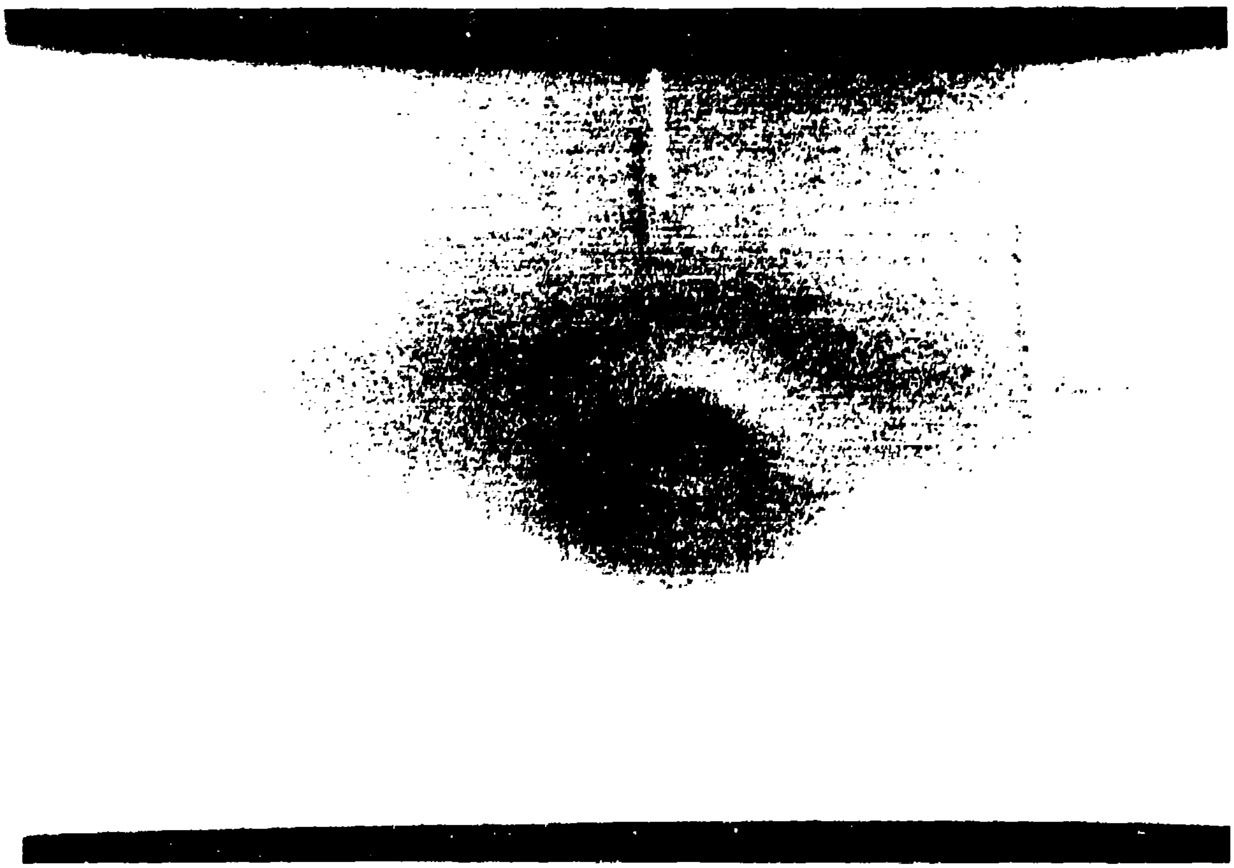


FIGURE 3-36. DIMPLED PIPE ***(Caimi, Smith, and Kocak, 1992)***

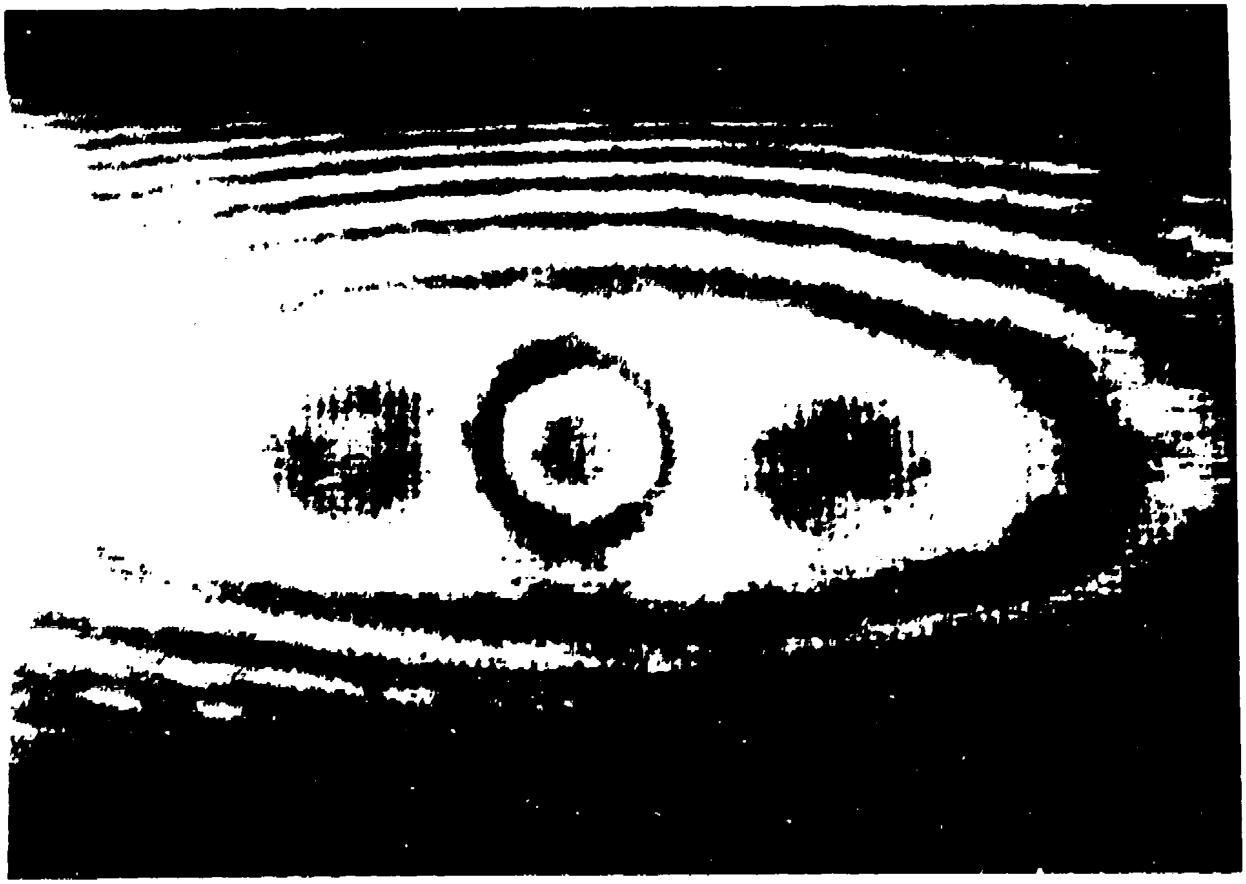


FIGURE 3-37. IMAGE OF DIMPLED PIPE
(Calmi, Smith, and Kocak, 1992)

acoustic techniques for medical imaging. Medical ultrasonic techniques include reflective (pulse-echo) imaging, direct transmission imaging,holography, interferometry, and tomography (time-of-flight, attenuation, reflection, diffraction).

There are two basic types of sonar systems, active and passive. An active sonar system both transmits sound and listens for the returning echo from objects. Conversely, a passive sonar system does not transmit any sound of its own. A passive system only listens for sound present in the medium. The basic elements of any active sonar system are the transducer, the receiver, the control/display, and the transmitter. These elements are shown in Figure 3-38. The transducer converts energy from one form to another. Piezoelectric crystals are most commonly used as transducers in sonar systems. The crystal converts the oscillating electric field produced by the transmitter into a sound pulse. The shape of the crystal affects the beam pattern of the emitted pulse. The sound travels away from the transducer, and an echo is returned to the transducer if the sound strikes an object located within a limited range of the sonar. The transducer converts the echo into an electrical signal. The receiver detects and amplifies this signal. Separate transducers can be used for transmitting and receiving the sound pulse. Systems which use separate transducers are called

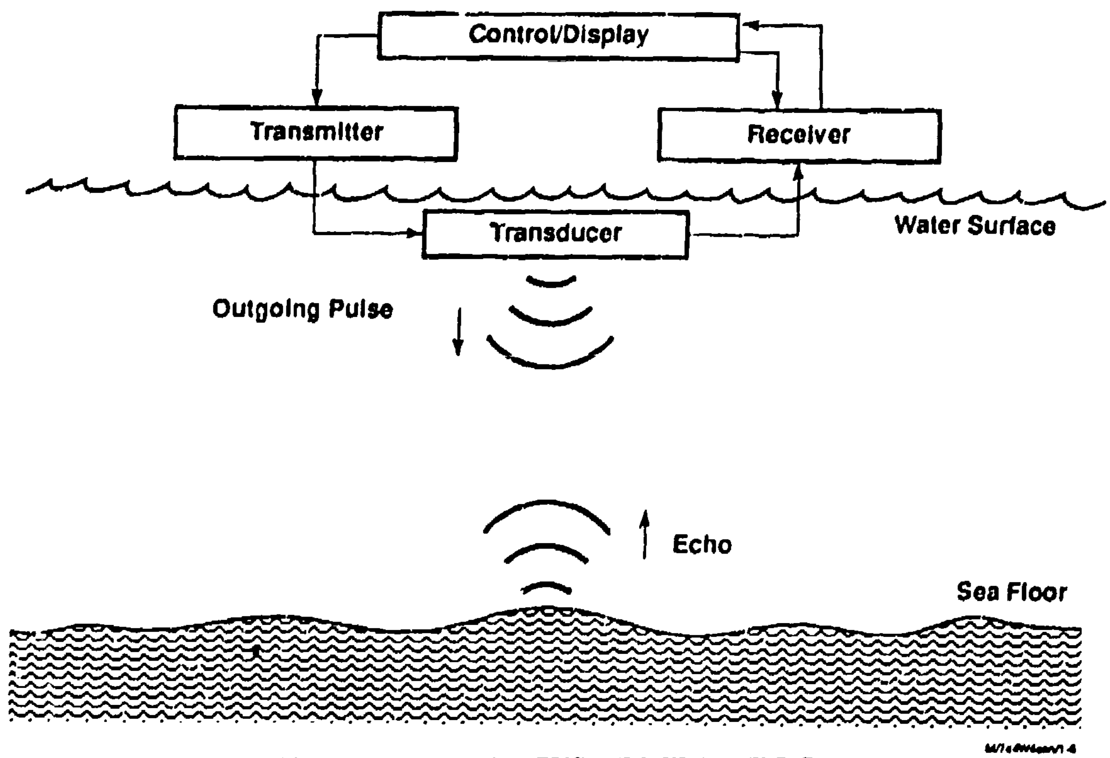


FIGURE 3-38. SONAR SYSTEM ELEMENTS
(Side Scan Sonar Record Interpretation, 1985)

monostatic systems. A single transducer is used for both transmitting and receiving in bistatic systems. The final element, the control and display, both commands the coordinated operation of the other elements and displays the results of the sonar operation.

Sonar systems determine depth or distance by measuring the time for the sound pulse to travel from the transducer to the target and back. The accuracy of the sonar is a function of the precision with which this time can be measured. The depth or distance can be calculated according to the equation:

$$D = \tfrac{1}{2} ST$$

where D = depth or distance
S = speed of sound in water
T = time for sound to travel out and return.

Although the speed of sound in water varies with changes in temperature and depth, an average value commonly used is 1492 meters per second. The speed of sound can be as low as 1410 meters per second in artic regions and as high as 1540 meters per second near the equator.

While increasing frequency improves lateral resolution, the range of the sonar decreases at higher frequencies. This is due to the increase in the acoustic absorption coefficient at higher frequencies. The absorption coefficient also increases when salinity increases or when temperature or pressure decrease.

Use of sonar to perform damage assessment of hulls is a much different application than was intended for most commercially available sonars. Most commercially available sonars, whether side-scan, obstacle avoidance, or bathymetric, are used to locate and characterize objects against backgrounds such as the sea bottom. The sea bottom gives some nominal return to the sonar, while any objects on or near the sea bottom will produce a return signal different from this nominal return. Damage assessment on a hull is a quite different situation. First, the hull itself could produce a very large return. If the hull is damaged, the damage, whether it is a hole or a crack, actually represents the absence of an object. Thus, in using sonar for damage assessment, the sensor operator might actually look for the absence of a return rather than a return. Second, the sea bottom is a relatively rough surface and will yield a return to the sonar regardless of the angle of incidence of the sonar wave. A ship's hull, however, can be relatively smooth and might reflect the sound pulse, producing little or no return to the sonar. In this scenario, the hull would be referred to as a specular reflector. The potential problem of specular reflectance is discussed later in greater detail.

Several different techniques are used to create an acoustic image. Generally, these techniques can be divided into (a) broad-beam acoustic sources with filled arrays and (b) synthetic aperture sonars. With broad-beam acoustic sources, the general area to be imaged is ensonified while the filled array gathers information from all locations of the image simultaneously. This approach is similar to a flash camera, which uses a flash to light up the area to be imaged while a sheet of film acts as the filled array and collects the image information. In an acoustic system, a filled planar array of hydrophones is used in place of the film.

Synthetic aperture sonars use a smaller array, which is scanned in some fashion to simulate the area of the filled array. While many different configurations are possible, the general idea of these sonars is to replace the large array of receiving transducers with significantly fewer transducers in a scanning arrangement. Though the reduced number of transducers results in cost savings, several disadvantages of synthetic aperture sonars include increased scan times, motion blurring, low signal-to-noise ratios, and increased signal processing.

There are three methods of acoustic imaging: electronic beam forming, focused acoustic imaging, and holographic acoustic imaging. These methods, along with the advantages and disadvantages of each, are summarized in Figure 3-39. In electronic beam forming, a signal-processing chip can be used to delay the signal from elements in the receiving array so that the resulting composite signal consists only of the signal from a specific direction. The delays can be adjusted to change the direction represented in the return signal. Focused imaging systems use a lens or lenses to focus the image onto an image plane. The operating principle of these systems is similar to that of a camera. Finally, a holographic imaging system performs a spatial Fourier transform of the received acoustic wavefront to create an image.

The lateral or transverse resolution of a sonar system is determined by the angular size of the acoustic pulse (beam). The beam angle is centered around the portion of the acoustic pulse where the signal is the strongest. The edges of the beam angle are defined by locating where the signal level drops 3 dB below the peak signal. The beam angle determines how much the signal will spread by the time it reaches the target. As the distance to the target increases, the signal continues to spread, increasing the size of the acoustic "footprint" on the target and decreasing the lateral resolution. An acoustic approach to damage assessment will always be limited in resolution to the width of the acoustic array. Fine damage narrower than the array itself will not be detectable by

	Configuration	Advantages	Disadvantages
Focused Acoustic Imaging	Lens → Hydrophone Array → Electronics → Display	Fast update rates High resolution	Temperature aberrations Complexity
Electronic Beam Formed	Hydrophone Array → Beam-forming → Electronics → Display	Relatively high resolution Available technology Adaptable to constraints	Fast processing required High power Difficult to correct in near field
Holographic Acoustic Imaging	Hydrophone Array → Channel processor → Recon-structor → Display	Robust information High resolution	Few proven applications High processing High stability required

FIGURE 3-39. METHODS OF ACOUSTIC IMAGING
(*University of New Hampshire, 1990*)

the array, even in the near field. Most array elements used in commercially available sonars are about 0.25 inch wide. Thus, fine cracks in hulls may not be detectable even with the best commercially available sonars.

Range resolution determines the precision with which a sonar can measure the distance from the transducer to the target. Range resolution of sonars is determined by the pulse length. The pulse length is the time over which the transducer transmits an acoustic pulse. The front edge of the sound wave is in front of the back edge of the sound wave by the distance sound travels during the pulse length. Thus, range resolution can be calculated as:

Range Resolution = ½ (Pulse Length x Speed of Sound).

Below, five types of sonar systems—side scan sonar, forward-look sonar, bathymetric sonar, profiling sonar, and 3D mapping sonar—are overviewed, and their possible applications to hull damage assessment are discussed.

3.3.1.3.1 Side-Scan Sonar

Side-scan sonar is the most common high-frequency sonar. It is most often used for mapping or imaging the sea ' ottom and for locating small objects. Because the sonar is turned on its side, it can be used to look at a series of echoes from along the bottom, rather than at just a single echo from a specific target. Common characteristics of side scan sonar include the following:

- Sideways look - the sonar is positioned to look sideways from a towed body,
- Two channels - two transducers are often used to obtain simultaneous information from both sides of the towed body.
- Narrow beam - a sound pulse, narrow in the horizontal plane, is used to obtain high resolution (axial resolution) to maximize the sonar's performance in locating objects on the bottom.

Figures 3-40 and 3-41 show the field of view of typical towed side-scan sonars. These figures illustrate the characteristics of sideways look, two channels, and narrow horizontal beam. The sonar beam is wide in the vertical direction, making it possible to search the bottom from very short ranges out to the maximum range (radial range) of the sonar in a single sweep of the towed body. Table 3-14 lists operating specifications for numerous commercially available side-scan sonar systems. In this table, the horizontal beamwidth and the range information can be used to calculate the width of the acoustic footprint (the lateral or along-track resolution) on a target. The pulse repetition rate (not included in the table) for Klein's very high resolution side-scan sonar, Model 422S-101EF is 30 pulses per second at a range of 25 meters.

TABLE 3-14. COMMERCIALLY AVAILABLE SIDE-SCAN SONARS

SONAR	FREQUENCY (kHz)	HORIZONTAL	VERTICAL	MINIMUM FIELD OF VIEW (degrees)	MAXIMUM RANGE SCALE (meters)
EG&G 272T	100	1.2	50	25	600
EG&G 272TD	500	0.5	50	25	600
Klein 422S-101AF	100	1	40	25	750
Klein 422S-101HF	100/500	1/0.2	40	25	750
Klein 422S-101EF	500	0.2	40	25	750
Klein 422S-101GF	50	1.5	40	25	750
Klein 422XS-101AF	100	1	20-40	25	750
Klein 422S-101F	100	0.75	40	25	750
Mesotech MS992	120/330	0.75/0.2	50	5	800
Sea Scan 1000	150/300	1/0.5	23	12.5	400
Wesmar SHD700SS	107/60	1.5	35	10	1000

The sound pulse sent out by the side-scan sonar is transmitted, absorbed, or reflected by the surfaces and objects it encounters. The strength of the reflected energy and the two-way travel time are used in generating an image of the bottom and any objects resting on the bottom. The vertical dimensions of some features of the image can be estimated from the length of the acoustic shadows cast by the features.

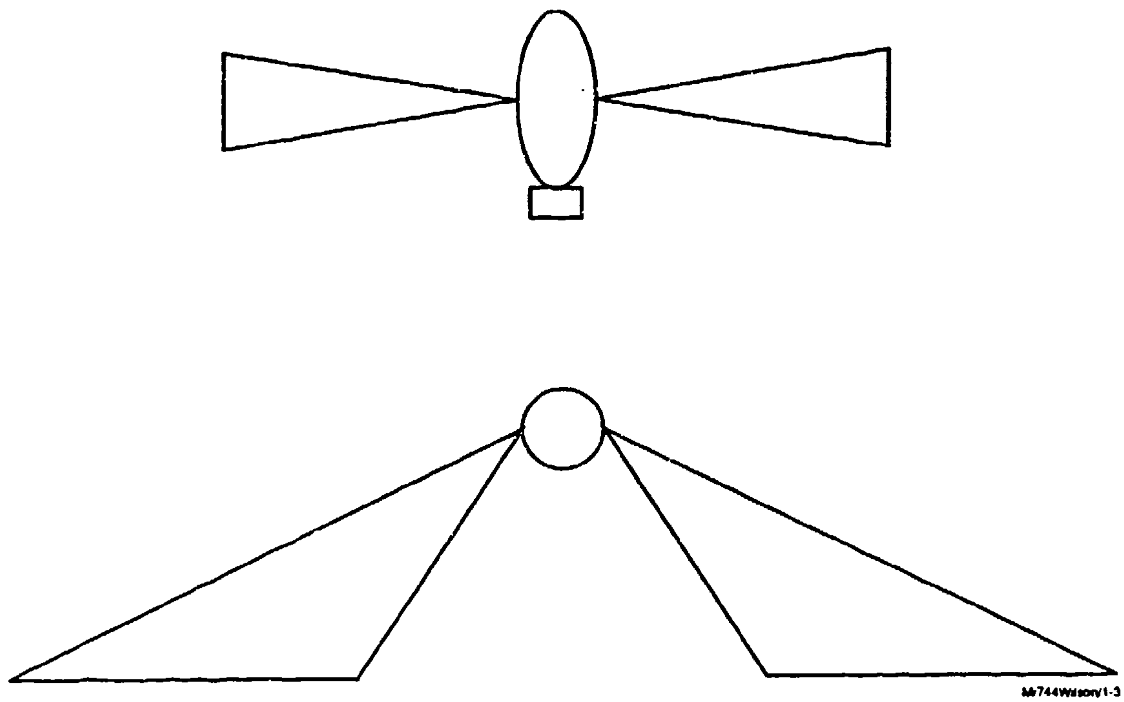


FIGURE 3-40. ACOUSTIC BEAMS VOLUME COVERAGE

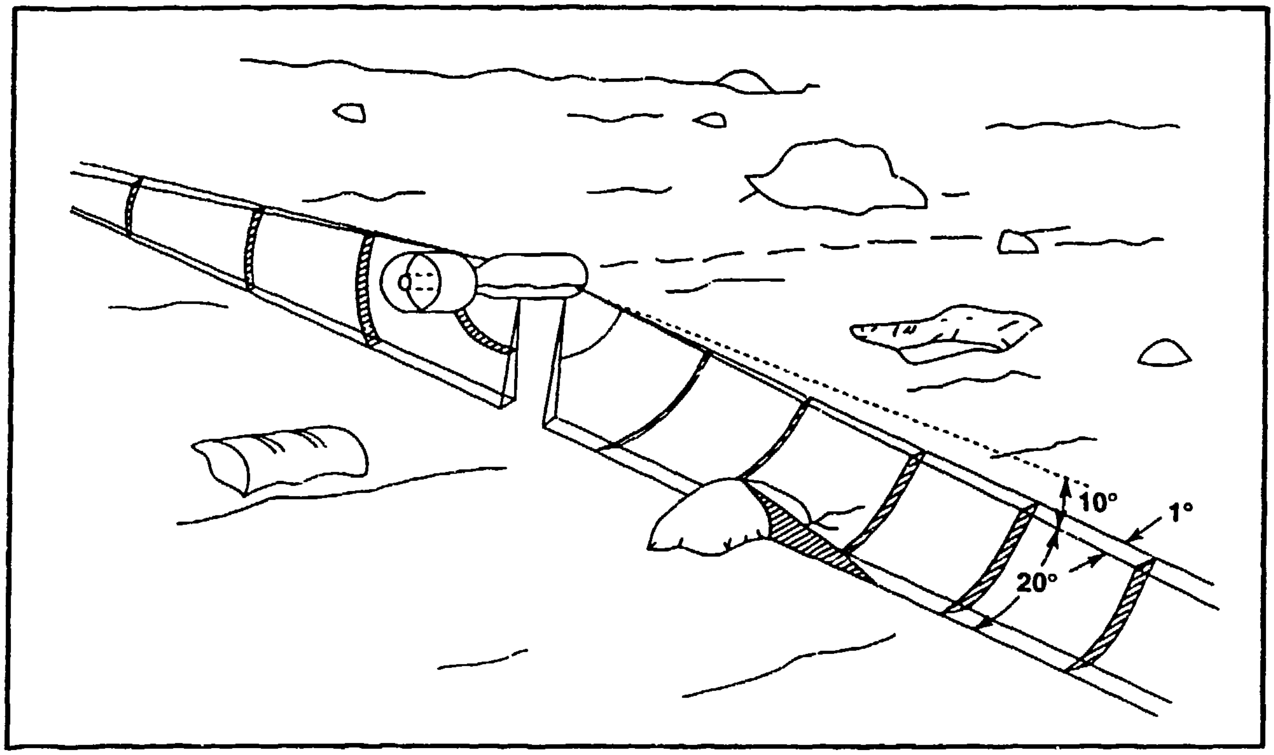


FIGURE 3-41. ARTIST'S SKETCH OF A TOWED SIDE-SCAN SONAR
(*Dybedal, Ingebrigtsen, Lovik, 1985*)

The altitude of the side-scan sonar above the bottom has an impact on the performance of the sonar. The primary effect of altitude on interpreting the sonar image is the size of the shadows. The altitude of the side-scan sonar affects shadow formation, particularly the length of the shadow. Directly below the towed body, there are no acoustic shadows. The shadows begin to form as the sound wave travels to the sides, away from the towed body. Thus, the field of view of the side scan sonar excludes a path directly beneath its axis of travel. The rule of thumb for optimal performance of side-scan sonars is an operating altitude of 10 to 20 percent of the maximum range.

The output of a side-scan sonar is often referred to as a "waterfall" display. Each pulse of the sonar appears on a screen and/or is printed as the signal is received. Each pulse signal appears as a line, and as the sonar travels along, successive lines are added to create an image.

For assessing damage to a ship or vessel, the side-scan sonar could be mounted on any remote vehicle. The side-scan sonar would be positioned relative to the hull as though the hull were the sea bottom. The flat, smooth surface of a clean and undamaged hull would not show any objects. A crack or hole on this same hull might produce a signal on the side-scan sonar. A hole or a crack might be referred to as a negative displacement contour as shown in Figure 3-42 (a). This is different than an object such as a barnacle, which would be a positive displacement contour (above the surface of the hull). The sequence of signal levels for a positive displacement contour would be an increase in signal level above the nominal, followed by zero signal in the acoustic shadow area, and then a return to the nominal signal level beyond the acoustic shadow. For a negative displacement contour such as a hole, the sequence of signals would be a drop to zero signal from the nominal level, followed by increasing signals from the upsloping side of the far end of the negative displacement contour as shown in Figure 3-42 (b), and then a return to the nominal signal. In the case of a hole, there may not be an increase in signal beyond the close edge of the hole due to the absence of upsloping contours.

Small or large scale dents may be detectable using side-scan sonar. The recessed area of the dent may appear as a shadow on the sonar output. Cracks may or may not be detectable, partly depending on the orientation of the crack. Cracks parallel to the travel path of the sonar would likely be easier to detect than cracks perpendicular to the direction of travel.

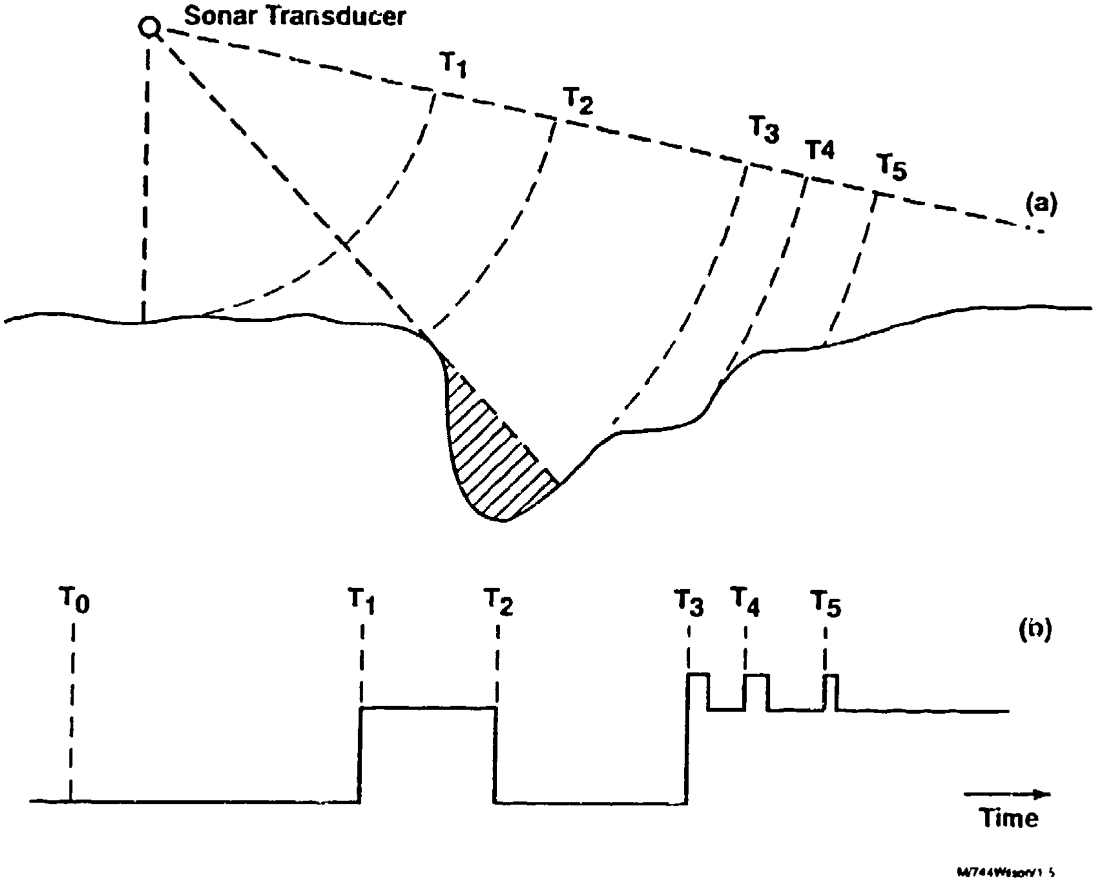


FIGURE 3-42. SEQUENCE OF SIGNAL LEVELS FOR A NEGATIVE DISPLACEMENT CONTOUR (A); RECTIFIED OUTPUT SIGNAL (B)
(J.M. Cuschieri and M. Hebert, 1990)

Cracks parallel to the travel would appear in several successive pulses of the sonar, where cracks perpendicular to the travel might appear in only one pulse of the sonar and would be easier to miss. This is especially true with the "waterfall" display of side scan sonars. A parallel crack would be more apparent in the printed record.

There are two primary advantages to using side-scan sonar for hull damage assessment. First, with the reasonably large field of view of the sensor, the entire hull could be scanned relatively quickly. Second, the sonar could be operated in turbid water without the degradation in performance which would occur in optical systems.

Despite these advantages, there are significant potential problems with a damage assessment approach using side-scan sonar. First, though the sonar might show some kind of anomaly for a hole, and a cross track with the sonar might reveal the edges of the hole, it would be very difficult to distinguish between anomalies resulting from hull damage and anomalies resulting from barnacles or other marine growths on a hull. This problem will exist despite the (above discussed) positive and negative displacement contours, which will be difficult to separate in actual practice. This problem was discovered by Klein Associates, Inc. in tests they conducted with their side-scan sonar instruments. During the tests, Klein concluded that sizable cracks (1 to 2 inches wide and 1 to 3 feet long) in concrete-faced piers were not identifiable using side-scan sonar. However, Westinghouse had a different experience. Traveling down the Mississippi River, they were able to see the cracks between revetments using a fairly low frequency side-scan sonar. Tests will be needed to resolve these conflicting results. Another problem is operating the sonar near the water surface. This arrangement could lead to interference with the transmission of the acoustic pulse by air entrained in the water column.

A clean steel hull might act as a specular reflector, producing no return signal to a side-scan sonar. In this case, the back edge of a crack or hole might be visible using side-scan sonar. Barnacles or marine growth on the hull may or may not hinder the damage assessment. On one hand, the damage might be difficult to distinguish from barnacles and marine growth. On the other hand, an even coating of barnacles or marine growth might make the hull appear more like the sea bottom, preventing the hull from acting as a specular reflector and actually improving the situation by providing a nominal return to the sonar. In this case, the return would change from some nominal level after encountering damage. Experts consulted during this program expressed both of these viewpoints.

3.3.1.3.2 Forward-Look Sonar

Forward-look sonars are used for obstacle/terrain detection and avoidance, fish finding, and area surveillance. Forward-look sonars can take two different forms. The first are single-beam sonars, which are mechanically or electronically scanned to cover a desired field of view. The second are multi-beam sonars, called scan within a pulse (SWAP) sonars, which scan the desired FOV in a single pulse period. Various configurations of forward-look sonars result from different combinations of these two forms. These include mechanically scanned pulsed sonars, mechanically scanned continuous transmission frequency modulation (CTFM) sonars, and SWAP sonars covering either one or two dimensional FOVs. Table 3-15 lists operating specifications for numerous commercially available forward-look sonar systems. Most of these systems are single-beam, mechanically scanned, pulsed sonars. The EG&G Model 728 is a mechanically scanned pulsed sonar with four beams to allow for faster image update rates. The Seabat 6012 is a SWAP sonar with 60 beams, each with a horizontal beam angle of 1.5 degrees and a vertical beam angle of 15 degrees. Knudsen Engineering's DAISY D90-01336 Planar Array uses electronic beamforming and 64 hydrophones to create receive-element beam widths of 1.3 x 1.7 degrees each. This sonar system can be used for three-dimensional imaging, but the 3-D image update rate of only one image every 5 seconds is probably too slow for a hull damage assessment system.

The mechanically scanned sonars require a large number of pulses to scan the FOV. It is similar to side-scan sonar in that information is obtained one sector at a time. The angular and range resolution are functions of the beam width and the duration of the pulse, respectively. Because each transmitted pulse must travel to the maximum range and back, the search rate of mechanically scanned sonars is very low. Movement between the pulses can distort the acoustic image. Thus, the mechanically scanned sonars operate best on stationary or very slowly moving platforms. To reduce the scan time, the beam width can be increased, but this would reduce the horizontal resolution.

Mechanically scanned CTFM sonars ensonify a large area and receive with a narrow beam which follows the transmit beam. The slow coverage of mechanically scanned pulsed sonars is improved with CTFM by transmitting a continuous sawtooth frequency slide signal. The CTFM transforms the time-based range information into the frequency domain, improving the scan rate as compared to pulsed sonar. Though the scan rate of CTFM sonars is somewhat faster than that of

TABLE 3-15. COMMERCIALLY AVAILABLE FORWARD-LOOK SONARS

MODEL NUMBER	TYPE	HORIZONTAL Field of View (degrees)	VERTICAL Field of View (degrees)	NUMBER OF BEAMS	NOMINAL FREQUENCY (kHz)	RANGE RESOLUTION (meters)
AMETEK 258	CTFM	3	15		122 (MAX)	0.061
AMETEK 258	CTFM	1.5	30		357 (MAX)	0.038
EG&G 728	MS	115	20 or 40	4	500	0.04
Wesmar HD600-E	MS	360	90	1	160	0.3
MEL 1640	MS	360	20	1	500	0.04
Mesotech 971	MS	360	30	1	675	0.012
Reson Seabat 6012	SWAP	90 (1.5 each)	15	60	455	0.05
Tritech ST325	MS	360	24	1	325	0.04
Tritech ST525 (BT)	MS	360	24	1	525	0.04
Tritech ST725	MS	360	24	1	725	0.04
UDI 4000	MS	360	27	1	150-1500	0.07
HISCAN 600	ES	360	10	16	600	0.05
Daisy	EB, SW	90	90	3600	50-200	0.05

mechanically scanned sonars, CTFM sonars can also produce distorted images when operated on a moving platform. The main advantage of CTFM sonars is the improved scan rate, which allows a higher horizontal resolution.

Of the forward-look sonars, the multiple beam SWAP sonars operate best on moving platforms because the entire image is created in a single pulse. The SWAP sonars also have the highest scan rates due to larger FOVs and the elimination of the need for mechanical scanning. The main advantages of multiple beam SWAP sonars are high rates of data gathering (reducing platform motion distortion), improved range resolution (tied to pulse length), and the elimination of moving parts.

The output of most forward-look sonars is a monochrome or color video display. The display usually allows for either sector or polar views of the scene. Most of these displays also include RS232 serial data ports for output to a computer and/or a video output for recording. Figure 3-43 shows the shape of a beam used in a typical imaging sonar. This beam would be scanned through a specified sector angle (or rotated 360 degrees for polar plots) to view the scene of interest. A multibeam system such as the Seabat 6012 sends out many of these beams simultaneously to cover a large field of view in a short period of time without sacrificing resolution. Figure 3-44 shows the intersection between a beam and targets on a flat surface. These targets would be classified as positive displacement contours rather than negative displacement contours like holes or cracks. Figure 3-45 shows the return echo strength for these targets received by the sonar over a short time

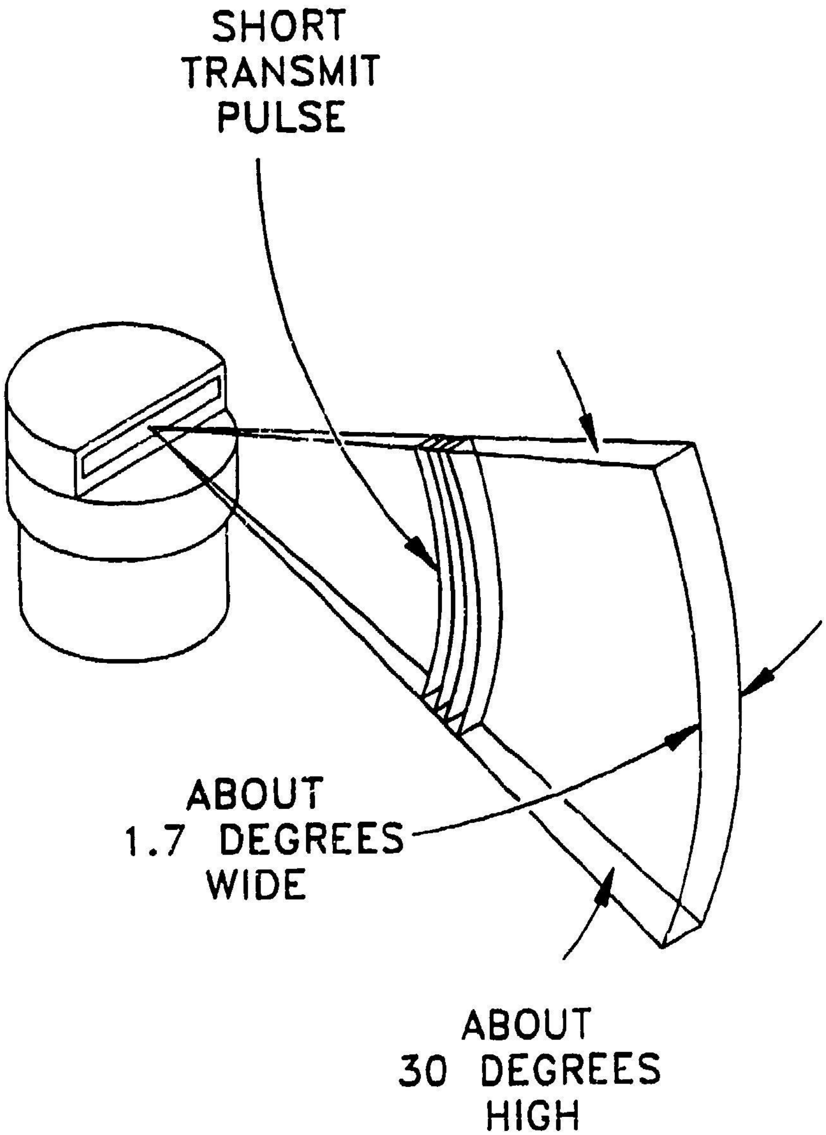


FIGURE 3-43. TYPICAL FAN-SHAPED BEAM AS USED ON IMAGING SONARS
(Imagenex Operator's Manual)

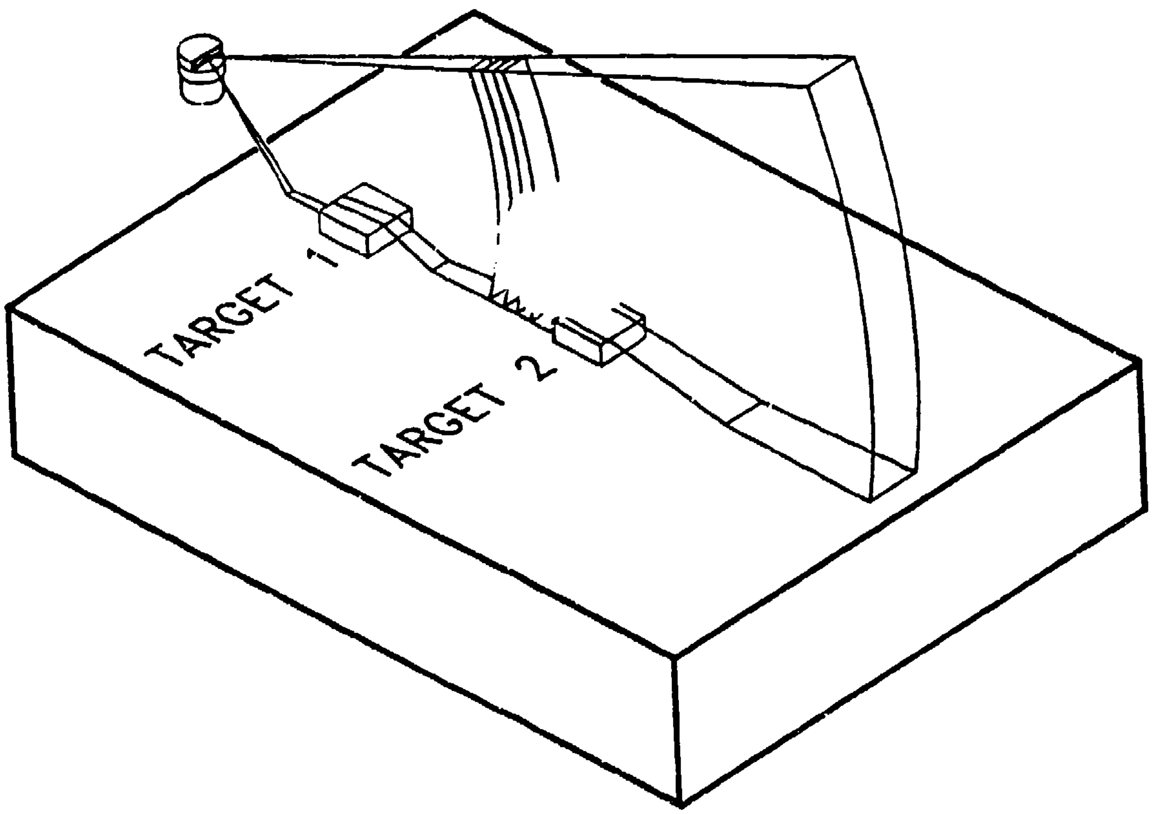


FIGURE 3-44. FAN-SHAPED SONAR BEAM INTERSECTS WITH A FLAT BOTTOM AND TARGETS
(Imagenex Operator's Manual)

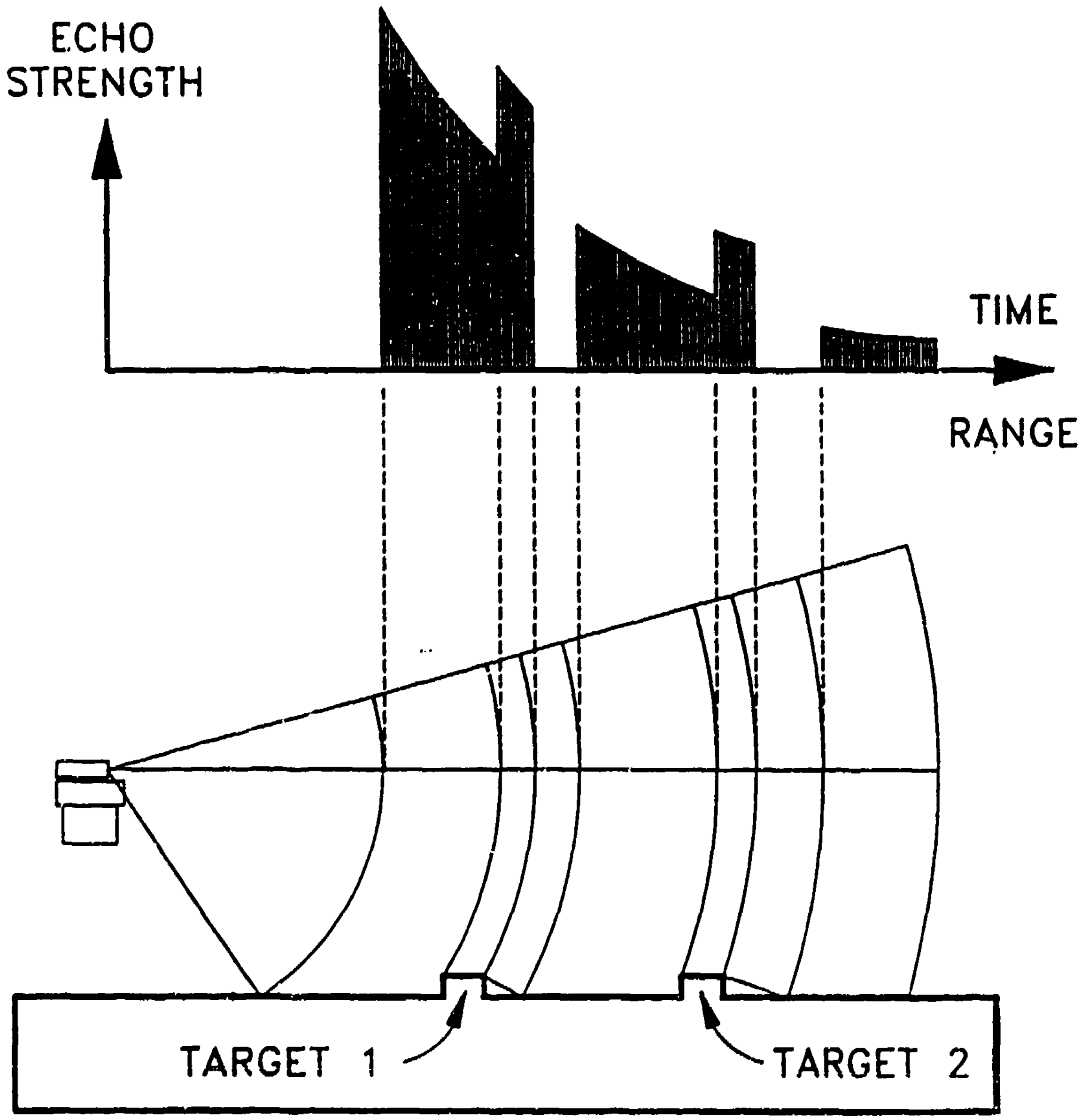


FIGURE 3-45. ECHO STRENGTH VS TIME WHEN FAN-SHAPED SONAR BEAM INTERSECTS WITH A FLAT BOTTOM AND TARGETS
(*Imagenex Operator's Manual*)

period. A time-varying gain correction such s that shown in Figure 3-46 can be applied to obtain the final signal.

Most forward-look sonars have beams that are wide in the vertical direction and narrow in the horizontal direction, similar to side-scan sonar. Thus, in locating a hole in a ship's hull, forward-look sonar would be used in much the same manner as would side-scan sonar. The main difference is the orientation of the sonar relative to the vehicle on which it is mounted. Where the side-scan sonar is mounted to look out toward the sides of the vehicle, the forward-look sonar would be mounted to image the area in front of the vehicle. Forward-look sonar would likely yield a return above nominal from the back edge of a hole. Once again, the hole might act as a negative displacement contour, with a shadowed area due to signal lost in the hole, followed by a strong return from the back edge of the hole. As with side-scan sonar, it may be difficult to distinguish hull damage from barnacles or marine growth using forward-look sonar.

Both side-scan sonar and forward-look sonar could be used to inspect large areas of the hull in a relatively short time, making these sonars candidate sensors for a damage assessment system. However, these sonars will probably not be capable of characterizing the damage once it has been located. These sonars do not provide adequate resolution to determine the size and shape of small holes or cracks.

3.3.1.3.3 Bathymeric Sonar

Bathymetric, or down-looking sonars, are used for bottom contour mapping, depth sensing, fish finding, altitude sensing, and other similar tasks. The bathymetric sonars are very similar to forward-look sonars except they are aimed downward. The transmitted beam is narrow along the travel path of the sonar and wide in the plane normal to the direction of travel. A fan of contiguous beams within the transmitted beam are used to receive detailed bottom mapping information over a wide swath centered beneath the sonar.

Multiple beam bathymetric sonar such as Reson's Seabat 9001 would be used much differently than side-scan sonar or forward-look sonar to detect hull damage. Seabat 9001 has 60 receive beams, each being 1.5 degrees by 1.5 degrees. These would be pointed directly at the hull.

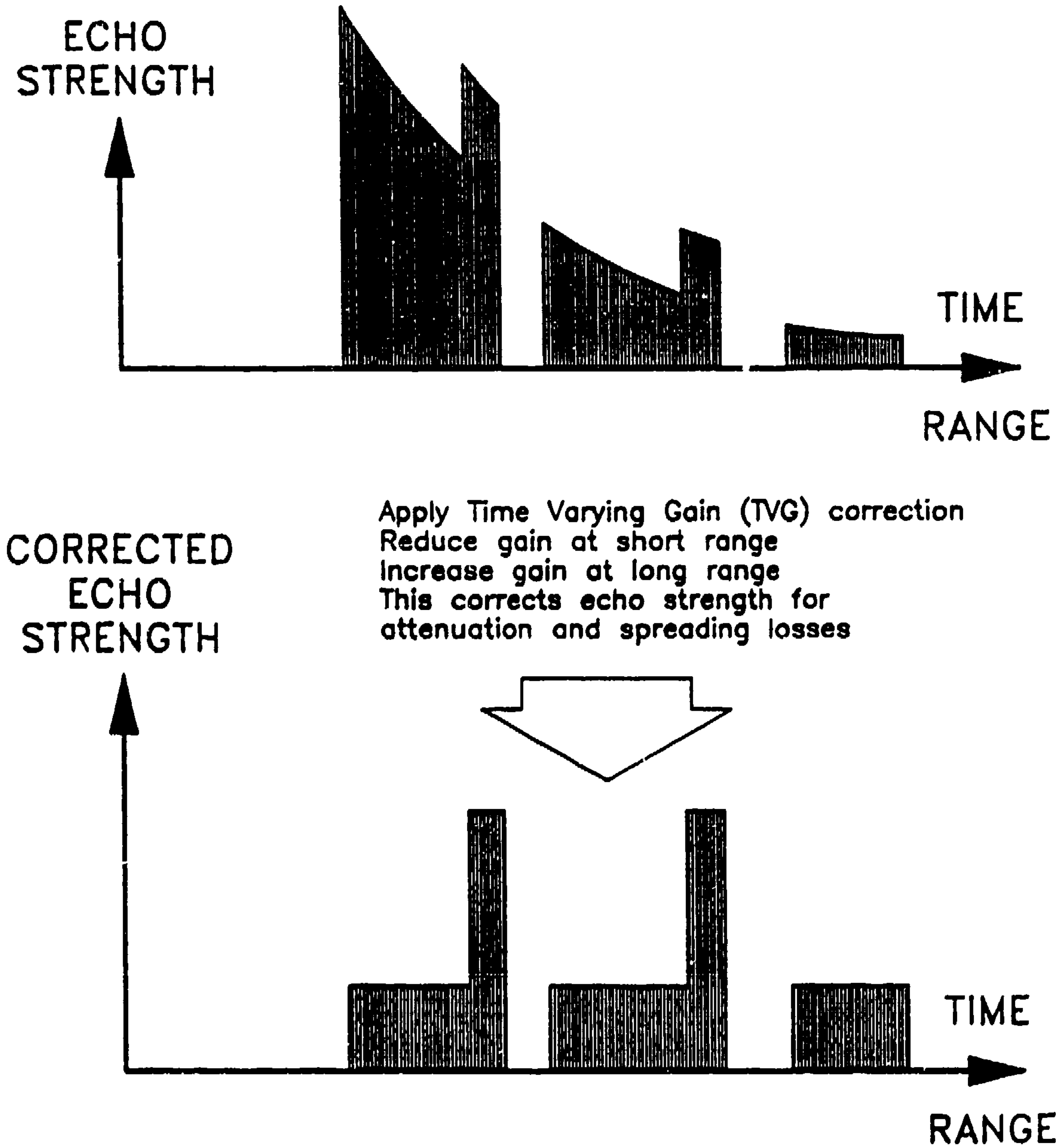


FIGURE 3-46. CORRECT ECHO STRENGTH FOR CHANGES DUE TO RANGE
(*Imagenex Operator's Manual*)

To detect a hole, one or more of the receive beams would need to be lost in the hole, leading to no return signal. Table 3-16 lists the specifications for the Seabat 9001 multibeam bathymetric sonar.

TABLE 3-16. SPECIFICATIONS FOR RESON'S SEABAT 9001

Operating frequency	455 kHz
Range settings	2.5, 5,10,25,50, and 100 meters
Range resolution	5 cm
Number of beams	60
Beamwidth (each beam)	1.5 degree horizontal 1.5 degree vertical
Update rate	30 times/sec at 2.5, 5, 10 meter ranges

The transmit and receive beam widths can vary for different sonar systems. Beam widths of 1 to 1.5 degrees are common. These beams spread farther as the standoff from the target increases. As the beam spreads, the size of the beam when it reaches the target (the footprint) increases, causing the axial, or along-track, resolution of the sonar to increase as well. If a 3-inch diameter hole in a hull (or in any structure) were to be detected, at least one of the receive beams would need to be lost in the hole. Thus, the size or footprint of the beam must be less than the size of the hole. Most manufacturers interviewed felt that the footprint should be about one half the size of the hole. Figure 3-47 shows that with a 1.5-degree beam width, the maximum sensor standoff to detect a 3-inch diameter hole in a hull is 4.8 feet. This value is calculated using the relationship

$$\text{Standoff} = \tfrac{1}{4}\,(\text{Hole Diameter}/\tan(\theta/2))$$

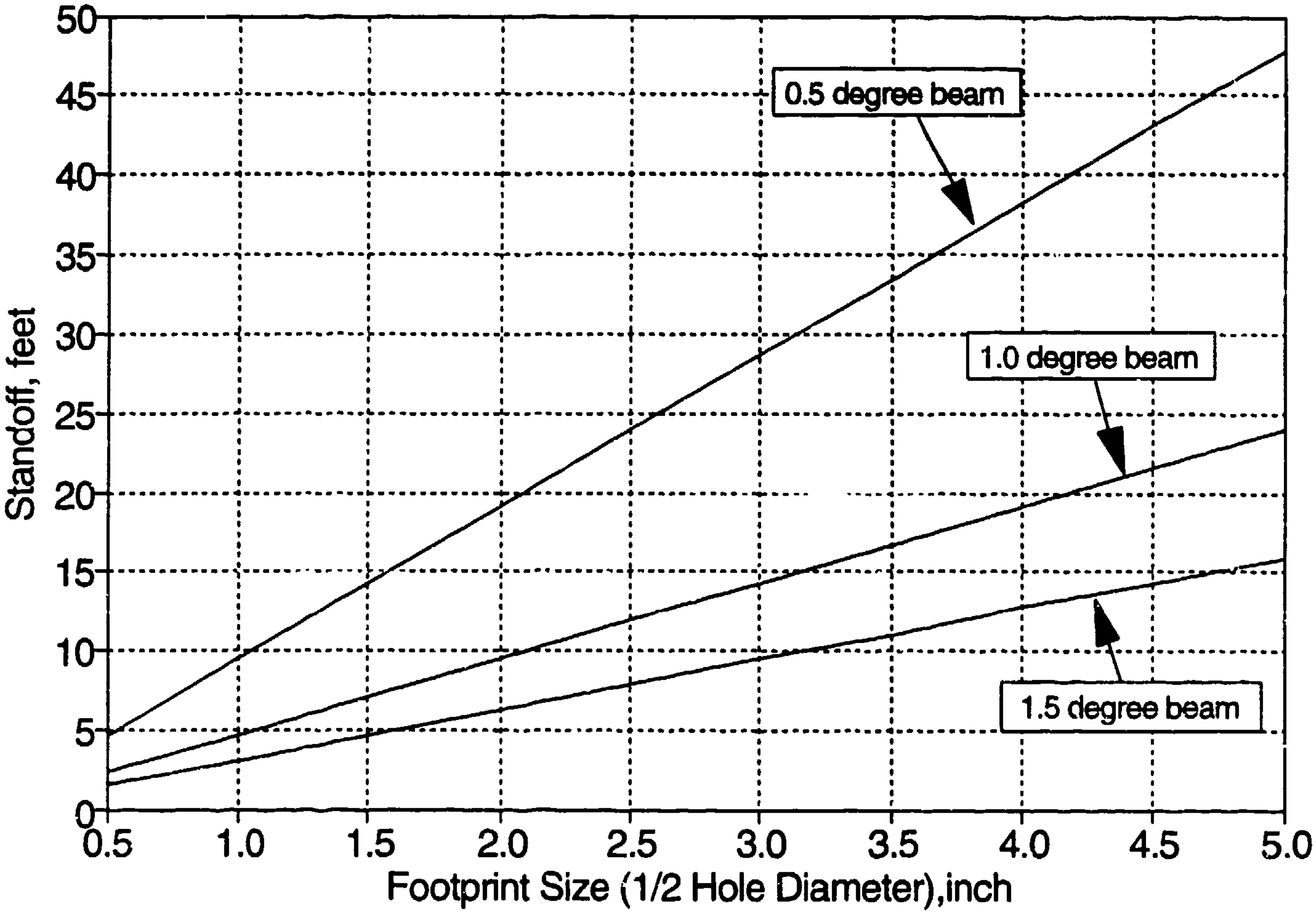


FIGURE 3-47. BATHYMETRIC SONAR

where θ is the beam width. This relationship assumes the beam footprint should be no more than one half the size of the hole to ensure detection. This relationship also assumes the beam to be perpendicular to the sur·. e of the hull. Figure 3-47 shows standoff as a function of desired footprint size for three different beam widths. If the beam is oblique to the hull surface, the footprint will elongate and the standoff must decrease below the values given by Figure 3-47.

As standoff is reduced to improve resolution, the field of view shrinks. The reduced field of view causes the area scan rate of the sonar to decrease as well. Because it might be necessary to be within a few feet of the hull to obtain acceptable resolution of the sonar to detect damage, poor visibility due to the possible presence of oil or due to turbidity may no longer be a factor, thus making video cameras viable damage assessment sensors.

3.3.1.3.4 Profiling Sonar

Here, profiling sonars are defined as those sonars that use a "pencil" acoustic beam scanned over an area to build a profile or image of an object. These profiling sonars are used for pipeline inspections, sewer, river, and canal bed surveys, positioning of subsea equipment, cabling and trenching applications, and ship hull inspections.

Profiling sonars operate on a "first return" echo basis. The pencil beam is scanned over the target and the profiler plots a series of points with accurate range information, giving the operator a clear indication of the shape of the environment. Profiles with accuracies and resolutions in millimeters are obtained through the use of high speed digital signal processing.

Figure 3 48 shows a pencil beam sonar aimed at a hole in a steel plate. From the range or standoff in this figure, the spot diameter or footprint of the beam is one half the size of the hole. Figure 3-49 shows the area covered by one sweep of the profiling sonar. Figure 3-50 shows the range and threshold of returns which are digitized by the sonar. Figure 3-51 is a plot of the digitized echo returns showing the profile of the bottom. The step in this figure can be clearly seen. For hole damage assessment, one or more of the beams should be lost in the hole as shown in Figure 3-48. This lost beam would produce a gap in the profile display.

At a range of 4 feet, 360 degrees can be scanned with a range resolution as small as 0.2 inch in less than 1.5 seconds using Marine Electronic's Model 1512 Pipe Profiling System. With this system, the beam width of the transducer is only 1.1 degrees, making the footprint of the pencil beam on the target from a standoff of 4 feet only 0.92 inch in diameter. The nearer the sensor is placed to

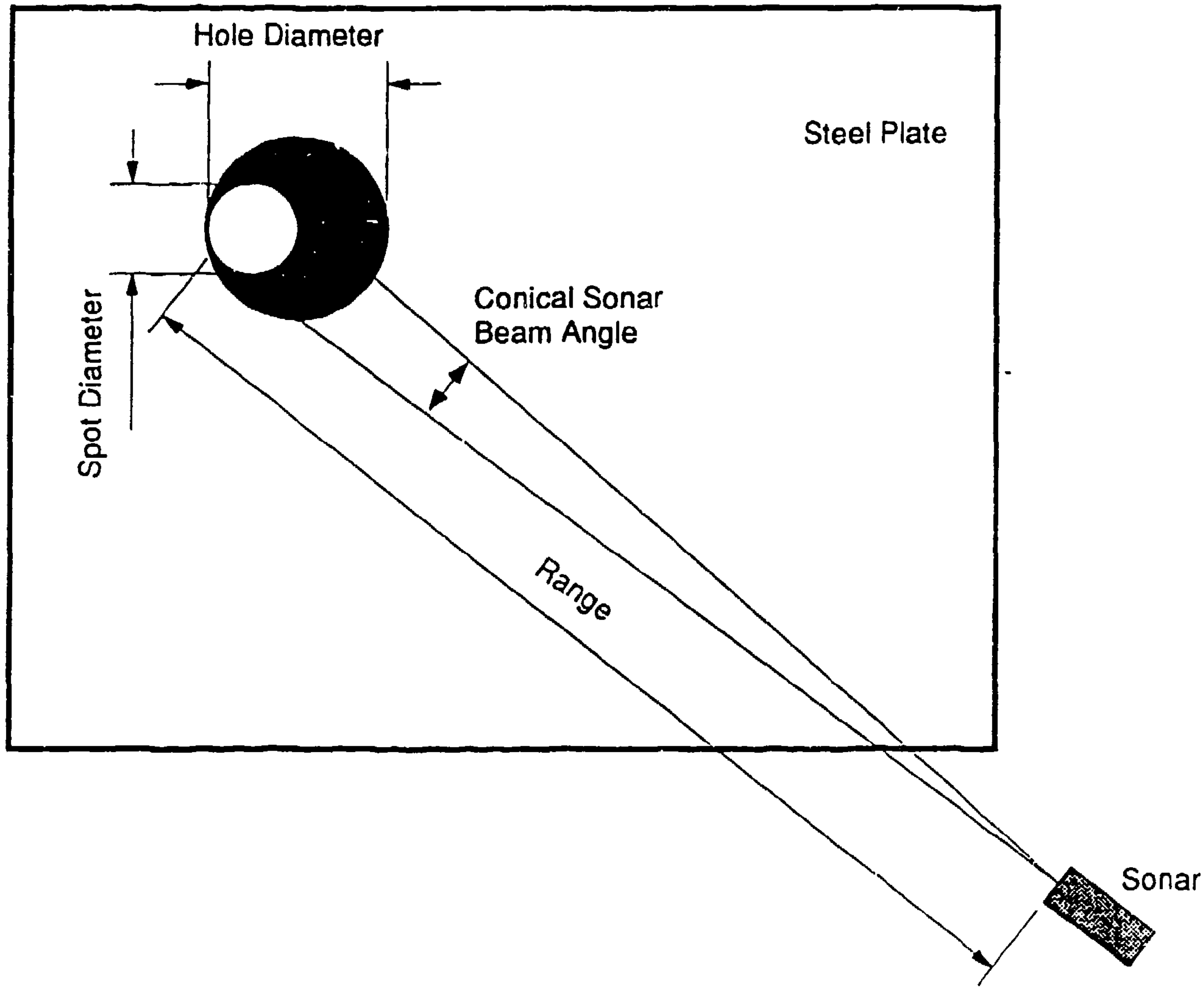


FIGURE 3-48. CONFIGURATION FOR DAMAGE ASSESSMENT USING A PROFILING SONAR

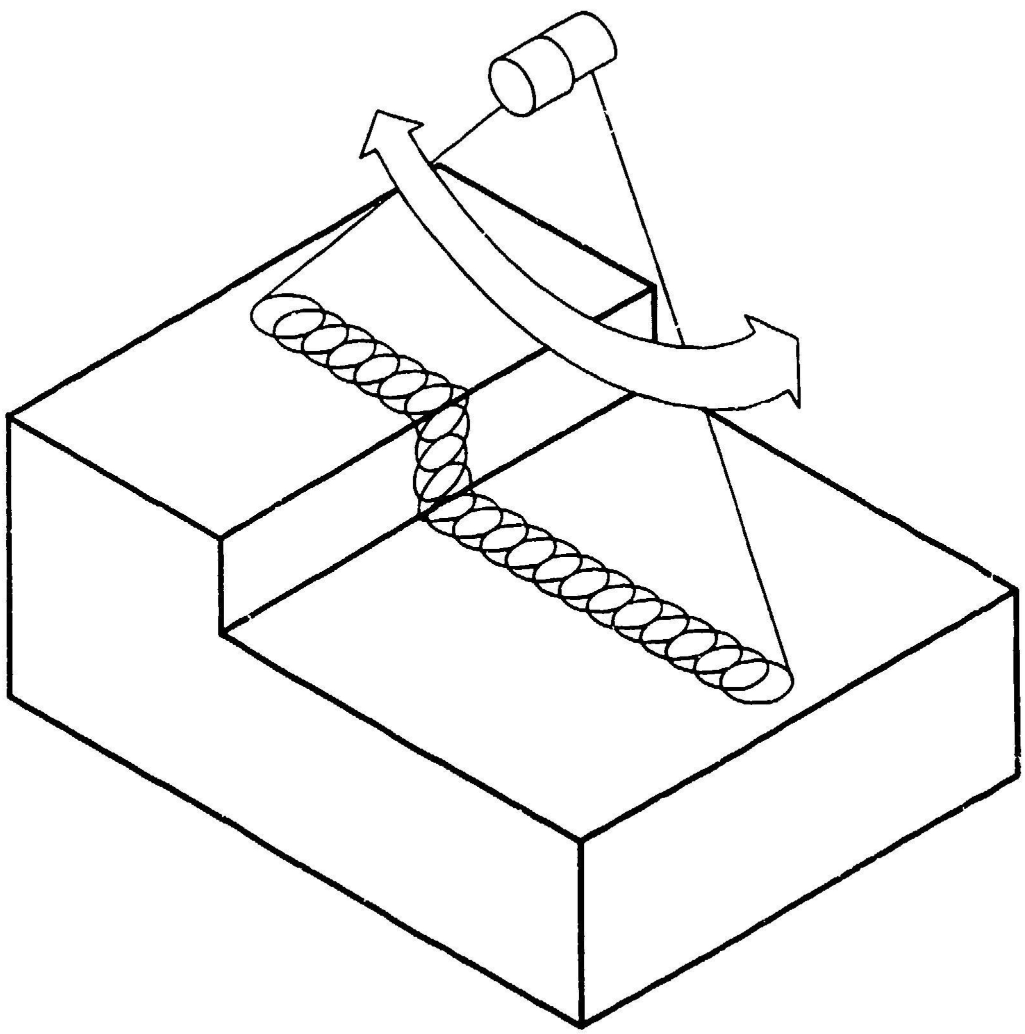


FIGURE 3-49. PENCIL SHAPED SONAR BEAM SCANS IN A VERTICAL PLANE TO MEASURE BOTTOM PROFILE
(*Imagenex Operator's Manual*)

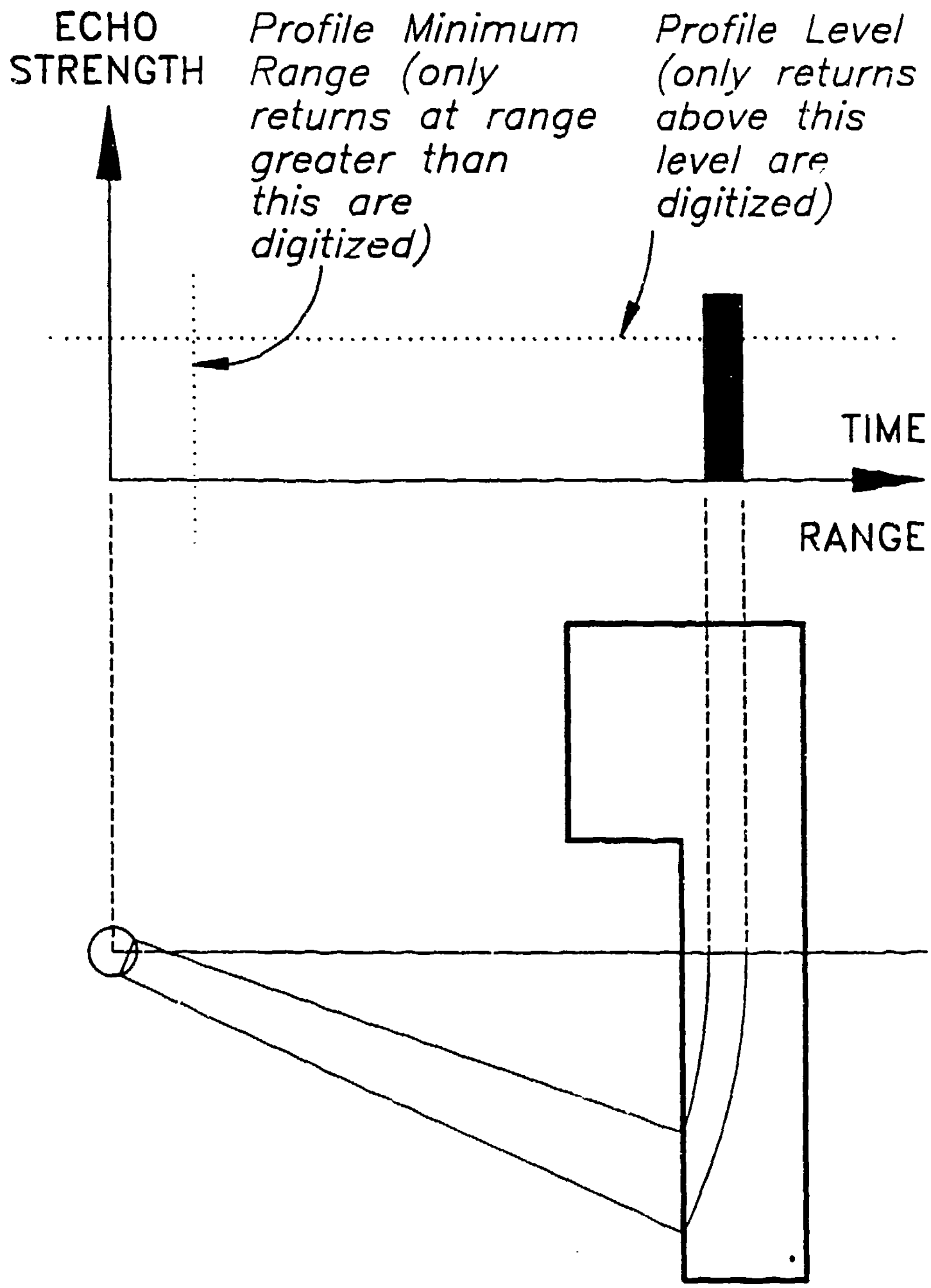


FIGURE 3-50. ECHO RETURN FROM PENCIL BEAM
(Imagenex Operator's Manual)

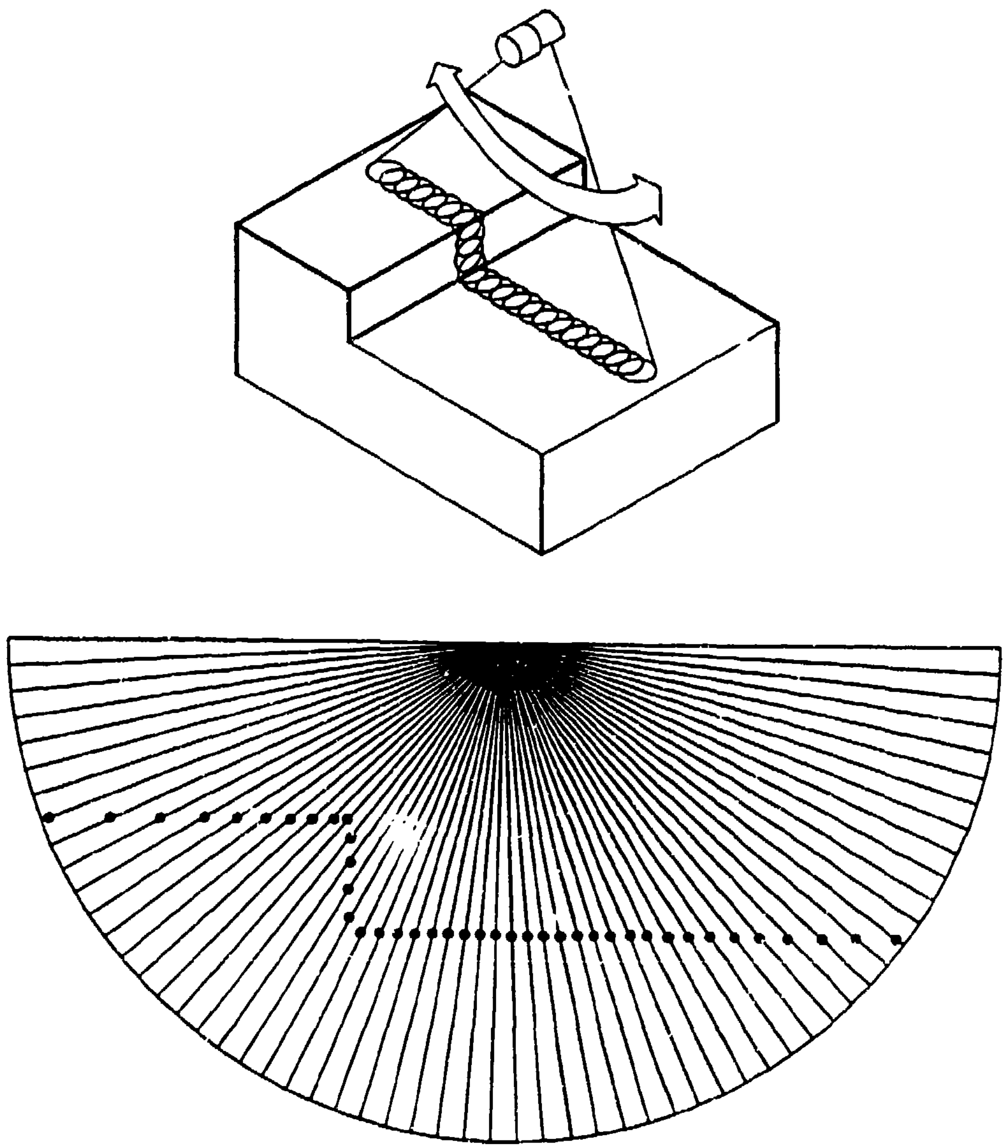


FIGURE 3-51. PLOT DIGITIZED ECHO RETURNS TO SHOW PROFILE (CROSS SECTION) OF BOTTOM
(*Imagenex Operator's Manual*)

the target, the better the resolution and the faster the scanning speed of the system per point. Mesotech and Tritech have pencil beam sonars similar to Marine Electronics Model 1512.

To detect a 3-inch diameter hole (assuming a water-filled volume behind the hole extending beyond the range of the sonar), the spot size of the sonar beam should be less than 1.5 inches. Again using Marine Electronics Model 1512 as an example, with a beam width of 1.1 degrees, the spot size diameter is only 1.5 inches at a range of 6.5 feet. The resolution and scanning speed improve linearly with proximity to the target, as does the stability with respect to external disturbances. As was the case with the multibeam bathymetric sonar, the resolution (footprint size) increases at scanning angles oblique to the hull surface. With a total scan sweep angle of 54 degrees, the outermost footprint at a standoff of 6.5 feet actually elongates to 1.87 inches. To decrease the width of this largest footprint to 1.5 inches, the standoff must be decreased to 5.2 feet. Because the sonar sweeps back and forth, during the time needed for the sonar to complete two successive sweeps, the sonar should not advance on the vehicle by more than one half the spot size.

Depending on the nature and orientation of a crack relative to the scanning direction of the sonar, the screen display for a profiling sonar would be affected in different ways. Because the amplitude of the echo signal is processed, compressed, and displayed as a color out of a palette of colors, information can be deduced about the nature of the target surface. Cracks would tend to scatter the sonar signal and produce a lower intensity than a flat plate. It is not possible to quote an exact standoff distance at which a crack will be positively detected as the width of the crack and orientation relative to the sonar are variables. Marine Electronics Model 1512 has been used in brick sewer pipes, at ranges from 2 to 4 feet, to measure the amount of mortar lost from between the bricks. A design study demonstrated the ability to detect cracks of 0.075-inch width and 0.5-inch depth into clay pipes under still conditions from a range of 2 feet.

Dents are more easily detected than cracks, as they show as a change in range. As the resolution is to the nearest 0.2 inch at a 4-foot range for the Model 1512 sonar, the dent would have to be deeper than 0.2 inch before it could be detected. The area of the dent would have to be greater than the spot size of the sonar beam at the standoff range.

Oily water will have a different velocity of sound than non-contaminated seawater and will alter the range calibration of profiling sonars slightly. The range accuracy is directly proportional to the velocity of sound, so if the velocity of sound in oily water is 5 percent faster than in seawater, the range shown by the sonar will be smaller than actual. The sonar can be calibrated prior to performing the survey to compensate for the effects of oil in water. The normal procedure for calibration is to fill a straight-sided bucket of known diameter with the contaminated water and then measure the bucket with the sonar. The on-screen cursors and overlays (a circle can be overlayed on the scanned data) enable easy and accurate measurements to be taken. The velocity of sound can then be compensated from a menu option until the bucket diameter is correct.

3.3.1.3.5 3D Mapping Sonars

Two 3D mapping sonars, a raster scanner sonar and an ultrasonic imaging sonar, were investigated. Prototypes of these systems have been tested. Though price quotations were not obtained, these systems would be more expensive than other commercially available sonars.

Raster Scanner Sonar. The Coastal Structure Acoustic Raster Scanner (CSARS) system is a prototype system developed by the Coastal Engineering Research Center and intended for underwater inspection of coastal structures. CSARS was developed in response to the need for a system which gives objective, detailed, and quantitative definition of the underwater shape of coastal structures.

CSARS is a narrow-beam scanning sonar. Range data is obtained through acoustic travel time. The system consists of a heavy bottom-sitting tripod transducer platform, a pointable acoustic transducer mounted on the tripod, and a topside controlling computer connected to the transducer by an umbilical. Because the transducer scans while the tripod is firmly seated on the sea bottom, range errors often encountered with boat-mounted or towed acoustic systems are avoided.

The transducer head transmits pulses of acoustic energy in a narrow conical pencil beam toward the target. A low acoustic frequency of 300 kHz is used, providing long-ranging capabilities. A pan-and-tilt mechanism is used for precise, stepwise pointing of the transducer. Figure 3-52 shows the three-dimensional scan volume within which range data are collected. The range data are collected by scanning the volume point by point along horizontal lines, similar to the way an electron beam moves in a CRT to create a television image. This technique is called raster scanning. Lack of data for portions of the spherical raster can result from shadowing effects or from oblique orientation of strongly reflective surfaces (specular reflectors). Once the scan is complete, the resulting digital data can allow for profiles, contouring, volume calculations, and 3D displays. Figure 3-53 shows a bottom contour plot created using the CSARS system. In assessing hull damage, the inspection could be performed through a series of set-downs of the tripod and transducer. The system would be

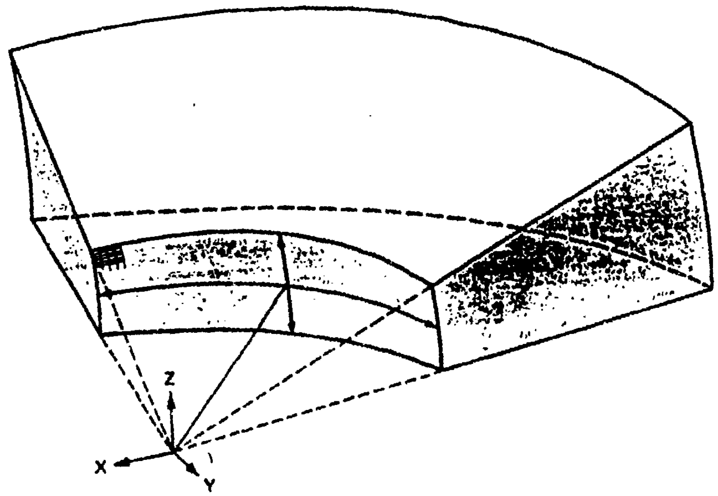


FIGURE 3-52. CSARS SYSTEM VOLUMETRIC FIELD OF VIEW
(Jonathan Lott)

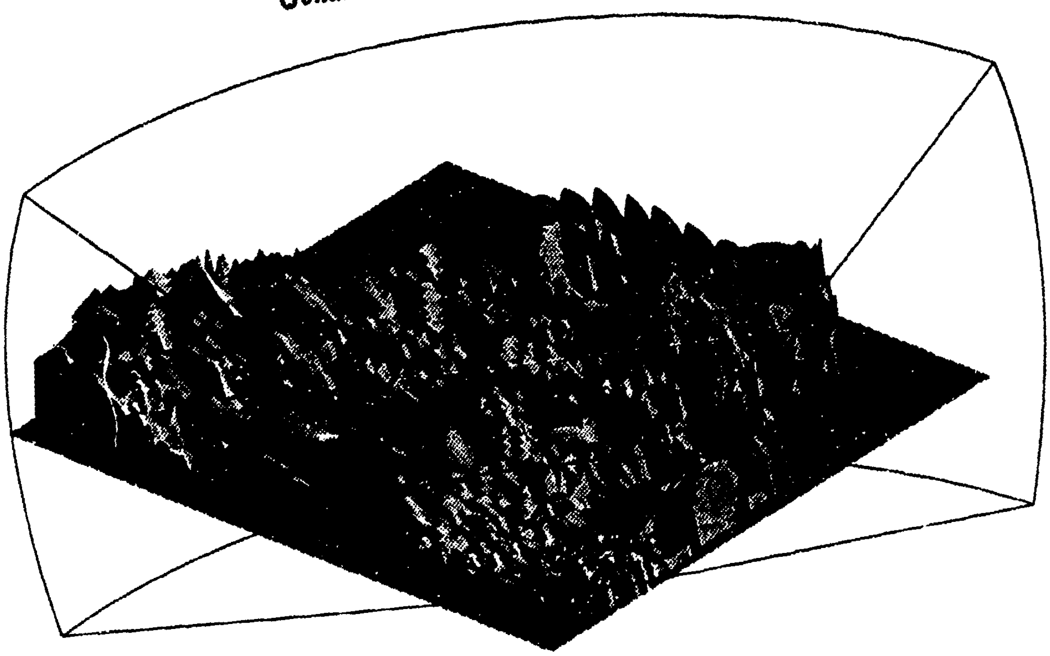


FIGURE 3-53. 3D CONTOUR PLOT OUTPUT OF CSARS SYSTEM
(Jonathan Lott)

insensitive to environmental conditions, but the water in which the assessment was being performed would need to be relatively shallow. While the low frequency provides good range capabilities, the resolution would not be good enough to detect small holes in a hull. A higher frequency (> 1 MHz like the profiling sonars) would be needed. Currently, CSARS performs only gross estimation of shapes of objects such as large rocks and dollas. An interview with the Coastal Engineering Research Center revealed that CSARS could not see the long arms of the dollas against a rock background. Also, although 6-inch pilings were detectable, the image was not very good.

Ultrasonic Imaging System. Raytheon's Ultrasonic Imaging System (UIS) is a high-resolution, three-dimensional acoustic imaging sonar. The system uses a multi-element receive array and operates at 1.5 MHz. It is intended to be a supplement or replacement for an optical imaging system in adverse environmental conditions such as turbid or oily water.

The UIS ensonifies the area to be imaged with a single pulse of a wide-beam projector. The receive elements are arranged in a two-dimensional hydrophone array, 48 receive elements wide in each dimension, and are electronically steered to create each image plane or range slice. The two-dimensional image planes or range slices are stacked to create a three-dimensional volumetric image for display. The 3-dB beam width of each receive element is 0.6 degrees, allowing for good lateral resolution from reasonable standoffs. The image frame rate or pulse repetition rate is once per second.

This system could be used much as a television camera in performing damage assessment of hulls. To detect a 3-inch hole, a standoff of 11.5 feet yields a maximum beam footprint of 1.5 inches. The field of view of the system would be 71 inches high by 71 inches wide. Thus, a 3-inch hole would occupy 4.2 percent of the vertical or horizontal field of view. For an operator to detect a 3-inch hole, it can be assumed that the hole should appear in the image for at least 2 seconds. Since the ping repetition rate is 1 per second, the hole should appear in at least two successive frames. Thus, the traverse rate would be 35.5 inches per second (71 inches/2 seconds). This converts to 1.8 knots and allows for a fairly large area inspection rate of about 63,000 square feet per hour.

This would be an excellent technology for performing damage assessment. The main drawbacks are that this system is still in the early stages of development, and it would be significantly more expensive than the many commercially available sonars discussed previously.

3.3.1.4 Other Key Sensor Technologies

Two additional sensor technologies were identified as potentially useful in a hull damage assessment system: oil sensors and eddy current sensors. Oil sensors would detect the presence of oil in water. Assuming the concentration of oil would increase as the damage assessment system approached the hole or crack in a hull, the oil sensors would assist the system in locating the damage. Eddy current sensors would be used to quantify very small holes or fine cracks, which may be difficult to detect or characterize using the sensors discussed previously in this chapter. Overviews of these two sensor technologies are presented below.

3.3.1.4.1 Oil Sensors

SEIMAC Limited of Canada has a prototype Total Oil Monitor (TOM), which is designed to be mounted on the bottom of a drifting buoy to aid the Canadian Coast Guard in search and rescue operations and in pollution prosecutions. Many oil-in-water sensors use infrared light to detect the carbon-hydrogen stretch evident in many substances including oil. TOM is based on measurement of the absorption of ultraviolet light at 260 nm. Using ultraviolet light to detect the carbon-hydrogen stretch allows TOM to differentiate aromatics from other substances. Because aromatics are dominant in oil, TOM can obtain a more specific measurement. The detector is sensitive to the carbon-carbon bonds found in the benzene ring configuration in oils. The sensor detects light oils, gasoline, diesel fuel, and crude oil. It also reacts to some organic compounds. The current design may be suitable for the shallow depths of a hull damage assessment mission. TOM can detect oil-in-water concentrations down to less than 1 ppm. The prototype TOM could easily be modified for use at greater depths mounted on an underwater vehicle.

Nereides manufactures an oil-spill-detection system which activates and sets off an alarm when oil is detected. The sensor consists of an elastic polymer membrane that is sensitive to hydrocarbons. The membrane dissolves and tears when it comes into contact with a thin oil layer floating on the water surface. A reed switch opens and triggers an alarm when the membrane dissolves.

Fluorometers are also commercially available devices that can be used to detect hydrocarbons in sea water. Fluorometry is the quantitation of the ability of fluorescent materials to convert light of one wavelength to light at a longer wavelength. Turner Designs has manufactured field units that can detect hydrocarbon concentrations between 0.1 ppm and 200 ppm for tests conducted on Prudhoe crude oil.

3.3.1.4.2 Eddy Current Sensors

An eddy current is an alternating current induced in the metal of the part to be inspected by a coil carrying alternating current. The frequency of the current in the coil and the frequency of the induced eddy current are the same. A probe coil placed on or near the surface of the metal part detects changes in the current. Variations in the conductivity, permeability, mass, and homogeneity of the metal part affect the current, as do temper, alloy, conductivity, and other metallurgical factors, making interpretation of the results difficult for a non-expert.

Eddy current probes are not affected by poor optical environments or contaminants, making them suitable for underwater inspections. The output of an eddy current probe can be recorded on tape or printed, and the signal can be transmitted to the surface. However, the use of eddy current in underwater operations is still fairly new. Overall, use of this technique for hull damage assessment would be limited, compared to photography, video, laser imaging, and sonar. There is one commercially available system, however, which might be useful to complement the sensors used on the damage assessment system. This is Millstrong Ltd.'s Lizard Divescan Electro Magnetic Array Scanning Crack Detection System.

The Lizard System allows rapid and reliable single-pass inspection of engineering structures. A path up to 45 mm (1.8 inches) wide can be inspected through coatings and surface fouling, minimizing the cleaning necessary. A personal computer acts as the controller and data acquisition system, making operation of the Lizard System simple. The specifications of the Lizard System are listed in Table 3-17.

The operating principle behind Lizard is fairly straightforward. An alternating magnetic field is used to induce electric current in the surface of a material to be inspected. A sensing array within the probe monitors this current for recording and analysis. The material and its properties can be analyzed through features of the recorded waveform. Lizard's electromagnetic array (EMA) combines composite field-gradient sensing and high-speed digital telemetry to allow reliable detection and sizing of defects in a single pass of the probe. The system allows a permanent record to be saved on PC software.

TABLE 3-17. LIZARD™ EDDY CURRENT INSPECTION SYSTEM OPERATING SPECIFICATIONS

Defect Detection Threshold:	
Length	10 mm (0.4 in)
Depth	2 mm (0.08 in)
Lift-off Tolerance (non-conductive coating, fouling, roughness, and geometry):	
Absolute limit	5 mm (0.2 in)
Variation	4 mm (0.2 in)
Scanning Speed:	
Minimum	20 mm/s (0.79 in/s, 0.04 knots)
Maximum	>70 mm/s (2.76 in/s, 0.14 knots)
Length of Tether, Umbilical, and Connecting Cables:	
Maximum	500 m (1640 ft)

Millstrong actually has a range of probes that could be used, the largest being a 6-inch wide probe. Typically, the probes are mounted in a mechanically sprung housing to accommodate lumpiness of the surface. Several probes can be used simultaneously, with a multiplexer unit combining their output. For hull damage assessment, a normal high-pressure cleaning system may be needed to remove barnacles or marine growth in front of the probe. The cleaning system uses a jet of water or water entrained with grit to dislodge objects attached to the surface. Because the Lizard System must be up against the hull to operate, it would be most easily operated when mounted on a hull crawling vehicle.

3.3.2 Summary

Many sensors are able to provide valuable information for damage assessment. The sensors discussed generally rely on sensing light, acoustic energy, or some specific physical characteristic of the environment. The performance of a sensing system is governed both by design and environmental/operational limitations. It is important to understand how each of these factors affect system performance and operability in order to make good choices regarding sensor selection. Each sensor has inherent capabilities with resultant advantages/disadvantages. For example, video sensors provide images which are clearly understood by an operator, but are often very range limited. Sonar systems, on the other hand, may not provide the same degree of resolution or ease of interpretation, but they can be operated at predictable distances because they are not significantly affected by turbidity/visibility. A review of the various sensors' capabilities as they relate to the overall damage assessment mission will be presented in the following sections. The use and integration of various sensors for damage assessment will be discussed as well.

3.4 Oil/Water Interface Sensor Analysis

3.4.1 Technology Review

Locating an oil/water interface is essentially a liquid-level-sensing operation. Due to the differences in density (specific gravity) between the two liquids, separation will occur; the oil generally floats on top of the water (neglecting mixing effects). The level at which the oil and water meet is referred to as the oil/water interface. Ideally, this level is clearly defined; however, if the liquid is not calm, some mixing of the oil and water will occur, resulting in a wider interface band.

If a ship carrying crude oil was to run aground, be involved in a collision, or suffer structural damage that resulted hole or crack, oil could leak out and with time be displaced by water. The total oil loss is most significant when the damage is at or slightly below the water line, in which case the gravity flow of water can displace nearly all of the oil in a tank. By determining the oil/water interface, the amount of water taken on, and thus oil lost, can be determined.

3.4.1.1 Level Measurement Methods

A brief review of methods commonly used for measuring liquid level is provided.

Buoyancy Devices. These devices are based on the principle that a liquid will exert an upward force equal to the weight of the liquid displaced when a solid object is submerged in that liquid. If the weight of the object is less than the weight of liquid that the object can displace (i.e., lower density than the liquid) the object will float and the position of the object can be measured and calibrated to determine the level of the liquid. See Figure 3-54 (a). A float (solid object) having a density greater than oil but less than that of water, will remain on top of the water; thus the interface can be detected. On the other hand, if the object is denser than the liquid, the apparent weight of the object will decrease due to the upward force created by the displaced liquid. This difference in apparent object weight can be calibrated to determine the liquid level or the interface between two liquids of varying densities. See Figure 3-54 (b).

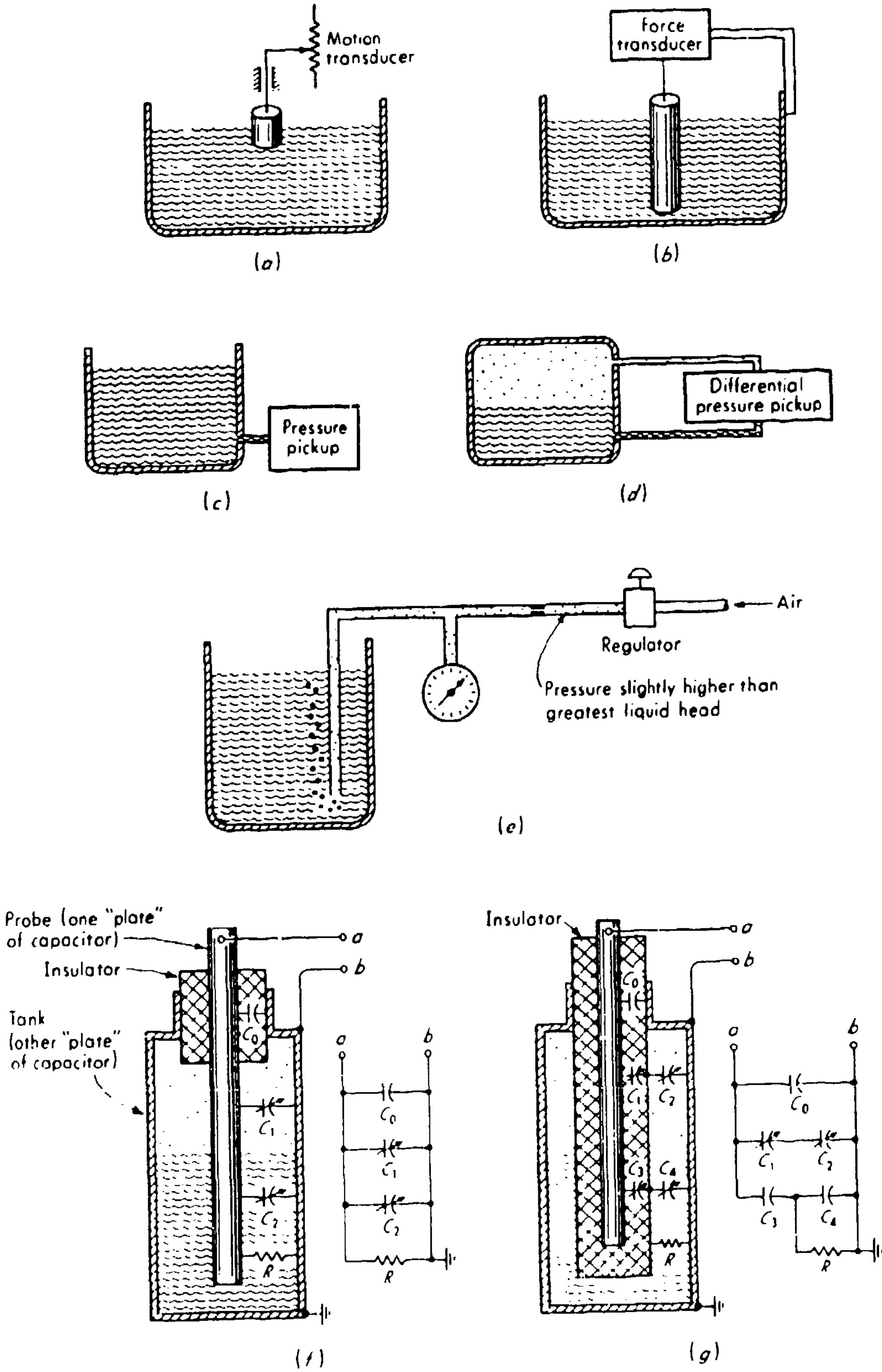


FIGURE 3-54. LEVEL MEASUREMENT METHODS
(Doebelin, 1990)

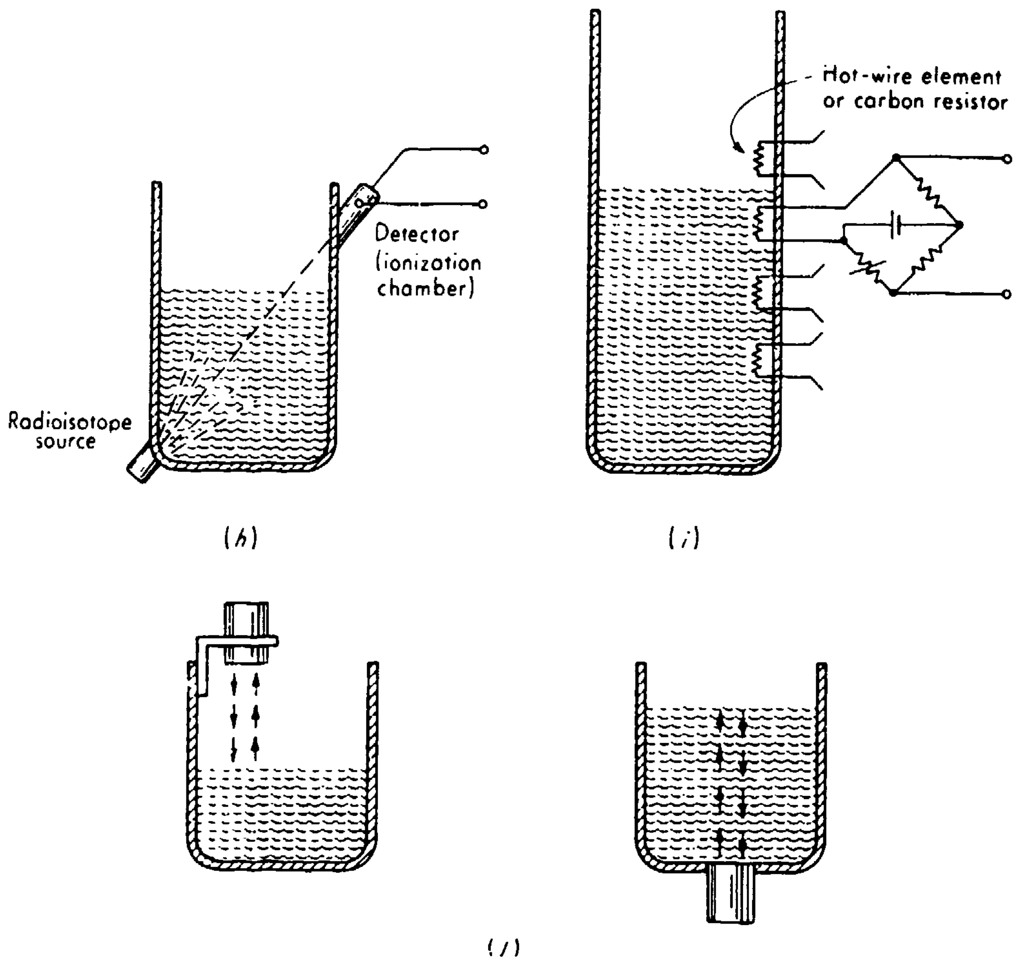


FIGURE 3-54 (CONTINUED). LEVEL MEASUREMENT METHODS
(Doebelin, 1990)

Pressure Devices. Pressure-based liquid level sensors rely on the fact that pressure increases linearly with the depth of a liquid column. At the surface, the pressure is 0 psig (14.7 psia). For water, the pressure at a depth of 33 feet is 1 atmosphere, or 14.7 psig (29.4 psia). The pressure increases as the sensor is moved deeper into the liquid or as the level of the liquid rises relative to the location of the sensor. From this relationship, the level of the liquid can be calculated relative to the position of the sensor. See Figure 3-54 (c). More accurate levels are obtained when the pressure difference from top to bottom is measured in a closed tank. See Figure 3-54 (d). The oil/water interface level can be calculated, given total tank level, specific gravities of both oil and water, and the pressure at the bottom of the tank. Another method based on pressure uses a tube to blow gas down into a known depth in the liquid. The pressure of the gas is essentially equal to the pressure at the tube outlet, which is the same as the pressure at the submergence level within the liquid. This pressure is used to calculate the depth of the fluid in the same manner as the direct liquid pressure readings.

Capacitance Devices. The dielectric constant of a material is related to its ability to resist electrical conduction relative to that of a vacuum. A capacitor uses an insulating material (dielectric) between two metallic plates which hold a voltage difference. The amount of capacitance depends upon the dielectric constant of the insulating material. As the dielectric constant increases, the capacitance increases. This same principle is used in detecting a liquid level. The liquid is used as the insulating material between the two metal surfaces. The differences in dielectric constant between water and air imply that the capacitance will be different. See Figures 3-54 (f) and 3-54 (g). This change in capacitance indicates that the liquid level is at least as high as the sensor. Note that only point detection can be performed with capacitance-based sensors unless several sensors are cascaded at known distances relative to one another.

The principal disadvantage of the capacitance level sensor is that it cannot be used with materials that build up on the probe, because this causes a permanent change in net dielectric value. Some manufacturers incorporate a coating (often Teflon™) on the probe to minimize these errors.

Conductivity Devices. Generally less expensive, conductivity-based sensors measure electrical resistance of a fluid. The calibrated resistance is translated to the fluid's presence at the level of the sensor. These sensors use the fluid under study as an integral part of an electronic circuit. An analogy of this circuit is putting the probes of a resistance-reading multimeter into a glass of water; the relative change in resistance from water to air is used to establish the liquid level.

Radioisotope Devices. The use of radioisotopes in detecting a liquid-liquid interface is based on the fact that absorption of beta ray or gamma ray radiation varies with the thickness of the absorbing material between the source and the detector. A signal relating to tank level can be developed. This results in an exponential relationship between level height and radiation intensity. See Figure 3-54 (h).

Hot-Wire Resistance Devices. The basic concept in using hot-wire resistance in detecting interfaces is that the heat-transfer coefficient at the surface of the resistance element changes radically when the liquid surface passes it. This changes the equilibrium temperature and thus the resistance, causing a change in bridge output voltage. Note that this is also a point detection scheme rather than a continuous level measurement. See Figure 3-54 (i).

Ultrasonic Devices. Ultrasonic devices transmit a high-frequency acoustic signal to the interface level due to a change in reflectivity. Part of the signal is reflected back at the liquid level interface The time required for signal travel is measured and translated into a level based on the known signal speed of travel and the dimensions of the tank. Most ultrasonic devices are mounted at the top of the tank but several are side-mounted and use point level indicators. In some cases, bottom-mounted ultrasonic level sensors are used. See Figure 3-54 (j). An intrinsic advantage of these sensors is the absence of moving parts.

Optical Devices. The advent of fiber optics has resulted in many new optical instruments. Optical liquid level sensors send a beam of light down a fiber-optic cable to a sensing tip. The light is reflected at the tip and sent back up the fiber-optic cable. The amount of light reflected at the sensing tip is related to the light index of refraction of the liquid in which the tip is immersed. In actuality, the sensor is differentiating between air and water (common case) based on the respective indices of refraction/reflection.

Miscellaneous Devices. Sensors in this classification do not measure differences in liquid properties but, rather, react differently to particular liquids. One example is absorption devices, which consist of a sealed cell made of specific materials. When in contact with oil, the cell remains unchanged, but when in water, the cell absorbs water and cell volume changes. This volume change can activate switches or be visually observed, based on sensor configuration.

Another device, often called a paddle wheel, senses the viscosity of the substance being measured. A torque-sensing motor relates the torque required to spin a finned-paddle to the presence or absence of a substance. This type of device is typically used to detect granular solids such as foods.

3.4.1.2 Considerations for Sensor Selection

The Liquid-level sensor methods and respective characteristics are outlined in Table 3-18. The following points should be taken into consideration in selecting a liquid-level sensor:

1. Most of the liquid-level sensors must be immersed or come into contact with the liquid column under observation. For example, buoyancy devices require that the "float" rest on the liquid surface. It is imperative that the sensor materials be compatible with the measured liquid. Contacting sensors often collect build-up or liquid residue. In some cases, this can cause erroneous level readings.

2. Point vs. continuous level indication is intrinsic to the detection method. Continuous sensors permit level readings over a vertical range of the sensor, typically via a 4 to 20 mA analog output. Continuous level indicating sensors do not require repositioning to track the interface level. On the other hand, a point level sensor will indicate only the presence (or absence) of a liquid at a particular tank height. "Continuous" level indication can be performed with a point level sensor if the sensor position is moved to the interface level or if multiple point-sensing devices are cascaded in a vertical arrangement. The sensor position must also be measured for this case.

3. Intrinsically safe sensors are highly preferred for level gaging ship tanks due to the presence of potentially explosive vapors in the ullage (above surface) area. Intrinsically safe sensors are those that have relatively little chance of igniting volatile vapors. Sensors are designed to various classes of safety.

3.4.2 Technology Implementation

Tank accessibility for instrumentation access is a critical factor in selecting a level sensor. Ships have two types of tanks: cargo tanks and material tanks. The access to cargo tanks is via an ullage cap. The ullage cap can be opened from the deck to fill/remove cargo as well as to take level readings. The dimensions of ullage caps vary from ship to ship and tank to tank. Diameters range

TABLE 3-18. LIQUID LEVEL SENSOR CHARACTERISTICS

SENSOR CLASSIFICATION	CONTACTING/ NON-CONTACTING	POINT LEVEL /CONTINUOUS	RELATIVE APPLICABILITY TO PORTABLE SHIP TANK OIL/WATER INTERFACE MEASUREMENT
Buoyancy Devices	Contact	Either	Moderate-High
Pressure Devices	Contact	Continuous	Low-Moderate
Capacitance Devices	Contact	Point Level	Moderate-High
Conductive Devices	Contact	Point Level	Moderate-High
Radioisotope Devices	Contact (Penetrate)	Continuous	Low
Hot-wire Resistance Devices	Contact	Point Level	Low-Moderate
Ultrasonic Devices	Contact/ Non-contact	Continuous/ Point Level	Moderate-High
Optical Devices	Contact	Point Level	Moderate-High
Miscellaneous Devices	Either	Point Level	Sensor Dependent

from 2 to 16 inches. The larger ullage caps are used as access for oil sampling. Several ullage caps are located in the center of tank hatches (36 to 42 inches diameter). Regulations require that all ullage caps and sounding tubes located below freeboard deck height must have an automatically closing lid; hence, it is required that the lid be held open while measurements are taken. Some caps incorporate a foot-operated linkage to hold the caps open.

An ullage tube viewing device (Patent No. 5,176,029) permits visual inspection of a cargo tank without releasing hazardous vapors. The configuration is essentially a viewing glass with an elastomer ring seal. It is possible that this could be used for the location of a non-contacting liquid-level sensor (e.g., ultrasonic, radar device).

Access to other tanks for purposes of level measurement consists of a "sounding tube" that extends from the deck of the ship to within inches of the bottom of the tank. The size of the sounding tube is standardized in the industry: 2 inch O.D. Schedule-80 tube (1.90 inch I.D.). Caps on sounding tubes are typically standard 2 inch pipe caps. Sounding tubes higher than freeboard are sealed by flush-mounted brass or bronze plugs with a square socket. This type of tube does not necessarily run straight to the tank bottom; often it is bent to accommodate the contours of the specific tank. Level measurements are taken manually by dropping a tape down into the sounding tube. When the end of the tape contacts the liquid surface, the tape is read (readings are typically to a fraction of an inch). This reading is then compared to a "tank table," which indicates the volume of liquid in the tank. The tank table is created when the ship is built and is specific to the tank's geometry. Correction factors for the trim of the ship are then used to determine the true tank volume. Originally, a brass plumb-bob was used to detect the liquid surface level. Currently, ultrasonic or capacitance sensors are located on the end of the tape. When fluid contacts the sensor, an audible alarm tells the ship's mate to read the tape.

To locate the oil/water interface, a sensor must be able to distinguish oil from water. It does this on the basis of differences between one or more physical/material properties of the two. For example, a sensor that measures density will be able to detect the interface because of the difference in densities of oil and water. In general, the greater the difference in material property, the better the sensor's ability to locate the interface. It is substantially more difficult to locate an oil/water interface than a water/air or oil/air interface because oil and water are both liquids with many similar properties.

3.4.3. New Technologies Applicable to Oil/Water Interface Detection

3.4.3.1 Electro Magnetic Level Indication (EMLI)

The Electromagnetic Tank Level Indicating (EMLI) System, developed at the David Taylor Research Center (DTRC), has successfully completed Advanced Development Model (ADM) testing. The EMLI is a highly reliable sensor for measuring the quantity of fuel oil in seawater-compensated storage tanks. Designed as the next generation tank level indicator (TLI) for shipboard use, the microprocessor-based EMLI is fully automated and has no moving parts.

The EMLI technique is based on time-domain reflectometry (TDR), which is used primarily for the inspection of long transmission cables. TDR is analogous to radar in the sense that a high-frequency signal is transmitted onto a cable and reflections from impedance mismatches and cable damage are measured. The location and amplitude of these can be determined from the TDR signal. The EMLI uses TDR and an open fiberglass transmission line sensor to interrogate the contents of shipboard fuel tanks.

The tank contents act as the transmission line dielectric, with impedance discontinuities occurring at the fluid interfaces. A unique algorithm, developed by DTRC engineers, allows the system to accurately determine the depth of fuel oil and the seawater in seawater-ballasted fuel oil tanks. In addition, the presence of an oil and seawater emulsion can be detected and measured, and the rugged fiberglass probes resist coating and corrosion. The EMLI is not limited to fuel oil tanks but may be applied to a variety of difficult level-sensing problems. The EMLI promises to be a low-cost, highly reliable, and rugged successor to TLIs currently in use by the fleet.

3.4.3.2 Apparatus for Determining Liquid/Gas Interfaces Through a Ship Wall

Battelle and the U.S. Navy developed a device designed to located the boundary between a liquid and a gas inside an underwater vessel. This apparatus, presently carried by a diver, incorporates a transducer that provides a low-frequency acoustic tone burst that is transmitted toward the hull of the ship. See Figure 3-55. The reflected signal from the inner surface of the hull is received by a hydrophone and processed. For the instrument frequency range (100 Hz to 5 kHz), the reflectivity of a water/steel/water medium is only 3 percent as compared to nearly 100 percent for a water/steel/gas interface. The reflected wave amplitude is measured to locate the interface level between water and gas on the other side of the steel hull. This device may have some application to detecting the oil/water interface from a submerged, remotely-operated vehicle, depending on the magnitude of difference between a water/steel/water medium compared to a water/steel/oil medium. One problem likely to be encountered would be double-walled cargo tanks (some of which have a 2-meter air ballast between the cargo (oil) and the outside seawater). The interfaces on these air-ballasted vessels could not be detected with this device.

3.4.3.3 Liquid-Level Sensor with Optical Fibers

A non-contacting, liquid-level sensor that uses three optical fibers has been shown to detect the level of oil in small tanks. A light is projected through a transmitting fiber, a receiving fiber picks up

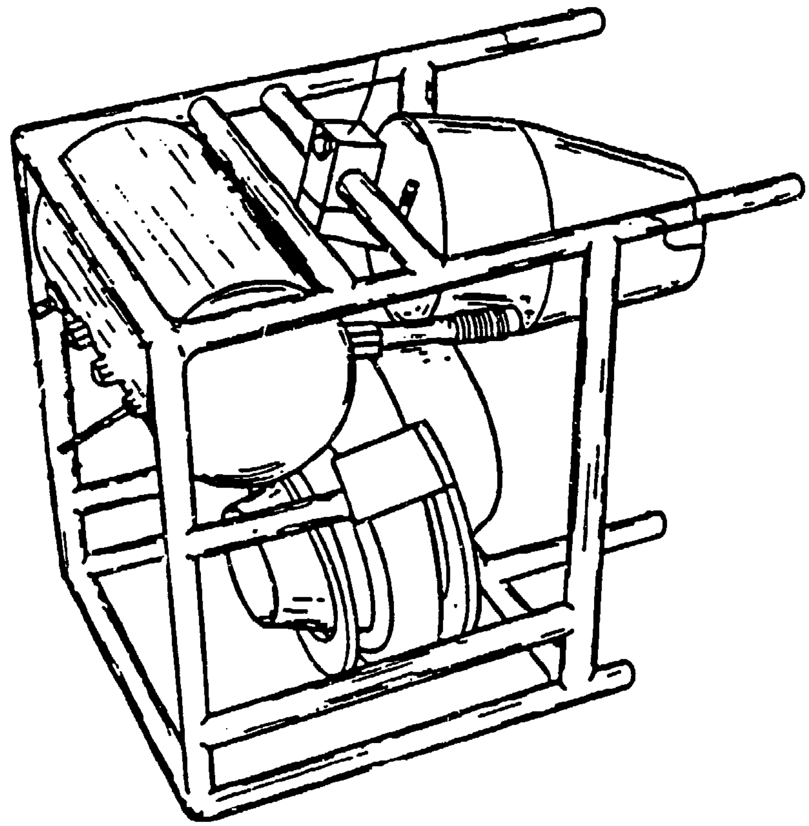


FIGURE 3-55. APPARATUS FOR DETERMINING LIQUID/GAS INTERFACE THROUGH A SHIP WALL
(Battelle, 1989)

the light from the oil surface, a reference fiber transmits the light from an LED back and forth along the same path as that of the transmitting and receiving fibers. See Figure 3-56. Division is accomplished by using the reflected signal and the reference signal, so it is possible to eliminate apparent distance variations that are due to the variations in light intensity, which are caused by external forces and temperature changes. Recorded accuracies are 1 percent over a 100-mm distance. This process has not been applied over greater distances.

3.4.4 Summary

The ideal system for detecting the oil/water interface does not currently exist. The ideal system would be one that a person could use by placing the sensor on the deck of the ship directly

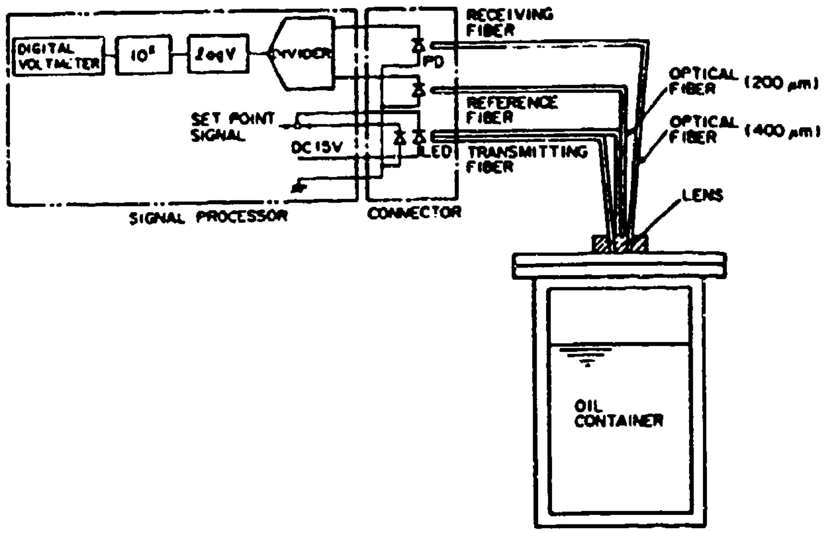


FIGURE 3-56. LIQUID LEVEL SENSOR WITH OPTICAL FIBERS
(*Katsuhara, 1992*)

above the tank to be observed. The ideal sensor would be able to penetrate, in a non-contacting manner, the deck, the ullage, the oil, and the water layers, and then indicate the relative levels of each.

Non-contacting devices (e.g., ultrasonic) are unable to determine the oil/water interface from a sensor position located above the oil/air interface. An externally located, side viewing sensor, such as the Navy liquid/gas interface detector encounters difficulties if required to penetrate a double-walled tank with an intermediate air layer. As a result, it appears that the best solution is a contacting sensor configuration. Intrinsically, a scaled tape (with interface sensing probe(s) on the tip) that is lowered into the liquid cargo seems to be the simplest and most versatile arrangement. The probe type—capacitance, conductance, optic, or other—depends upon the specific application. A custom arrangement with interchangeable, pre-calibrated probes would be desirable for ship cargo- tank level sensing.

3.5 Non-Destructive Tests

Many types of Non-Destructive Testing (NDT) techniques are used in industry, but only a few of these have been used successfully underwater. The techniques that have been successful, or which have the potential to be successful, include radiography, magnetic particle inspection, acoustography, eddy current, and tomography. Eddy Current was discussed previously in this chapter and will not be covered here. Unlike a TV camera but similar to the profiling sonars, most of these techniques map an object by looking at it one point at a time and ranging each point. These testing techniques are presented here primarily for information purposes only. These techniques are used for detecting extremely small flaws or subsurface flaws or damage and, thus, are not as well suited as the techniques discussed previously for assessing larger damage on hulls.

In radiographic inspection, x-rays or gamma rays to penetrate the object under investigation. These rays can penetrate opaque objects due to their very short wavelengths, but the rays are attenuated according to the thickness and density of the material and its physical and chemical properties. A radiographic film placed in the path of the penetrated rays can be developed and will capture the intensity of the rays. The film creates a negative image of the object and can reveal cracks, flaws, material thickness, and other structural defects. The greatest drawback of this technique in hull inspections is the need to place a film on the opposite side of the X-ray device. The inside of the hull will not be accessible, eliminating radiography as a candidate technology.

Magnetic particle inspections use ferromagnetic materials to detect surface and subsurface defects. The technique involves spreading magnetic particles dispersed in a liquid onto a material during or after magnetization. The magnetization is created by a strong magnet or high electric currents. Surface or shallow subsurface flaws or cracks will create a leak in the field, causing the magnetic particles to gather around the flaw or crack. This technique is not appropriate for hull damage assessment for a number of reasons. First, a magnet would be needed to create the magnetic field, allowing only a small area of the hull to be inspected at any time. Second, the magnetic particles must be applied to the hull surface, which adds a great deal of complexity to the damage assessment system. The technique is used for defects orders of magnitude smaller than the types of damage expected in hulls involved in groundings or collisions. Finally, a video camera would still be needed to record and transmit the results to the surface for analysis.

Acoustography produces images by measuring the attenuation of the uniform ultrasound field as it passes through an object. The shadow image can be visualized using an acousto-optical display, which converts the ultrasound into a visual image. Parallel molecules in a liquid crystal display produce a uniform dark field when viewed under cross-polarized light. When exposed to the ultrasound, the crystals change orientation and the birefringent properties of the liquid crystals create a brightness proportional to the intensity of the ultrasound. As with radiography, this technique cannot be used for hull damage assessment due to the inaccessibility of the inside of the hull. Acoustography would require that a display and video camera be positioned either inside or outside the hull and an ultrasonic unit be positioned on the opposite side of the hull to the display and camera.

Tomography determines the distribution of density in the part inspected. A three-dimensional image of the density distribution is created using a large number of two-dimensional images of the material density obtained by scanning techniques such as x-ray or ultrasonics. The part being inspected is divided into a series of overlying slices, with images of density distribution of each slice being taken repeatedly around the part. A computer integrates the data into a three-dimensional image. The drawbacks to this approach for hull damage assessment are that the hull should be looked at from 360 degrees to create an image, a great deal of data must be collected and complex mathematics must be performed to create the image, and the technique is capable of internal mapping only, not external mapping.

4.0 VEHICLE AND SENSOR SYSTEM MFEPS AND CONCEPTUAL SYSTEM DEVELOPMENT

This section describes how the MFEP can be used to assist in developing conceptual systems. An understanding of the methodology developed herein will allow mission-specific systems to be similarly developed if different operational requirements or operating environments are established.

4.1 Vehicle System MFEP

4.1.1 Vehicle System MFEP Overview

The various types of underwater vehicles reviewed in the preceding sections all have unique features. These unique features may allow them to perform certain aspects of the vessel damage assessment in a superior manner compared with the capabilities of other underwater vehicles. The main objective of this analysis is to exercise the MFEP in order to identify which vehicle system or systems will be best able to meet the general mission requirements established in previous sections. It should be noted that the resultant rankings derived in this section are not intended to provide a definitive "best vehicle system." Ranking is a function of mission requirements and the relative importance of mission factors. As various aspects of the mission are defined, specific requirements may change, thereby changing the suitability of the various vehicle systems for delivering specific sensors. The MFEP allows the vehicles to be evaluated with consideration given to both operational and environmental factors that can affect the delivery and positioning of damage assessment sensors. The MFEP has been performed on "nominal" vehicles which have the attributes required to efficiently deliver the envisioned damage assessment sensors (i.e., size, weight, maneuverability). The characteristics of these nominal vehicles are assumed to be consistent with systems that are either commercially available or exist in prototype form.

The mission factors and weighting assignments have been established on the basis of an analysis of oceanographic and environmental conditions throughout the U.S. coastal and inland waterways and on an operational analysis based on Coast Guard Standard Operating Procedures and a survey of Coast Guard personnel. The factors being rated in this underwater vehicle evaluation are detailed as follows:

Maximum Endurance	This is defined as the maximum mission duration that can be achieved. For example, the tethered vehicles are not limited by the availability of onboard power as is the case for autonomous underwater vehicles.
Traverse Rate	This is defined as the maximum speed of traverse for each vehicle type. The traverse rate affects the maximum area coverage that can be achieved, although the maximum traverse rate allowable is often driven by sensor requirements, as will be discussed in later sections.
Accessibility	This is defined as the ability of a given vehicle system to access the various vessel areas. Vertical areas include the sides, bow, stern (including the rudder and propellors); and horizontal area consists of the vessel bottom.
Position Keeping	This is defined as the ability to maintain position in various sea-state and current conditions. Most sensors require some degree of stability for imaging. Stability requirements are a function of factors such as field of view, beam angle, image-update rate, and sensitivity to geometric positioning variations.
Command, Control, and Logistics	This category comprises the factors that have direct impact on the operator/user, including the logistics of vehicle transportation to and from the inspection site and vehicle operations once on site. The operator skill level required is important to system selection because the ability to guide the underwater vehicle to a desired location or trajectory will directly affect the comprehensiveness of the information gathered. System complexity will also affect the ease with which maintenance and repairs can be performed.

Command, Control, and Logistics (continued)

Increasing system complexity also increases the probability of having to abort a mission due to failure of a subsystem or components. The complexity of each vehicle system is determined by the degree of component and subsystem integration required for system operation. Examples of components and subsystems that can affect overall complexity include those required for navigation, propulsion, power conversion and distribution, vehicle attitude and status sensing, and microprocessor controls. The command, control and logistics factors are evaluated subjectively, based on a comparison of the desired manning levels, training, and simplicity of system operation to actual requirements.

Surface Condition Degradation

This is defined as the point at which system performance is significantly impaired by the presence of oil, ice, or hazardous conditions on the surface of the sea. Adverse surface conditions can affect towing, umbilical fouling/abrasion, fouling of sensors as the pass through the air/sea interface, and the proximity to the damaged vessel that can be achieved.

Launch and Recovery Limitations

Launch and recovery are affected by the presence of waves, current, and ice. An estimation of the effects of these variables on the ability to place the vehicle in the water are important to determining the availability of given system under a variety of environmental conditions.

Relative Reliability	This is an estimation of both the overall availability of the system and the impact on mission performance as a result of failure of vehicle component or subsystem (fault tolerance). System availability is defined as the mean time to failure divided by the mean time between failures. Previous studies have shown that for ROVs system availability up to 85 percent of operational time is achievable for units that are being heavily used in the field. It is expected that this availability could be increased with proper preventive maintenance procedures. The ability to complete a mission is a function of a system's fault tolerance. Fault tolerance is a measure of the ability to continue operation if a component or subsystem fails. The fault tolerance is a function of the number and complexity of components that must be integrated for mission performance. Component redundancy and self-monitoring can minimize or reduce the effects of failure of a single component. The relative reliability is established on the basis of a comparison of the subject system complexity and fault tolerance with that of ROV systems.

4.1.2 System Ranking

The MFEP forms that contain the scoring for each vehicle can be found in Appendix C. The weighting values used for the MFEP were derived from an analysis of operational requirements and Coast Guard questionnaire response. The scoring of each vehicle system is based on a review of technical literature for each vehicle type. An analysis of the MFEP results indicates that for the given mission requirements, an underwater vehicle that is able to act as both an ROV and a hull crawler ranks most highly. The relative rankings for the various vehicle systems is as follows;

Hybrid ROV/Hull Crawler	0.75
Hull Crawler	0.74
ROV	0.61
Towed Vehicle	0.58
AUV	0.38

The vehicle attributes derived from this MFEP process are summarized in Table 4-1. This table shows the strengths and weaknesses of each underwater vehicle system as related to the specific mission requirements. The hybrid vehicle received the highest score compared with the other vehicle systems, primarily due to its position-keeping ability in a wide range of sea state and current conditions. The hybrid system scored slightly higher than a crawling vehicle primarily, due to its ability to operate from an increased standoff distance and also its ability to access all portions of the hull. This small difference is not significant, given the assumptions and somewhat subjective nature of some of the evaluation categories. The ability to change between various operating modes does provide flexibility that would allow a user to make on-scene decisions to optimize performance. For example, in low sea state-conditions, the vehicle could be used as a free swimmer, thereby allowing ready access to all areas of the hull at standoff distances optimum for sensor performance. In high sea-state or low-visibility conditions, the vehicle could be operated in a crawling mode, which would allow good vehicle control and sensor presentation to the hull.

It should be noted that the ranking is a function of the relative importance assigned to the factors being evaluated. Changing the importance of a factor will have direct impact on the relative ranking. For example, if the ability to operate in the presence of degraded surface conditions (ice, oil, hazardous material) is given a significantly higher weighting than the other factors, an AUV may become a more desirable system due to inherent ability to operate more effectively in that specific environment. Another example would be if a specific mission scenario calls only for the inspection of the sides of a vessel, in which case a towed vehicle may score more highly than the other vehicle types. These illustrations show how the MFEP process can be used in conjunction with a set of mission and environmental factors to assist in selecting an underwater vehicle system sensor systems.

4.2 Sensor System MFEP

4.2.1 Sensor System MFEP Overview

As was the case for the vehicle system MFEP, the Sensor System MFEP analyzes each sensor system in its ability to achieve mission inspection requirements under a given set of operational

Sensor System	Predicted Damage Assessment Function	Estimated Inspection Rate (sf/hr)	Estimated Standoff (ft)	Estimated Traverse Rate (knots)	Geometric & Positional Stability Sensitivity	Interpret-ability	Probability of Crack Detection (0.25"x3")	Prob. of Dent Detection (large scale, small slope)	Prob. of Dent Detection (small scale, large slope)
Side Scan Sonar	DL	92,000	6.2	0.5	High	Complex	Low-Moderate	Low	Low-Moderate
Multiple beam Bathymetric Sonar	DL, DC	34,000	2.5	1.1	High	Moderate	Low-Moderate	Low	Moderate-High
Profiling Sonar	DC	2,300	5.2	0.1	Very High	Moderate	Low-Moderate	Low	Moderate-High
Multiple beam Forward Look Sonar	DL	10,900	1.6	0.8	High	Moderate	Low-Moderate	Low	Low
3D Mapping Sonar	DL, DC	63,000	11.5	1.8	Moderate	Moderate	Low-Moderate	Low-Moderate	Moderate-High
Color CCD Television Camera	DL, DC	45,000	2.3	1.5	Low	Simple	Moderate-High	Low	Moderate-High
SIT or ICCD Television Camera	DL, DC	76,000	7.3	2.3	Low	Simple	Moderate-High	Low	Moderate-High
Range Gated Laser	DL, DC	14,500	16.4	0.8	Low	Simple	Moderate-High	Low	Moderate-High
Laser Line Scan- Long Range, 5 atten. lengths	DL, DC	778,000	16.4	5.0	High	Simple	Moderate	Moderate	Moderate-High
Laser Line Scan- Short Range, 2 atten. lengths	DC	2,000	6.6	0.05	High	Moderate	Low-Moderate	Low	High
3D Mapping Laser	DC	4,700	6.6	0.2	Very High	Moderate	Moderate-High	Low	High

ASSUMPTIONS:

(1) For acoustic sensors, inspection rate is at the maximum standoff & traverse rate for theoretical detection of a 3-inch dia. hole
(2) For visual sensor, inspection rate is calculated at the maximum standoff and traverse rate attainable for object imaging in 1 meter water
(3) Crack and dent detection probabilities are estimated for the standoff distances calculated
(4) A large scale, small slope dent was estimated to have dimensions of 100 ft long, 25 ft wide, and 1 ft deep
(5) A small scale, large slope dent was estimated to have dimensions of 1 ft long, 1 ft wide, and 4 in deep
(6) Inspection rates for TV cameras, range gated laser, and 3D sonar are based on a 3" hole appearing in the image for at least 2 seconds

KEY: DL = damage location, the sensor would be capable of searching a large area quickly to detect damage and determine its location
DC = damage characterization, the sensor would be very useful for quantifying the damage once the damage was located

TABLE 4-1. SUMMARY OF VEHICLE ATTRIBUTES

and environmental conditions. The ranking of sensors contributes to an understanding of how well each sensor, by itself, would be able to perform independent of the other sensors in the inspection of a ships hull. For this MFEP, the following definitions apply:

Inspection Rate	This is the maximum rate at which the surface area would be inspected with the objective of detecting a 3-inch hole. Assumptions governing detectability can be found in Appendix C. As a general rule, it was assumed that the defect had to remain visible to an operator for a period of 2 seconds for those sensor systems that provide a "passing" display (i.e., video display), and at least two sonar "hits" or defect detections were required for hardcopy displays (i.e., side-scan sonar waterfall printout or 3D computer-generated images).
Sensor Presentation Requirements	This is a measure of the stability and geometric positioning sensitivity required for a given sensor. As a general rule, the narrower the beam width and the slower the image update or scan rate, the more sensitive the sensor is to platform motion.
Sensor Output Interpretation	This is a measure of the simplicity with which a sensor output can be interpreted. Sensor outputs that require a significant amount of training for interpretation, or which are not intuitively clear in the manner in which information is presented, do not score as highly as simple displays such as video.
Crack Detection Capability	An estimation of the sensor's ability to detect cracks 0.25 inches wide by 3 inches in length is made on the basis of a sensor operating configuration selected for the detection of 3-inch holes. Detection assumptions made for 3-inch hole detection are carried through for crack detection assessment.

Dent Detection Capability	This is a measure of the sensor's ability to detect dents of various sizes; again, it is based on the operating configuration selected for the detection of 3-inch holes. Two different dent sizes were selected, one small size (1 square foot with 4-inch depth) and one large (100 feet long by 25 feet wide by 1 foot depth).

The sensors were ranked according to their ability to meet the inspection requirements using the MFEP previously discussed. The relative weighting factors and performance requirements were based on U.S. Coast Guard Standard Operating Procedures and input from Coast Guard personnel. Again, it should be noted that the ranking is not intended to eliminate technologies from being used as inspection tools, but only provides a measure of how well each sensor (by itself) is able to provide the information for the performance of damage assessment. As mission requirements are refined, different relative rankings may arise. For example, if area coverage requirements are low (as might be the case for collision-induced damage), lower area-coverage-rate sensors may become more suitable for the performance of the task (e.g., short-range laser line-scan or profiling sonars).

This analysis revealed that video cameras and laser imaging devices (long-range) are most able to perform vessel damage assessment as described. The MFEP scores received by each of the sensors are as follows:

Video Display (CCD/ICCD/SIT)	0.75
Laser Line Scan (Long Range)	0.67
Range Gated Laser	0.66
3D Mapping Sonar	0.58
Multibeam Bathymetric Sonar	0.47
Multibeam Forward Look Sonar	0.33
Side Scan Sonar	0.32
3D Mapping Laser	0.29
Laser Line Scan (Short Range)	0.27
Profiling Sonar	0.20

The attributes of the different sensors are shown in Table 4-2. It can be seen from this analysis that those sensors that provide video type displays are able to most adequately meet the overall requirements for damage assessment if used singularly. There is little scoring differentiation between the first three sensors listed since each will provide essentially the same information if used in its designated operating configuration. For this analysis, sonar systems did not score as highly primarily due to the increased ambiguity in interpreting the sensor output, and the lower probability of detecting small dents or cracks. Low area coverage rates resulted in the last three sensors listed receiving their relatively low scores.

4.3 Conceptual System Development

Based on the results of the MFEP and following the systems engineering approach, a conceptual damage assessment system was developed. This conceptual system is not simply a matching up of the "best" vehicle and "best" sensor, but is instead a composite system in which all of the damage assessment system needs are analyzed and the weaknesses of given technologies are supplemented and strengthened by the incorporation of other technologies where possible.

4.3.1 Component Integration

4.3.1.1 Underwater Vehicle

Based on the finding that a composite hull-crawler/ROV would be the best vehicle platform for delivering the sensors, a conceptual vehicle system Figure 4-1 was developed. As previously described, there are several ways in which a hull crawler can be "attached" to a hull, including magnetically, through buoyant forces, or by thrusting against the hull. The last method could be enhanced by incorporating mechanisms that would allow suction to be developed by the thrusters (i.e., a suction force of only a few psi would result in hundreds of pounds of holding force over a relatively small area). It is recommended that, prior to actually building a vehicle or inspection platform, a trades analysis and preliminary design effort be performed to address these issues. The features of this vehicle that have been incorporated to meet the operational requirements are described in the following paragraphs.

Vehicle Type	System Complexity	Operator Skill Level	Maximum Endurance (hrs)	Position Keeping-6 foot waves	Position Keeping-1 knot current	Vessel Accessibility	Ice Presence Degradation	Oil Presence Degradation	Launch & Recovery System Required	Remote Survey Capability Haz. Env.	Relative Cost (see note 2)	Traverse Rate (knots)
ROV	Moderate-High	Moderate-High	Unlimited	Poor	Fair-Good	Complete	Moderate	Moderate	Simple	Possible	Moderate	0-5
AUV	High	Moderate-High	8 hrs at 3 knots	Poor	Fair	Complete	Low	Low	Complex	Possible	High	0-5
Towed Vehicle	Low	Low-Moderate	Unlimited	Poor-Fair	Good	Sides Only	High	Low-Moderate	Simple	Not Possible	Low	1-5
Hull Crawling Vehicle	Moderate	Moderate	Unlimited	Good-Excellent	Good-Excellent	Complete except stern	Moderate	Low-Moderate	Simple	Not Possible	Moderate	0-4
Hybrid ROV/Hull Crawler	Moderate-High	Moderate-High	Unlimited	Good-Excellent	Good-Excellent	Complete	Moderate	Moderate	Simple	Possible	Moderate	0-5

NOTES.
(1) Attributes are based on "nominal" vehicles of size and capability envisioned to be necessary for mission performance
(2) Based on normalizing system costs to lowest priced system

TABLE 4-2. SUMMARY OF SENSOR ATTRIBUTES

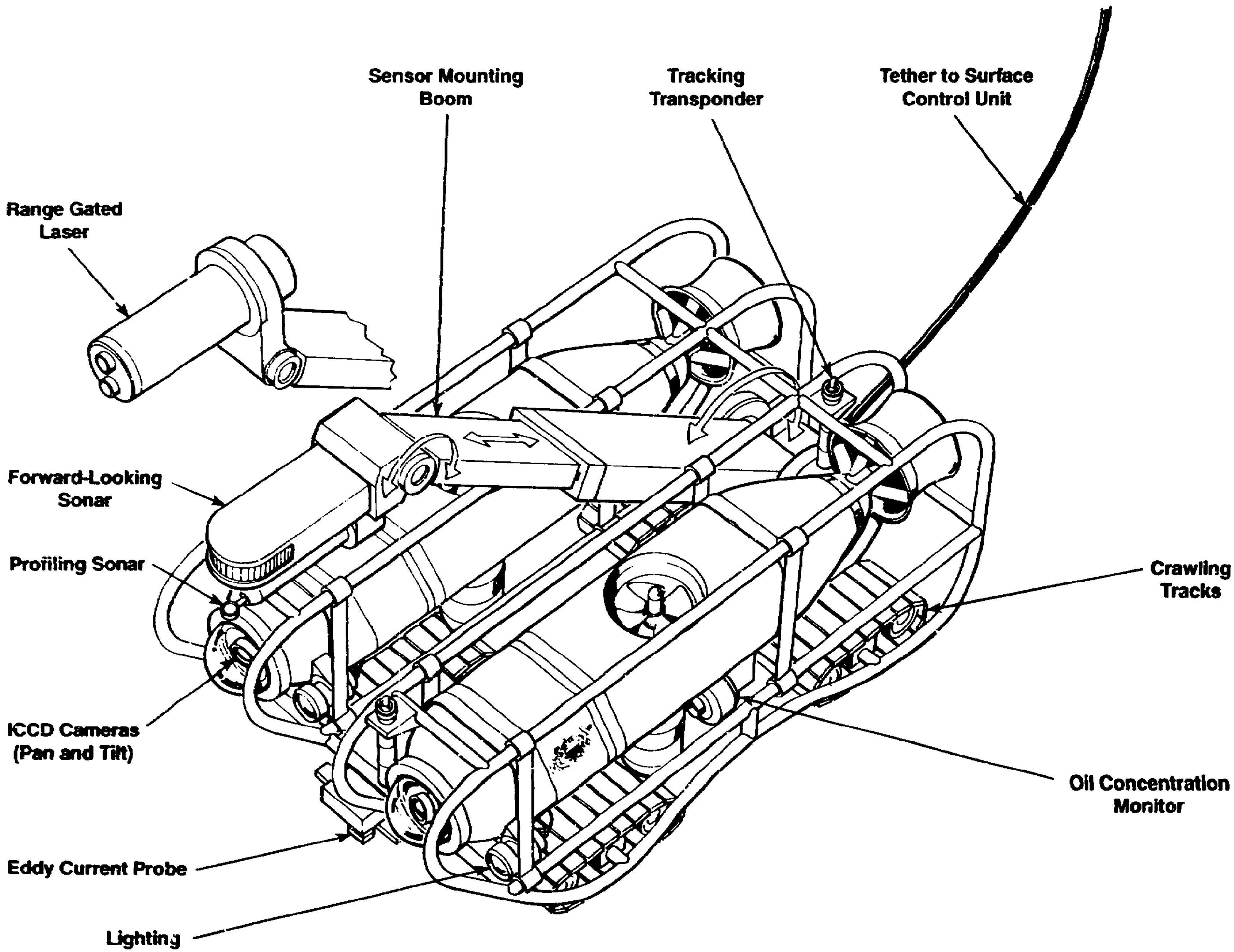


FIGURE 4-1. REMOTELY OPERATED HULL INSPECTION VEHICLE

Two identical thruster "modules" have been incorporated into the conceptual system design. A spare module carried on a mission could replace an existing module if component failure occurred. This would allow rapid redeployment of the inspection system while the disabled components were repaired. This capability is important because of the rapidity with which an inspection must be performed and the negative consequences of any component failure. An additional benefit of this design is that two cameras are available to the operator, effectively increasing the field of view and resulting in a higher area-coverage rate.

An equipment "bay" has been located between two thruster modules to accommodate the different inspection sensors. It is envisioned that the width of this bay could be expandable to allow sensors of varying sizes to be installed between the thruster modules.

A rotate feature could be incorporated into the vertical thrusters to allow operation to be rapidly shifted and performance optimized between the hull-crawling and free-swimming modes of operation. Rotating the vertical thrusters to a 45-degree orientation would allow both vertical and lateral thrusting in the free-swimming mode.

For the conceptualized system, movement about the hull would occur via the horizontal thrusters. The tracks allow the vehicle to roll freely along the hull. The vehicle frame is configured to allow the vehicle to crawl over a gentle radius (approximately 3 feet) without having the tracks lose their contact surface.

Tracking transponders are installed on one thruster module. As will be discussed in the following section, these tracking transponders provide vehicle heading and position input into the vehicle control system.

It is envisioned that, for free-swimming operations, the vehicle would be operated as shown (tracks down) to provide the operator with a vehicle orientation that allows the sensor outputs to be easily understood. The vehicle would have a center of buoyancy and center of gravity that are very close to each other, allowing the vehicle to be rotated about its longitudinal axis for transition into the hull-crawling mode of operation.

Where possible, composite and high strength-to-weight ratio materials should be used to minimize weight, thus enhancing transportation and portability of the vehicle. Because the design depth of the vehicle is not anticipated to exceed 100 feet, component weight savings may be realized in the form of thinner pressure housings, lighter-weight foam for buoyancy, air-filled (vice oil-filled) thruster housings, etc.

4.3.1.2 Sensors

The sensor modules selected for the conceptual system design are intended to provide imaging under the broad range of environmental conditions that could be expected for the performance of a damage assessment. As seen in Figure 4-1, two interchangeable modules are shown that could be installed on the vehicle. The features of the inspection modules are described below.

The sonar module (shown on the vehicle) is intended for use in extremely low visibility conditions. The sonar module is mounted on a boom that has three degrees of freedom: rotation at the base, extension, and rotation at the sensor. The boom would allow the sensor presentation to be optimized for information-gathering purposes. The sonar module consists of a forward-look sonar device (Seabat™ shown for illustrative purposes) that is installed as a damage-locating device. The forward-look sonar system selected should have a relatively high image- update rate to allow the search rate to be maximized. A large vertical beam width probably would not be required because the surface being investigated is generally flat. Located beneath the forward-look sonar is a profiling sonar. This sonar, with its narrow beam, would be used for damage characterization.

The range-gated laser module is intended for use in visibility conditions where the low-light cameras installed in the thruster modules are inadequate for imaging purposes; but the increased performance capability of the range-gated laser allows visual analysis of a damaged area. An optimized range-gated laser system (8 inch diameter by 24 inch length) could be mounted to the boom arm in the same manner as the sonar module. The manufacturer has stated that an ROV system could be built to these dimensions. Further analysis and testing of the range-gated laser system is recommended as detailed in later sections.

An eddy-current detector is shown mounted on the vehicle for detection of cracks in the hull. An eddy-current sensor is capable of detecting cracks that visual or sonar systems are unable to detect. This method of detecting cracks is a simple, reliable NDT method that is compatible with the inspection objectives.

An oil-water analyzer is included for rapidly tracking leaks to their source. The method of detecting the concentration of oil in water may have to be changeable on the vehicle because detectors generally operate over a fixed range of concentrations. Most systems able to detect low concentrations of oil will saturate at concentrations seen in the envisioned operating environment; therefore, the development of a custom sensor able to monitor higher concentrations may be required.

4.3.2 Navigation and Positioning Requirements

There are several viable options for navigation systems to be used for the damage assessment mission. The following navigation system attributes desired for the hull-inspection vehicle are as follows:

- Provide as great a positional accuracy and precision as possible. Positional accuracy (knowing where the system is relative to a fixed location) and precision (repeatability of the measurements) are desired to ensure there are no "holidays" in hull coverage. Less accuracy and precision would result in a requirement to provide a greater degree of overlap in the inspection paths to ensure that no gaps in coverage exist. Since large scale dents (small slope over large areas) are especially hard to detect, an accurate and precise navigation system could alleviate this problem.
- Simple to operate and deploy.
- Interface capability with the vehicle control system to allow the vehicle path to be controlled with a preset plan. This would allow the vehicle operator to assume a more supervisory role, which is especially desirable when operator training is limited.

An example of a commercially available system that embodies these attributes is the SHARPS™ or EXACT™ navigation systems coupled with the ROV-DP™ vehicle control system. The SHARPS and EXACT navigation systems are designed for precise, short-range surveying and ROV tracking. They are basically small versions of the long-baseline (LBL) acoustic navigation system previously discussed. Both systems require that the vehicle carry an onboard transceiver and have line of sight to at least three tracking transceivers or transponders. The SHARPS system uses hardwired transceivers while the EXACT system uses transponders. There are advantages and disadvantages associated with each system. The hardwired system (SHARPS) is less susceptible to multipath returns but is not as easily deployed as the EXACT system due to the long cable runs that are required. This may be especially significant for a hull inspection where the grid area or "net" must be moved several times during the inspection of a complete hull. The range of the transceivers/transponders is approximately 300 feet, which would be a factor for large vessel inspection. Multiple transceiver units (up to 24) could be used to create a larger grid area to alleviate this problem.

The rms position error of this system is advertised to be ± 2 cm, which is well within the desired ± 1 foot desired for damage assessment purposes. The precision of the system is such that it could be used for establishing vehicle heading by placing two transceivers on the vehicle. Large-scale dents could be detected if this navigation system was used in conjunction with a high-accuracy pressure transducer to measure vehicle depth. A pressure transducer would be required because the vehicle must be more than 10 percent off the plane of the transceivers to get good z-axis information (i.e., 30 feet for a 300 foot grid). This may not always be possible, especially if the ship is run aground.

The ROV-DP system is designed to provide automatic feedback control of the position, velocity, and heading of an ROV with respect to a fixed or moving network of acoustic transceivers. This allows pre-programmed or interactively generated trajectories to be flown without touching the joystick. It also enables the vehicle to hover at an assigned position and heading in the presence of currents or other disturbances. The manufacturer has stated that this system could be modified to operate with hull-crawling vehicles with minor modifications to the current algorithms.

4.3.3 Information Management

A final important aspect of the conceptual vehicle design is the management of information received during the damage assessment process. One of the more-promising systems for the management of information identified during the performance of this study is the Ship Shape system currently being developed by Oceaneering Technologies for the Supervisor of Salvage, Naval Sea Systems Command. Ship Shape interfaces a computer mapping system to a diver navigation system, ultrasonic thickness gauge, and diver's helmet video camera. The manager displays a window which depicts a 40 x 40-square-foot section of the hull. As the diver's navigation system tracks the diver outside this area, a new area is scrolled automatically with the current position being centered. The operator can select features of interest and mark them with symbols on the display. Another system, C-Map by Houston Geoscan, Inc., allows operator interface for the storage of video images, positioning information from SHARPS or EXACT, and NDT sensors as well.

Maintaining information in the forms discussed above allows the operator to focus on the inspection without having to divert his attention for the purposes of log-keeping; it also allows the information to be rapidly retrieved for reconstruction or reanalysis of an area that has been inspected.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The analysis of underwater vehicle and sensor systems has revealed that the process of vessel damage assessment could be enhanced significantly through the use of underwater vehicle and sensor systems. The hazards associated with placing divers in the water to perform damage assessments are great in many instances. The presence of jagged metal, pollutants, high currents, and high sea-state conditions may often preclude the use of a diver, thereby degrading the damage assessment process.

The multifactor evaluation process (MFEP) used for analyzing vehicle systems and sensors proved useful for ascertaining how specific vehicles or components can be ranked, given a divergent set of analysis criteria. The conceptual system design presented in this report was developed on the basis of a defined set of mission requirements, operational and environmental scenarios, and relative weightings of the evaluation factors. It should be noted that changing the mission requirements, operational and environmental scenarios, or relative importance of the evaluation factors would influence what vehicle or sensor systems are most appropriate for the task. The subjective nature of some of the evaluation criteria used in the MFEP also introduces variance into the scoring; therefore, it is useful to incorporate several expert opinions into the grading process to mitigate these effects.

Based on this investigation, it appears that an underwater vehicle system for performing damage assessment could be implemented using currently available technology, with performance enhancement occurring through specific research and development efforts.

The technology areas identified where research and development would result in significant enhancement of the Coast Guard's damage assessment capabilities are summarized as follows:

Validation of Sensor Performance. The actual performance of the sensors described herein, and those which may become available in the future, should be validated. A baseline testing program for the sensors should be implemented in an environment which is carefully controlled and configured for repeatability. For example, the validation of acoustic sensors could occur in a test area in which acoustic multipath and reverberation problems are controlled through the use of anechoic coatings, and visual sensor testing could be performed in an environment in which the turbidity/attenuation length is carefully controlled through the addition of turbidizing agents.

This baseline test program could be used to compare the sensor performance in a controlled setting to the results obtained in field experiments. Those sensors which are unable to perform adequately in this controlled environment could be eliminated from field test programs which are likely to be more costly to run.

Development of a Sensor Test Bed and Test Targets. The development of an at-sea sensor test bed is recommended to allow the various sensors to be tested in a field environment. This will allow baseline performance data to be compared to at-sea test information. A test bed that allows the vehicle to be operated at a standoff required for proper sensor presentation, and which also allows the sensors to be placed in a stable manner on the hull, would provide a range of operating configurations which would likely be seen. A test bed similar to the conceptual design vehicle presented in Section 4 (without sensors installed) would be a likely candidate to use for field testing.

Along with the test bed, a transportable field test target, or targets should be developed to simulate damage conditions that might be encountered. These test targets could be configured with various surface conditions (e.g., painted, bare metal, barnacles) and defects (e.g., cracks, holes, tears) to simulate a range of likely damage scenarios.

Analysis of Oil/Water Mixes and Air Entrainment on Sensor Performance. No manufacturer could give a definitive response regarding their sensors' performance in an oil/water mixture. It is recommended that testing be performed on sensors that "pass" the field test to determine the effects of various oil/water mixes on the sensor performance. During this phase of development, methods to protect the sensors from the effects of oil should be developed and tested if necessary. Testing of sensors used to detect oil leak sources (e.g., TOM, fluorometers) should be conducted during this phase as well to ascertain whether they operate satisfactorily in the various oil/water environments. Acoustic sensor performance is also severely degraded in the presence of air bubbles entrained in the water column. The degradation in performance as a function of air entrainment requires further analysis as well.

Sensor Development and Testing. Several sensors may require development or modification to optimize their performance. The specific sensors for which significant mission enhancement could be gained are described below.

- **Range-Gated Laser.** It is recommended that a parametric analysis be performed to determine the effects of varying the laser pulse length and field-of-view with different attenuation length water. It may be possible to enhance vessel inspections by allowing the user to make system adjustments to optimize performance during a mission. A larger depth of field, resulting in a smaller standoff distance, may be desirable if the underwater vehicle is operated in a crawling mode, whereas a greater standoff distance, resulting in a smaller field of view, may be desirable in the free-swimming mode. The use of polarization filters to enhance an image should also be investigated. The features of damage that will probably be present in the event of grounding or collision may provide distinct image characteristics due to the polarization or depolarization of the laser light. These effects depend on the angle of incidence of the laser light on the surface, therefore, the test program should encompass a range of imaging angles, standoff distances, fields of view, and pulse lengths.

- **3D Sonar Systems.** The 3D sonar system Raytheon is currently developing should provide good imaging capability at increased standoff distances when video systems are limited by visibility. The large number of beams that are digitally formed allow for good resolution, and the "snapshot" nature of the device is desireable, especially on a moving platform such as an ROV or AUV. This system is in the early stages of development. If development of this system is pursued, factors such as projector power, resolution, and image update rates should all be investigated. Saturation of side lobes due to the strong returns that could be expected from a ship's hull are a major concern for this system as well as for the DAISY™ sonar system; therefore, special attention should be given to this performance parameter.

- **Eddy-Current Detectors.** Investigation and optimization of an eddy-current detector or array of detectors designed to detect 3-inch cracks would be desirable. Following design optimization, testing the detector system on the vehicle test bed and test targets would be desirable.

- **Vehicle Deployable Oil/Water and Oil/Air Interface Detector.** Mounting a detector capable of determining an oil/water and oil/air interface within a tank would free the operator from having to make these measurements from the deck of the ship, and it would also be intrinsically safe. As discussed in previous sections, technologies exist that could be modified and adapted for incorporation into an ROV/crawler vehicle system.

- **Underwater Vehicle Development and Testing.** The vehicle configurations that could be used may vary as a function of the specific environmental and operational scenarios under which the damage assessment must be performed. Several areas of research and development could advance the state of the art in underwater vehicle capabilities. With advancements in underwater vehicle capabilities would come enhanced inspection capabilities under a broader range of operating conditions. Recommended areas of development are summarized below.

- **Autonomous Underwater Vehicles.** AUVs offer several advantages over tethered ROVs for performing vessel damage assessment, especially in those cases where increased standoff is required due to hazardous surface conditions (e.g., oil, fire), when the damaged vessel is in danger of sinking, or if hazardous chemicals or materials being released present a personnel hazard. The primary disadvantage of AUVs is their limited communications capability via acoustic links which degrades real-time control capabilities. This disadvantage may be overcome through improvements in data transmission rates, through the implementation of alternate control schemes such as an expendable fiber-optic cable that pays out as the vehicles moves through the water, or through use of a towed surface buoy that allows communications through the air. Tradeoffs which bear further investigation exist for each of these control schemes. Advances in the power density of onboard power supplies would allow the system weight to be decreased and/or the mission duration to be increased, both of which would enhance AUV system performance. Research that addresses this problem is currently being conducted in the area of aluminum-oxygen fuel cells.

- **ROV/AUV Image Stabilization.** Vehicle motion due to wave action often results from operating near the surface. This motion results in a degradation of the ability to image an inspection area. Incorporating image stabilization techniques into the vehicle would mitigate these effects. One of the simplest methods of image stabilization would be through the control of platform orientation to keep the video camera or other sensor pointed at the same point in space. This would require control algorithms that incorporate information on vehicle status (e.g., heading, depth, tilt angles) and the relative position of the inspection area to the vehicle.

In addition to the research and development recommendations presented above, new sensor and underwater vehicle technologies resulting from Coast Guard, Industrial, or other Government-agency research efforts should be evaluated for their applicability to the damage assessment mission.

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APPENDIX A

U/W INSPECTION MISSION FUNCTIONAL FLOW BLOCK DIAGRAMS

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U/W INSPECTION MISSION FUNCTIONAL FLOW BLOCK DIAGRAM

The following pages represent our understanding of the functional relations which apply to an inspection mission to assess damage to the submerged portion of a hull which has been involved in a collision or grounding.

We have chosen to use an existing relational model called Design/IDEF which automates the processes of Structured Analysis Design Technique (SADT) to identify the functions and capture the sequences of actions involved in such a survey. The following explains the software, so that those unfamiliar with the system should be able to interpret the diagrams.

IDEF may be used to model any system, where a clear hierarchical organization applies; that is, the diagrams at each "level" completely and exclusively capture all of the aspects of interest of all other diagrams "below" them in the hierarchy.

The heart of each diagram consists of one or more boxes, representing specific functions to be performed. The boxes are linked by arrows which show the sequential flow of data or information. The top sheet, or "node" (A-0 in this case), provides a legend of key features which apply to all nodes:

Regarding arrows:

- Arrows entering from the left are inputs
- Arrows leaving to the right are outputs
- Arrows entering the top are controls
    - Arrows entering the bottom are agents or mechanisms

• "Tunnels" (coded by parentheses) around either the head or tail of an arrow indicate that the arrow disappears at lower or higher levels (respectively) of the diagrams. This is frequently done for clarity, when the presence of the arrow would not contribute much new information.

Regarding labels:

• Nodes are numbered in the lower left hand corner of each sheet, with successively lower levels of decomposition shown by more numbers, e.g., A2, A23, A235, A2352 . . .

• Boxes are labeled with functions, and coded with their own node number in the lower right hand corner of the box.

• Arrows are labeled to describe data, or annotated to show flow of information or action.

• Arrows entering or leaving a box carry a designator code (which shows up in the next level down): I = inputs, O = outputs, C = control, M = mechanism. A numeral indicates the order in which the arrow appears coming out of, or into, the boxes (e.g., C1, O2 etc.).

Regarding Hierarchy:

• The "CONTEXT" box in the upper right hand corner of each sheet shows how that sheet fits into the structure of the next sheet up in the hierarchy. For example, node A1 (Strike Team Response) shows up as the (shaded) upper left box in a set of five functional boxes on node A0.

• The Tree Diagram is an alternative, pictorial way of viewing the hierarchical breakdown of all of the functional diagrams.

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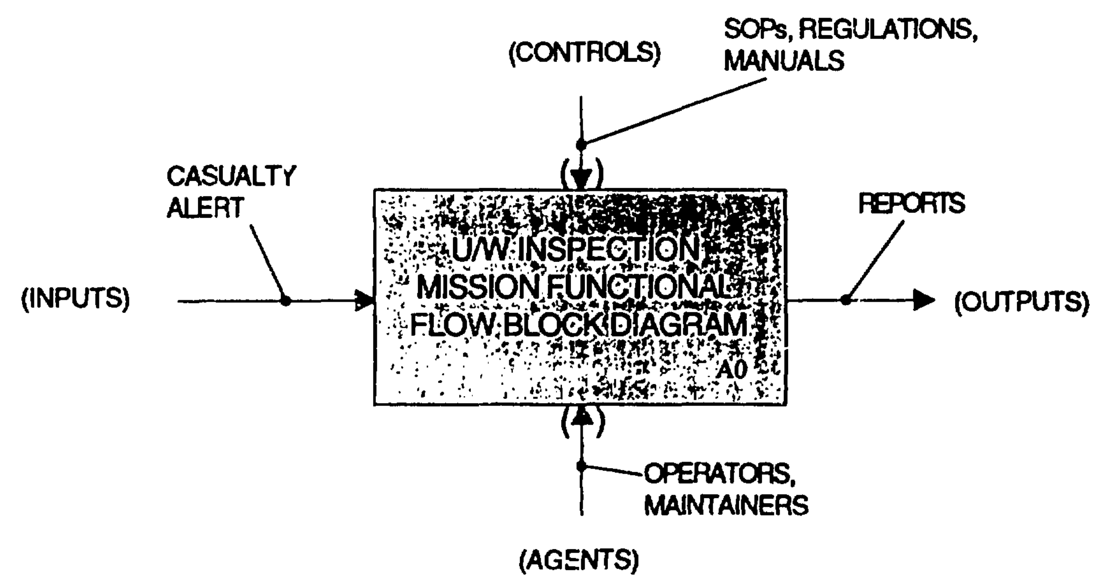
				PUBLICATION			



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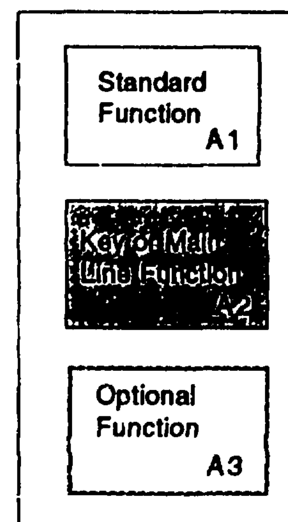

Point of view: Coast Guard Spill Response Officer

NODE: A-0	TITLE:	NUMBER:

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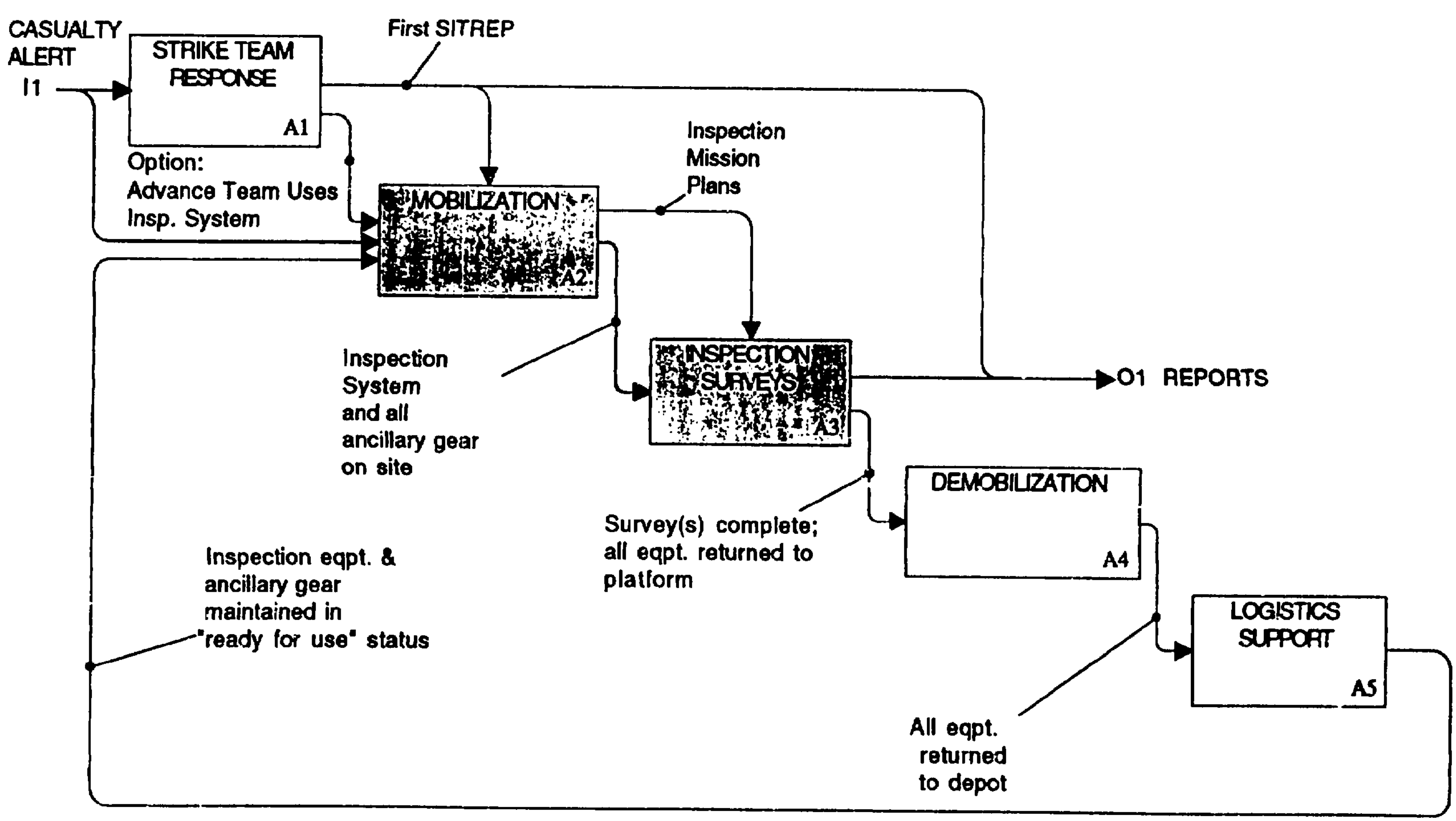
				RECOMMENDED		
				PUBLICATION		



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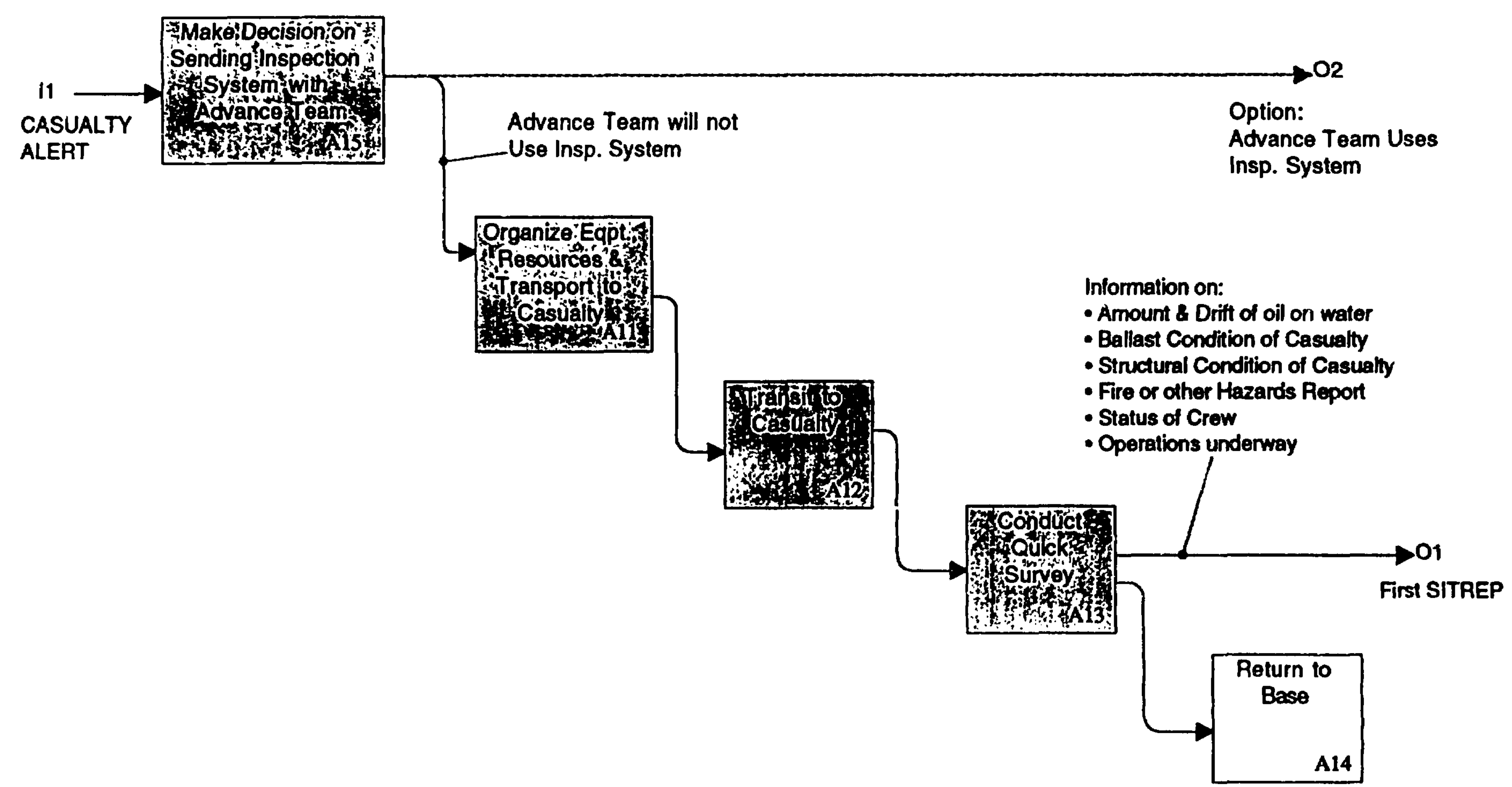
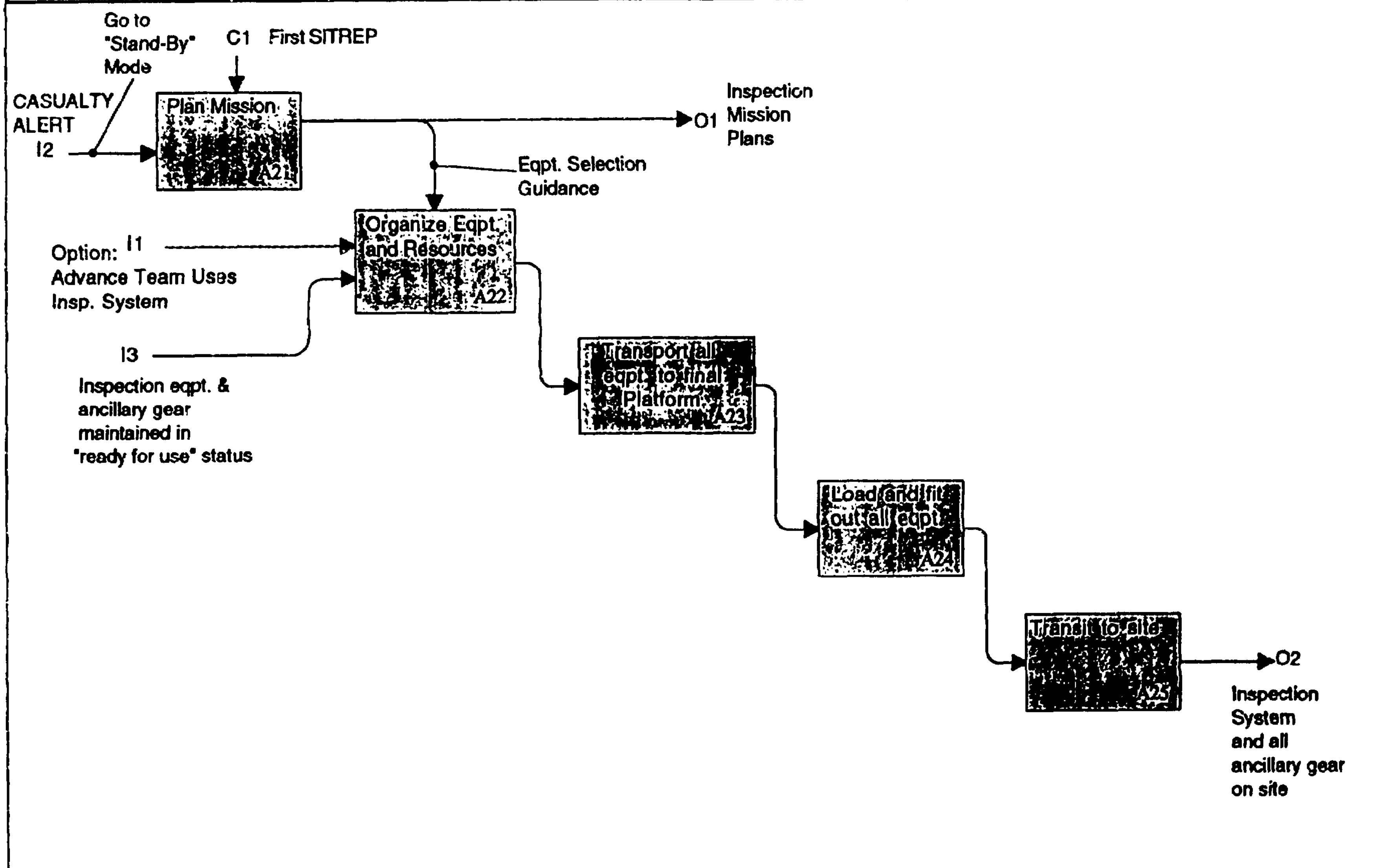
USED AT:	AUTHOR: PROJECT: COAST GUARD INSPECTION SYSTEM NOTES: 1 2 3 4 5 6 7 8 9 10	DATE: 1/5/93 REV:		WORKING	READER	DATE	CONTEXT:
			X	DRAFT			
				RECOMMENDED			
				PUBLICATION			



NODE: A1	TITLE: STRIKE TEAM RESPONSE	NUMBER:

USED AT:	AUTHOR: PROJECT: COAST GUARD INSPECTION SYSTEM NOTES: 1 2 3 4 5 6 7 8 9 10	DATE: 12/29/92 REV:		WORKING	READER	DATE	CONTEXT:
			X	DRAFT			
				RECOMMENDED			
				PUBLICATION			



NODE: A2	TITLE: MOBILIZATION	NUMBER:

USED AT:

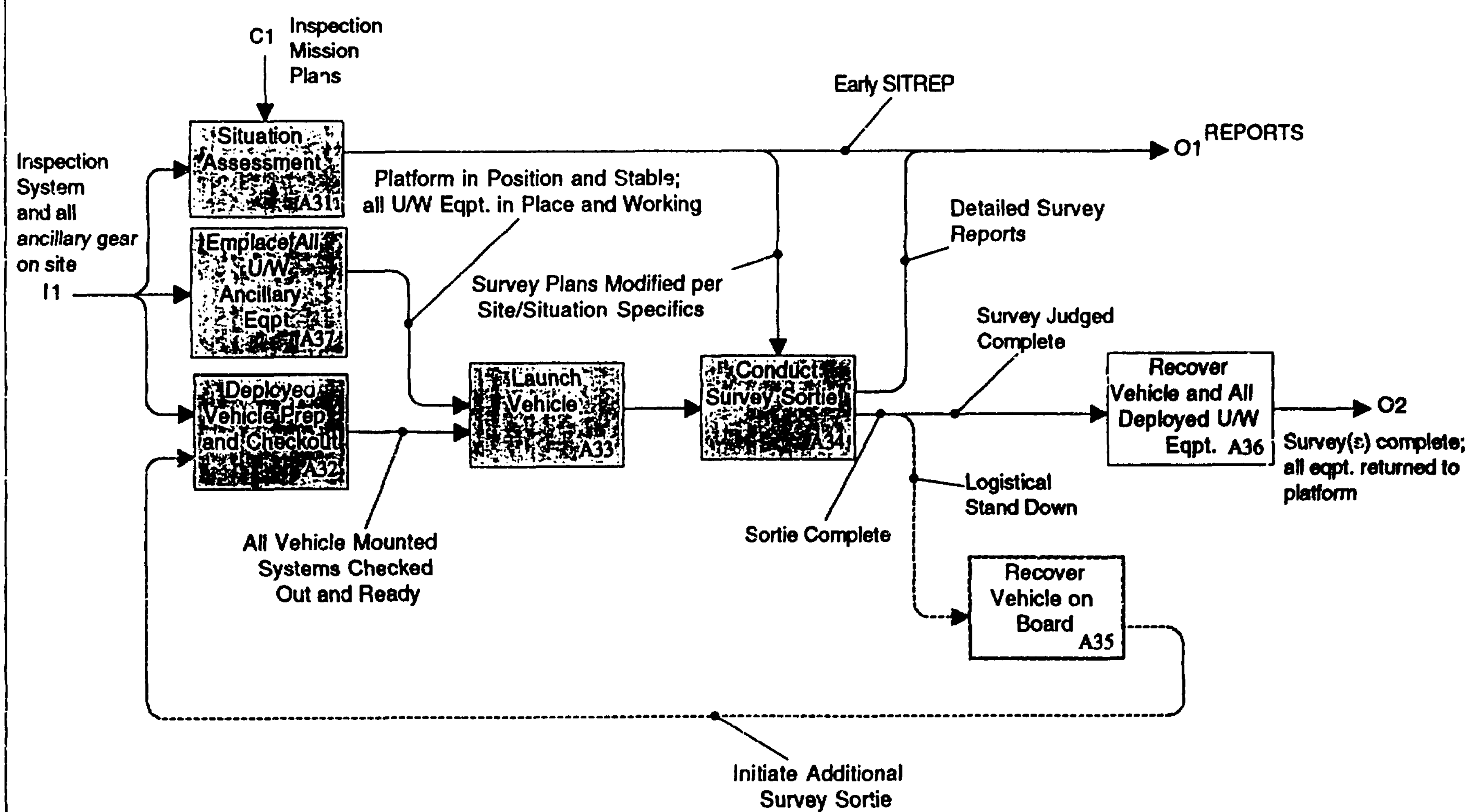
AUTHOR:
PROJECT: COAST GUARD INSPECTION SYSTEM

DATE: 12/29/92
REV:

NOTES: 1 2 3 4 5 6 7 8 9 10

	WORKING	READER	DATE
X	DRAFT		
	RECOMMENDED		
	PUBLICATION		

CONTEXT:

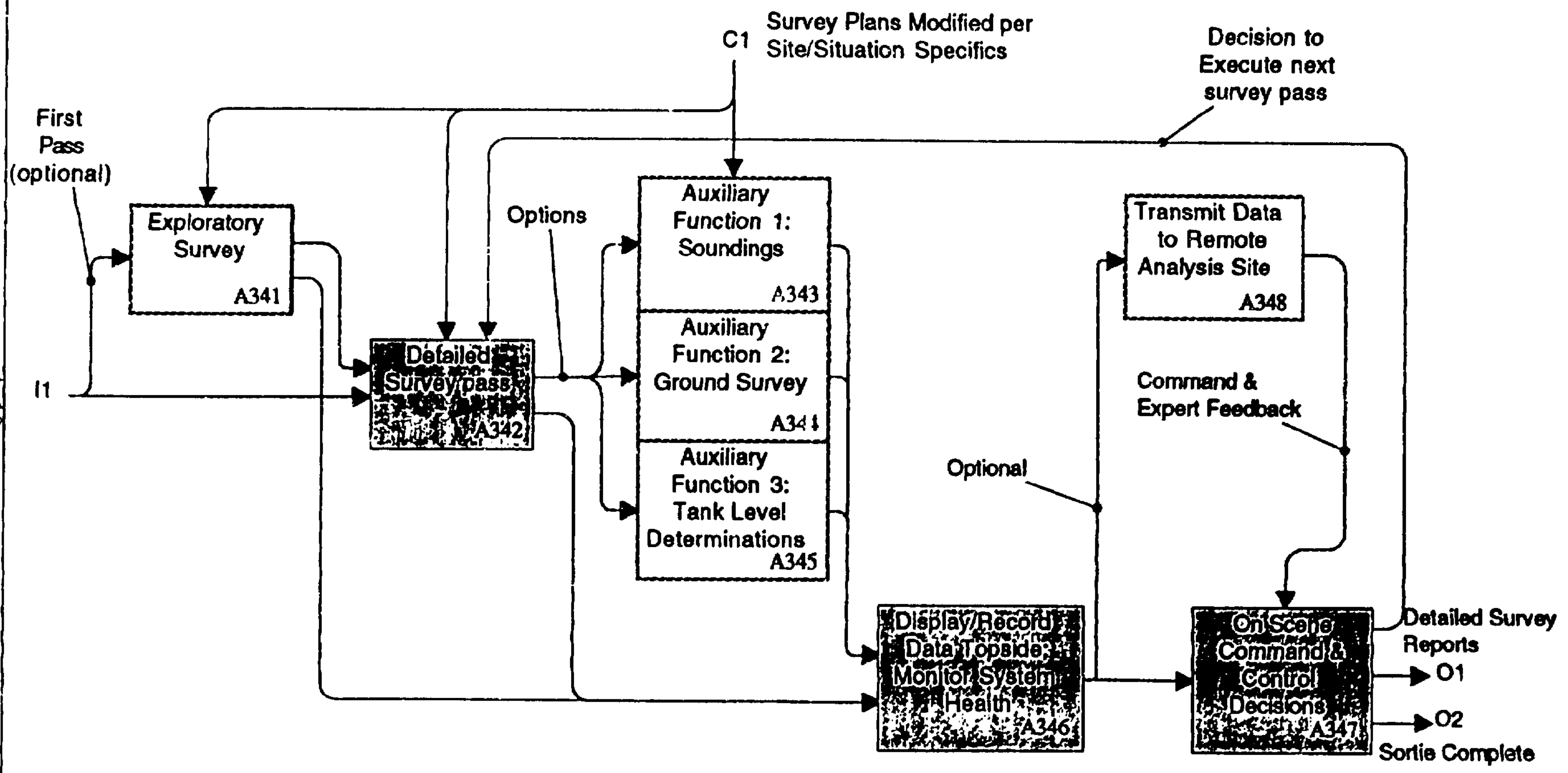


NODE: A3

TITLE: INSPECTION SURVEYS

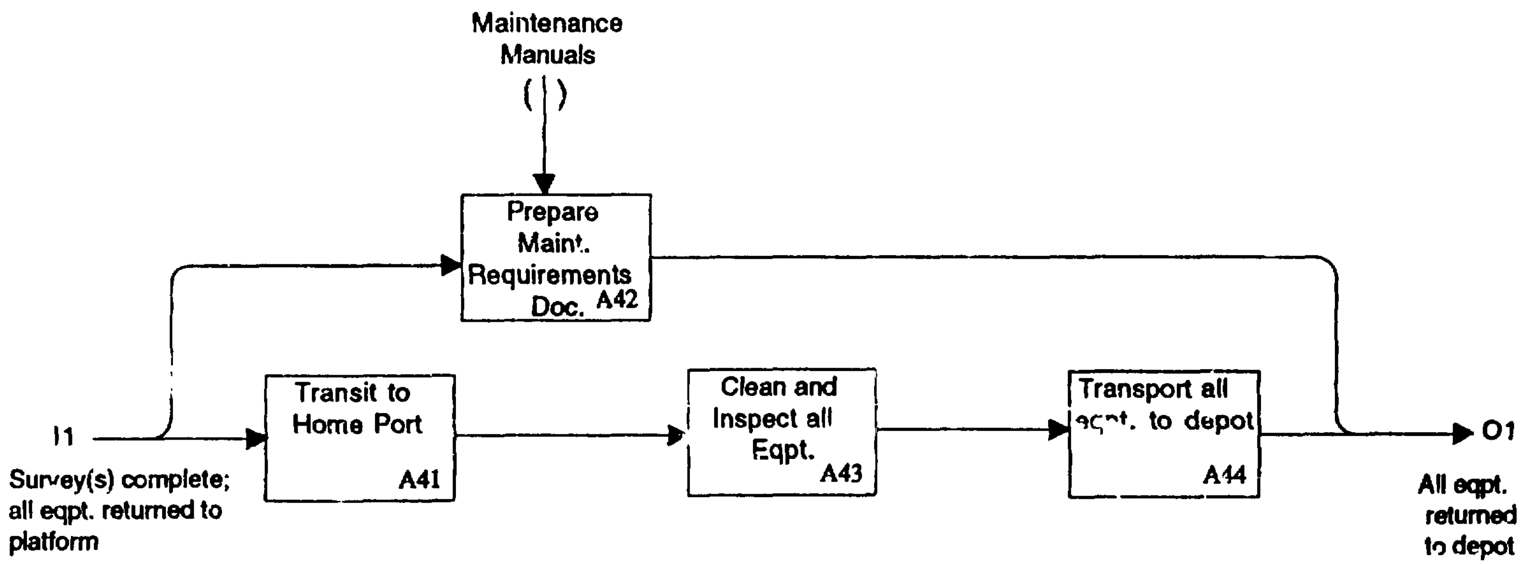
NUMBER:

USED AT:	AUTHOR:	DATE: 12/30/92		WORKING	READER	DATE	CONTEXT:
	PROJECT: COAST GUARD INSPECTION SYSTEM	REV:	X	DRAFT			
				RECOMMENDED			
	NOTES: 1 2 3 4 5 6 7 8 9 10			PUBLICATION			



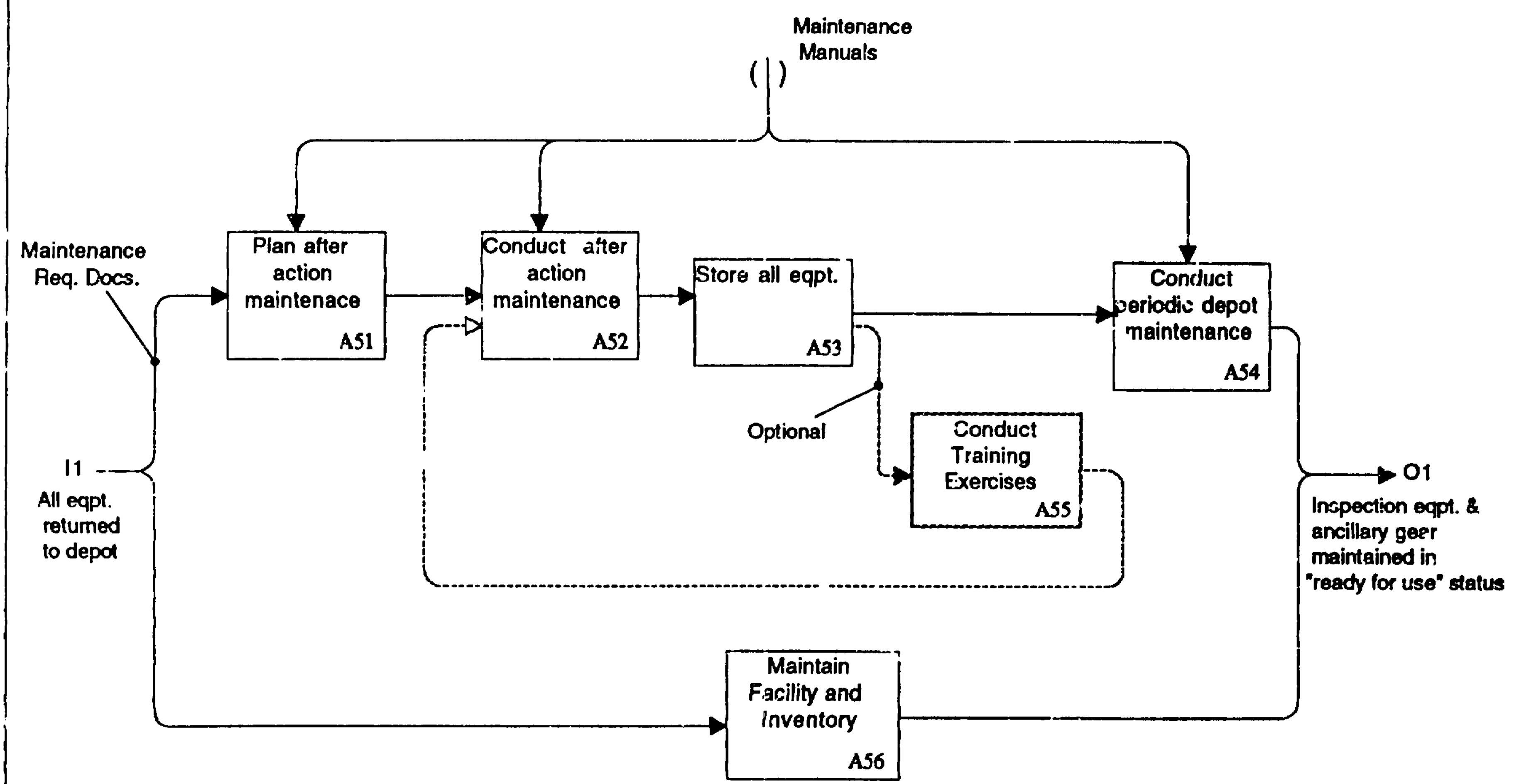
NODE: A34	TITLE: Conduct Survey Sortie	NUMBER:

USED AT:	AUTHOR:	DATE: 12/29/92		WORKING	READER	DATE	CONTEXT:
	PROJECT: COAST GUARD INSPECTION SYSTEM	REV:	X	DRAFT			
				RECOMMENDED			
	NOTES: 1 2 3 4 5 6 7 8 9 10			PUBLICATION			



NODE: A4	TITLE: DEMOBILIZATION	NUMBER:

USED AT:	AUTHOR: PROJECT: COAST GUARD INSPECTION SYSTEM NOTES: 1 2 3 4 5 6 7 8 9 10	DATE: 12/29/92 REV:		WORKING	READER	DATE	CONTEXT:
			X	DRAFT			
				RECOMMENDED			
				PUBLICATION			



NODE: A5	TITLE: LOGISTICS SUPPORT	NUMBER:

APPENDIX B

OPERATOR SURVEY RESULTS

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SURVEY COMPOSITE RESULTS

MISSION/SYSTEM REQ.		**FREQUENCY**				
System Capability	Value	Never	In-frequent	Half Time	Often	Always
Manning: How often do you think the number of men listed could be dedicated to the operation of the system?	1	2			1	2
	2			2	2	1
	3		1	2	1	1
	4	1	1	1	1	1
	5	1	3	1		
Resolution, holes: How often do you anticipate the system will be required to detect holes no larger than the listed diameter?	.3 in.	1		1	1	
	1 in.	1	1	1		2
	3 in.			2	1	2
	10 in.			1	1	4
	30 in.			1		4
Resolution, cracks: How often do you anticipate the system will be required to detect cracks no larger than the	0.3 in.	2	2		1	2
	1 in.	1	1	1		2
	3 in.		1	1	1	4
	10 in.			1		4
	30 in.					
Accuracy: How often do you anticipate the listed accuracies will be required to adequately locate damage in relation to known features on the ship? Within . . .	0.1 ft.	1	2	1	1	
	1 ft.			3		2
	3 ft.			1		4
	10 ft.				1	4
	30 ft.	1				4

Comments/Suggestions:

MISSION/SYSTEM REQ.		FREQUENCY				
System Capability	Value	Never	In-frequent	Half Time	Often	Always
Product Resistance: How often must the system be able to operate in the following water conditions?	Clean water			1	1	3
	Chem spill		3			2
	Oily water			1	1	3
	Pure Oil		2	1	1	1
Damage Location: How often must the locations listed be surveyed/inspected during the performance of damage assessment?	Rudder/Prop		3		1	1
	Sides, Fwd		1	1		3
	Sides, Mid		1	1		3
	Sides, Aft		2		1	2
	Bottom, Fwd			1	1	3
	Bottom, Mid			1	1	3
	Bottom, Aft		1		2	2
	Bow		1	1	1	2
	Stern		2	2		1
	Deck		3	1		1
Characterization of Damage: How often must the system be able to distinguish the following characteristics?	Holes			1		4
	Cracks			1		3
	Tears			1	1	4
	Buckling				3	1
	Dents			1	3	1
Weather Restrictions: How often would the system be operated in the specified wave height?	0		1	1	1	2
	3'			1	1	3
	6'		2		1	2
	9'	2	1	1	1	
	11'	2	2		1	

Comments/Suggestions:

MISSION/SYSTEM REQ.		FREQUENCY				
System Capability	Value	Never	In-frequent	Half Time	Often	Always
Current Restrictions: How often would the sytem be operated in the specified current?	0 kts.		1	1	2	1
	0.5 kts.			2	3	1
	1 kts.			2	2	1
	2 kts.		2	1		1
	3 kts.		2	2	1	
	4 kts.	2	1	1	1	
	> 4 kts.	2	1	2		
Air Temp: How often would the system be operated in the air temperatures ranges (in deg F) listed?						
	< -30		5			2
	-30 to +30			3		2
	30 to 100			1	2	1
	> 100		3	1		
Ice cover: How often would the system be operated with ice cover of aprox. the % listed?						
	0%				2	3
	25%		2	1	1	1
	50%	1	1	2	1	
	75%	3	1	1		
	100%	4	1			
Visibility: If you have worked with divers doing a damage assessment, how often are the following visibility conditions encountered?						
	0-1 ft.		1		3	
	1-3 ft			1	3	
	3-10 ft.		1	3		
	10-30 ft.	1	2	1		
	>30 ft.	2	2			

Comments/Suggestions:

Mission Requirement Questionnaire - Part II

1. What shelf life do you con: ı ʌ · to be acceptable for this inspection system?

   10 years
   15 years
   15 years
   5 years
   10 years - Make it as modular as possible for parts replacement

2. If schooling is required to train system operators, how much personnel training time do you think would be acceptable (total man-hours)?

   236
   120
   40 hours
   40 hours
   40-80

3. How much time do you think could be devoted to refresher/proficiency training each year for the system operators (total man-hours)?

   40
   20
   8 hours
   10 hours
   10

4. How long of a time delay do you think would be acceptable between the time the data is collected by the inspection system until interpretation of this data is complete (i.e., some post processing may be required after the data has been collected)?

   1/2 day
   3 hours
   2 hours
   1/2 hour - 1 hour
   <4 hours, real time if possible

5. At what air temperature do you feel operations such as handling equipment on the deck of a ship, or movement of equipment from one platform to another become significantly impaired?

   40 °F
   20 °F and below
   20 °F
   32 °F and below
   32 °F and below

6. If the failure of a certain component severely hinders the system's ability to complete the inspection, what is the longest mean time to repair that you would consider to be acceptable?

   1 day
   2 hours
   2 hours
   1 hour
   2-4 days

7. What is the lowest mean time between failures that would be acceptable for an inspection system?

   45 days
   4 days
   200 days
   None

8. On a monthly basis, how many man-hours of periodic maintenance do you think would be acceptable?

   16 hours
   10 hours
   4 hours
   2 hours

9. Would the system ever be deployed by a ship of opportunity? If yes, how frequently?

   Yes, always
   Yes, always
   Yes, frequently
   Yes, also should be air deployable to site
   Yes, 90-100% of the time

Comments____

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APPENDIX C

MFEP WORKSHEETS AND TABLES

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Summary of Vehicle Attributes (see note 1)

Vehicle Type	System Complexity	Operator Skill Level	Maximum Endurance (hrs)	Position Keeping-6 foot waves	Position Keeping-1 knot current	Vessel Accessibility	Ice Presence Degradation	Oil Presence Degradation	Launch & Recovery System Required	Remote Survey Capability Haz. Env.	Relative Cost (see note 2)	Traverse Rate (knots)
ROV	Moderate-High	Moderate-High	Unlimited	Poor	Fair-Good	Complete	Moderate	Moderate	Simple	Possible	Moderate	0-5
AUV	High	Moderate-High	8 hrs at 3 knots	Poor	Fair	Complete	Low	Low	Complex	Possible	High	0-5
Towed Vehicle	Low	Low-Moderate	Unlimited	Poor-Fair	Good	Sides Only	High	Low-Moderate	Simple	Not Possible	Low	1-5
Hull Crawling Vehicle	Moderate	Moderate	Unlimited	Good-Excellent	Good-Excellent	Complete except stern	Moderate	Low-Moderate	Simple	Not Possible	Moderate	0-4
Hybrid ROV/ Hull Crawler	Moderate-High	Moderate-High	Unlimited	Good-Excellent	Good-Excellent	Complete	Moderate	Moderate	Simple	Possible	Moderate	0-5

NOTES:
(1) Attributes are based on "nominal" vehicles of size and capability envisioned to be necessary for mission performance
(2) Based on normalizing system costs to lowest priced system

Sensor System	Predicted Damage Assessment Function	Estimated Inspection Rate (sf/hr)	Estimated Standoff (ft)	Estimated Traverse Rate (knots)	Geometric & Positional Stability Sensitivity	Interpret-ability	Probability of Crack Detection (0.25"x3")	Prob. of Dent Detection (large scale, small slope)	Prob. of Dent Detection (small scale, large slope)
Side Scan Sonar	DL	92,000	6.2	0.5	High	Complex	Low-Moderate	Low	Low-Moderate
Multiple beam Bathymetric Sonar	DL, DC	34,000	2.5	1.1	High	Moderate	Low-Moderate	Low	Moderate-High
Profiling Sonar	DC	2,300	5.2	0.1	Very High	Moderate	Low-Moderate	Low	Moderate-High
Multiple beam Forward Look Sonar	DL	10,900	1.6	0.8	High	Moderate	Low-Moderate	Low	Low
3D Mapping Sonar	DL, DC	63,000	11.5	1.8	Moderate	Moderate	Low-Moderate	Low-Moderate	Moderate-High
Color CCD Television Camera	DL, DC	45,000	2.3	1.5	Low	Simple	Moderate-High	Low	Moderate-High
SIT or ICCD Television Camera	DL, DC	76,000	7.3	2.3	Low	Simple	Moderate-High	Low	Moderate-High
Range Gated Laser	DL, DC	14,500	16.4	0.8	Low	Simple	Moderate-High	Low	Moderate-High
Laser Line Scan- Long Range, 5 atten. lengths	DL, DC	778,000	16.4	5.0	High	Simple	Moderate	Moderate	Moderate-High
Laser Line Scan- Short Range, 2 atten. lengths	DC	2,000	6.6	0.05	High	Moderate	Low-Moderate	Low	High
3D Mapping Laser	DC	4,700	6.6	0.2	Very High	Moderate	Moderate-High	Low	High

ASSUMPTIONS:

(1) For acoustic sensors, inspection rate is at the maximum standoff & traverse rate for theoretical detection of a 3-inch dia. hole

(2) For visual sensor, inspection rate is calculated at the maximum standoff and traverse rate attainable for object imaging in 1 meter water

(3) Crack and dent detection probabilities are estimated for the standoff distances calculated

(4) A large scale, small slope dent was estimated to have dimensions of 100 ft long, 25 ft wide, and 1 ft deep

(5) A small scale, large slope dent was estimated to have dimensions of 1 ft long, 1 ft wide, and 4 in deep

(6) Inspection rates for TV cameras, range gated laser, and 3D sonar are based on a 3" hole appearing in the image for at least 2 seconds

KEY: DL = damage location, the sensor would be capable of searching a large area quickly to detect damage and determine its location
DC = damage characterization, the sensor would be very useful for quantifying the damage once the damage was located

U/W VEHICLE DELIVERY SYSTEM: AUV	Levels / Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. AREA COVERAGE ATTRIBUTES		50	175						
1.1. Traverse Rate	kts.		50	0	0.5	1.25	5	H	5
1.2. Max. Endurance	hrs.		50	0	0	16	24	H	8
1.3. Accessibility	-		75	100					
1.3.1. Vertical Areas	%			25	0	85	100	H	100
1.3.2. Horizontal Areas	%			75	0	85	100	H	100
2.0. POSITION KEEPING		75	90						
2.1. Wave Height Effects	ft.		30	0	0	4.5	9	H	3
2.2. Current Effects	kts.		60	0	0	2.5	4	H	1
3.0. COMMAND AND CONTROL AND LOGISTICS		75	90						
3.1. Portability and Handling	-		30	0	1	5	9	H	3
3.2. Human Factors Considerations	-		60	0	1	5	9	H	4
4.0. ON-SCENE OPERATIONAL ATTRIBUTES		50	100						
4.1. Launch and Recovery			50	140					
4.1.1. Wave Height Effects	ft.			70	0	4.5	9	H	4.5
4.1.2. Current Effects	kts.			50	0	2.5	4	H	2
4. .3. Ice Cover Effects	%			20	0	25	75	H	50
4.2. Surface Condition Degradation			50	180					
4.2.1. Ice Coverage Effects	%			30	0	25	75	H	75
4.2.2. Oil Coverage Effects	%			90	0	50	100	H	100
4.2.3. Hazmat/fire Effects	-			60	1	5	9	H	9
5.0. RELATIVE RELIABILITY		50	0		1	5	9	H	5
SYSTEM LEVEL SUMMARY RATING		300							0.47

NOTES:

1.1. Under nominal conditions, and for nominal performance.

1.2. Max. time between Launch and mandated recovery (e.g., maintenance, battery recharge etc.)

1.3. Can conduct satisfactory inspection up to the max. % of specified surface condition.

2.0. System maintains position within acceptable tolerance, up to max. specified level of wave height or current.

3.1. Relative ease of dock side load out, set-up and handling on a wide variety of platforms.

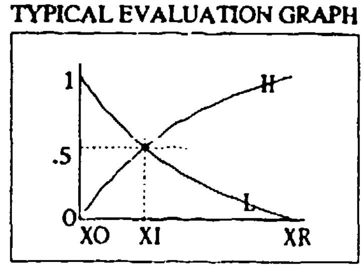
3.2. Relative ease of use of system in terms of simplicity, efficiency, tra' ing, inherent safety etc.

4.1. Risk of damage/loss is 10% at the specified level of the effect.

4.2. Performance is degraded by 25% in the coverage specified.

5.0. Engineering estimate of relative reliability of delivery system.

TYPICAL EVALUATION GRAPH



U/W VEHICLE DELIVERY SYSTEM: Towed Vehicle	Levels / Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. AREA COVERAGE ATTRIBUTES		50	175						
1.1. Traverse Rate	kts.		50	0	0.5	1.25	5	H	5
1.2. Max. Endurance	hrs.		50	0	0	16	24	H	24
1.3. Accessibility	-		75	100					
1.3.1. Vertical Areas	%			25	0	85	100	H	100
1.3.2. Horizontal Areas	%			75	0	85	100	H	0
2.0. POSITION KEEPING		75	90						
2.1. Wave Height Effects	ft.		30	0	0	4.5	9	H	4.5
2.2. Current Effects	kts.		60	0	0	2.5	4	H	2
3.0. COMMAND AND CONTROL AND LOGISTICS		75	90						
3.1. Portability and Handling	-		30	0	1	5	9	H	7
3.2. Human Factors Considerations	-		60	0	1	5	9	H	6
4.0. ON-SCENE OPERATIONAL ATTRIBUTES		50	100						
4.1. Launch and Recovery			50	140					
4.1.1. Wave Height Effects	ft.			70	0	4.5	9	H	4.5
4.1.2. Current Effects	kts.			50	0	2.5	4	H	2
4.1.3. Ice Cover Effects	%			20	0	25	75	H	25
4.2. Surface Condition Degradation			50	180					
4.2.1. Ice Coverage Effects	%			30	0	50	75	H	10
4.2.2. Oil Coverage Effects	%			90	0	50	100	H	25
4.2.3. Hazmat/fire Effects	-			60	1	5	9	H	1
5.0. RELATIVE RELIABILITY		50	0		1	5	9	H	8
SYSTEM LEVEL SUMMARY RATING		300							**0.58**

NOTES:

1.1. Under normal conditions, and for nominal performance.

1.2. Max. time between Launch and mandated recovery (e.g., maintenance, battery recharge etc.)

1.3. Can conduct satisfactory inspection up to the max. % of specified surface condition.

2.0. System maintains position within acceptable tolerance, up to max. specified level of wave height or current.

3.1. Relative ease of dock side load out, set-up and handling on a wide variety of platforms.

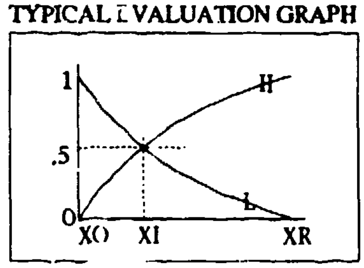
3.2. Relative ease of use of system in terms of simplicity, efficiency, training, inherent safety etc.

4.1. Risk of damage/loss is 10% at the specified level of the effect.

4.2. Performance is degraded by 25% in the coverage specified.

5.0. Engineering estimate of relative reliability of delivery system.

TYPICAL EVALUATION GRAPH



C-6

U/W VEHICLE DELIVERY SYSTEM: ROV	Levels / Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. AREA COVERAGE ATTRIBUTES		50	175						
1.1. Traverse Rate	kts.		50	0	0.5	1.25	5	H	5
1.2. Max. Endurance	hrs.		50	0	0	16	24	H	24
1.3. Accessibility	-		75	100					
1.3.1. Vertical Areas	%			25	0	85	100	H	100
1.3.2. Horizontal Areas	%			75	0	85	100	H	100
2.0. POSITION KEEPING		75	90						
2.1. Wave Height Effects	ft.		30	0	0	4.5	9	H	4.5
2.2. Current Effects	kts.		60	0	0	2.5	4	H	2
3.0. COMMAND AND CONTROL AND LOGISTICS		75	90						
3.1. Portability and Handling	-		30	0	1	5	9	H	7
3.2. Human Factors Considerations	-		60	0	1	5	9	H	4
4.0. ON-SCENE OPERATIONAL ATTRIBUTES		50	100						
4.1. Launch and Recovery			50	140					
4.1.1. Wave Height Effects	ft.			70	0	4.5	9	H	4.5
4.1.2. Current Effects	kts.			50	0	2.5	4	H	2
4.1.3. Ice Cover Effects	%			20	0	25	75	H	50
4.2. Surface Condition Degradation			50	180					
4.2.1. Ice Coverage Effects	%			30	0	50	75	H	25
4.2.2. Oil Coverage Effects	%			90	0	50	100	H	25
4.2.3. Hazmat/fire Effects	-			60	1	5	9	H	6
5.0. RELATIVE RELIABILITY		50	0		1	5	9	H	8
SYSTEM LEVEL SUMMARY RATING		300							0.61

NOTES:

1.1. Under nominal conditions, and for nominal performance.

1.2. Max. time between Launch and mandated recovery (e.g., maintenance, battery recharge etc.)

1.3. Can conduct satisfactory inspection up to the max. % of specified surface condition.

2.0. System maintains position within acceptable tolerance, up to max. specified level of wave height or current.

3.1. Relative ease of dock side load out, set-up and handling on a wide variety of platforms.

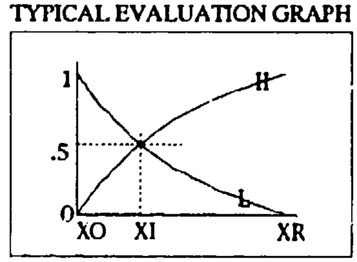
3.2. Relative ease of use of system in terms of simplicity, efficiency, training, inherent safety etc.

4.1. Risk of damage/loss is 10% at the specified level of the effect.

4.2. Performance is degraded by 25% in the coverage specified.

5.0. Engineering estimate of relative reliability of delivery system.

TYPICAL EVALUATION GRAPH



U/W VEHICLE DELIVERY SYSTEM: Crawler	Levels / Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. AREA COVERAGE ATTRIBUTES		50	175						
1.1. Traverse Rate	kts.		50	0	0.5	1.25	5	H	4
1.2. Max. Endurance	hrs.		50	0	0	16	24	H	24
1.3. Accessibility	-		75	100					
1.3.1. Vertical Areas	%			25	0	85	100	H	85
1.3.2. Horizontal Areas	%			75	0	85	100	H	100
2.0. POSITION KEEPING		75	90						
2.1. Wave Height Effects	ft.		30	0	0	4.5	9	H	9
2.2. Current Effects	kts.		60	0	0	2.5	4	H	4
3.0. COMMAND AND CONTROL AND LOGISTICS		75	90						
3.1. Portability and Handling	-		30	0	1	5	9	H	7
3.2. Human Factors Considerations	-		60	0	1	5	9	H	5
4.0. ON-SCENE OPERATIONAL ATTRIBUTES		50	100						
4.1. Launch and Recovery			50	140					
4.1.1. Wave Height Effects	ft.			70	0	4.5	9	H	7
4.1.2. Current Effects	kts.			50	0	2.5	4	H	2
4.1.3. Ice Cover Effects	%			20	0	25	75	H	50
4.2. Surface Condition Degradation			50	180					
4.2.1. Ice Coverage Effects	%			30	0	25	75	H	25
4.2.2. Oil Coverage Effects	%			90	0	50	100	H	25
4.2.3. Hazmat/fire Effects	-			60	1	5	9	H	1
5.0. RELATIVE RELIABILITY		50	0		1	5	9	H	7
SYSTEM LEVEL SUMMARY RATING		300							0.74

NOTES:

1.1. Under nominal conditions, and for nominal performance.

1.2. Max. time between Launch and mandated recovery (e.g., maintenance, battery recharge etc.)

1.3. Can conduct satisfactory inspection up to the max. % of specified surface condition.

2.0. System maintains position within acceptable tolerance, up to max. specified level of wave height or current.

3.1. Relative ease of dock side load out, set-up and handling on a wide variety of platforms.

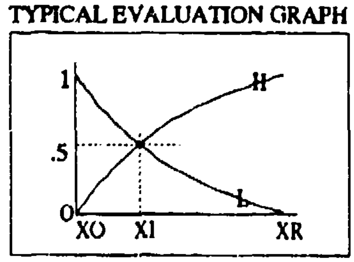
3.2. Relative ease of use of system in terms of simplicity, efficiency, training, inherent safety etc.

4.1. Risk of damage/loss is 10% at the specified level of the effect.

4.2. Performance is degraded by 25% in the coverage specified.

5.0. Engineering estimate of relative reliability of delivery system.

TYPICAL EVALUATION GRAPH



U/W VEHICLE DELIVERY SYSTEM: Composite Vehicle (ROV/Crawling)	Levels / Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. AREA COVERAGE ATTRIBUTES		50	175						
1.1. Traverse Rate	kts.		50	0	0.5	1.25	5	H	5
1.2. Max. Endurance	hrs.		50	0	0	16	24	H	24
1.3. Accessibility	-		75	100					
1.3.1. Vertical Areas	%			25	0	85	100	H	100
1.3.2. Horizontal Areas	%			75	0	85	100	H	100
2.0. POSITION KEEPING		75	90						
2.1. Wave Height Effects	ft.		30	0	0	4.5	9	H	9
2.2. Current Effects	kts.		60	0	0	2.5	4	H	4
3.0. COMMAND AND CONTROL AND LOGISTICS		75	90						
3.1. Portability and Handling	-		30	0	1	5	9	H	7
3.2. Human Factors Considerations	-		60	0	1	5	9	H	4
4.0. ON-SCENE OPERATIONAL ATTRIBUTES		50	100						
4.1. Launch and Recovery			50	140					
4.1.1. Wave Height Effects	ft.			70	0	4.5	9	H	7
4.1.2. Current Effects	kts.			50	0	2.5	4	H	2
4.1.3. Ice Cover Effects	%			20	0	25	75	H	50
4.2. Surface Condition Degradation			50	180					
4.2.1. Ice Coverage Effects	%			30	0	50	75	H	25
4.2.2. Oil Coverage Effects	%			90	0	50	100	H	25
4.2.3. Hazmat/fire Effects	-			60	1	5	9	H	6
5.0. RELATIVE RELIABILITY		50	0		1	5	9	H	7
SYSTEM LEVEL SUMMARY RATING		300							0.75

NOTES:

1.1. Under nominal conditions, and for nominal performance.

1.2. Max. time between Launch and mandated recovery (e.g., maintenance, battery recharge etc.)

1.3. Can conduct satisfactory inspection up to the max. % of specified surface condition.

2.0. System maintains position within acceptable tolerance, up to max. specified level of wave height or current.

3.1. Relative ease of dock side load out, set-up and handling on a wide variety of platforms.

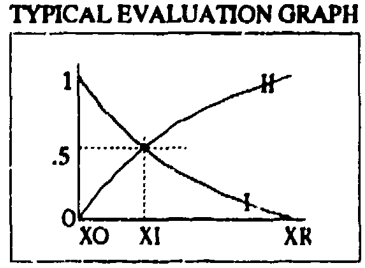
3.2. Relative ease of use of system in terms of simplicity, efficiency, training, inherent safety etc.

4.1. Risk of damage/loss is 10% at the specified level of the effect.

4.2. Performance is degraded by 25% in the coverage specified.

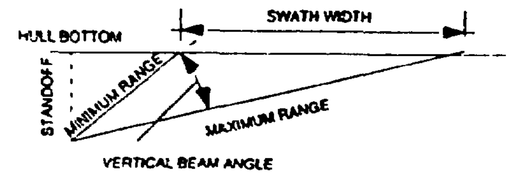
5.0. Engineering estimate of relative reliability of delivery system.

TYPICAL EVALUATION GRAPH

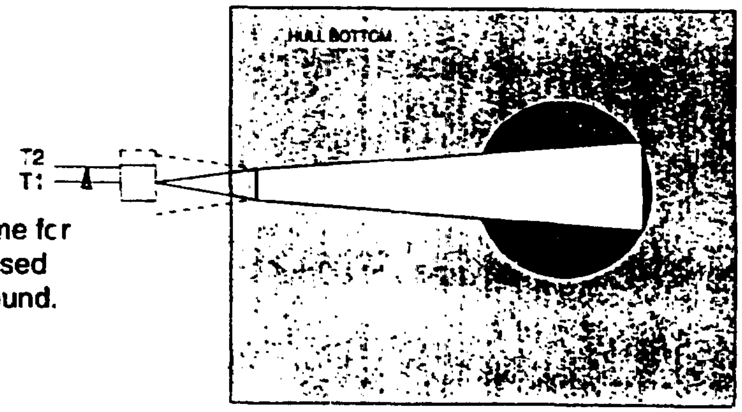


INSPECTION RATE CALCULATION - SIDE SCAN SONAR

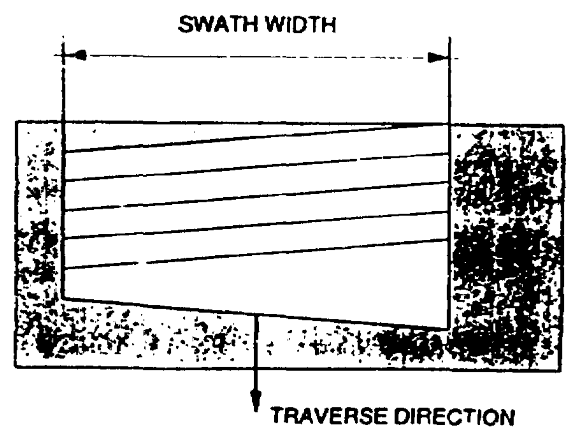
1. Calculate the range at which the maximum width of the transmitted beam equals one half the desired hole detection size. Based on this calculation and knowledge of the vertical beam angle, calculate the minimum range, the sonar standoff, and the "swath" width.



2. Calculate the maximum traverse rate allowable to prevent any return beams from falling outside the field of view of the receiving array (based on 2-way travel time of pulse). This traverse rate is one half the minimum width of the footprint travel divided by the time for the acoustic pulse to reach the target and return. This traverse rate is based on the minimum range calculated above and is limited by the speed of sound.



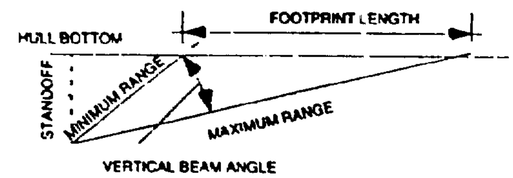
3. Calculate the required pulse repetition rate based on the traverse rate calculated in 2 above. This required pulse rate is the traverse rate (from 2 above divided by the minimum width of the footprint. If the actual sensor pulse repetition rate is less than this required pulse rate, recalculate the traverse rate as the minimum footprint width travel divided by the time between pulses (or pings). This traverse rate is limited by the update rate of the sensor and will eliminate the risk of "holidays".
NOTE: At short ranges as required to detect small holes, the sensor update rate will dictate the maximum traverse rate.



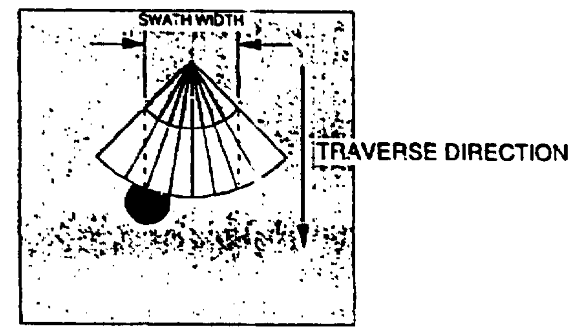
4. The inspection rate is the traverse rate times the width of the swath.

INSPECTION RATE CALCULATION - MULTIBEAM FORWARD LOOK SONAR

1. Calculate the range at which the maximum width of the transmitted beam equals one half the desired hole detection size. Based on this calculation and knowledge of the vertical beam angle, calculate the minimum range, the sonar standoff, and the footprint length.

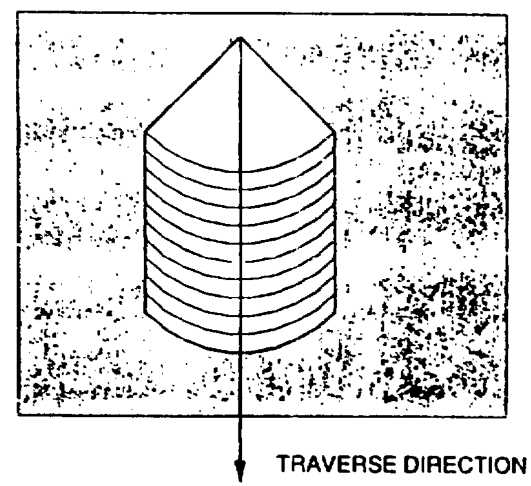


2. Calculate the traverse rate as the length of the footprint divided by two seconds. This will allow the hole to appear in the image for 2 seconds. The pulse repetition rate should be at least 1 pulse per second. If the pulse repetition rate is less than 1 pulse per second, calculate the traverse rate which allows the hole to appear in two successive images ("snap shots").



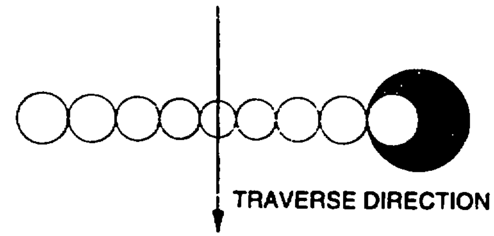
3. The swath width is the width of the scanned image area between the outermost footprints at the minimum range measured in the plane parallel to the travel direction of the sonar.

4. The inspection rate is the traverse rate times the swath width.

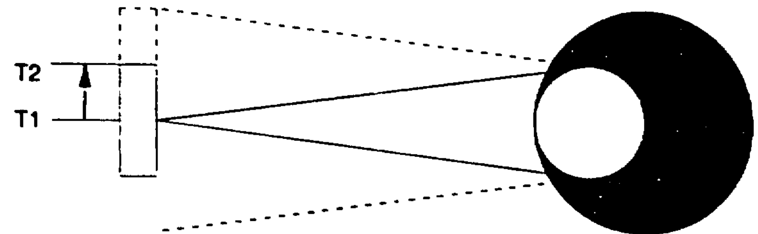


INSPECTION RATE CALCULATION - MULTIBEAM BATHYMETRIC SONAR

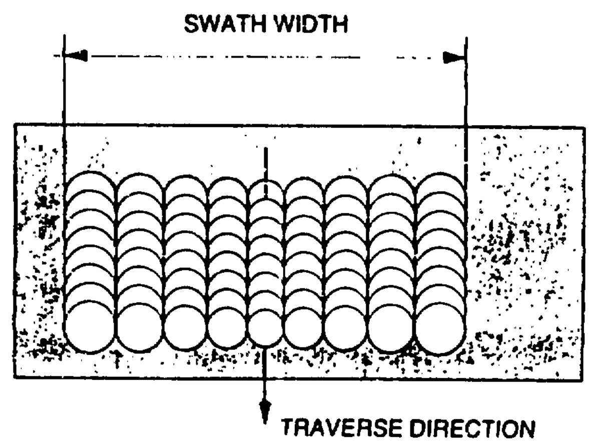
1. Calculate the standoff range at which the largest footprint dimension equals one half the desired hole detection size.
NOTE: footprint elongation effects as a function of scan angle must be accounted for. The sketch shows a multibeam bathymetric sonar. The largest beam footprint is the one at the outermost position of the swath.



2. Calculate the maximum traverse rate allowable to prevent any return beams from falling outside the field of view of the receiving array (based on 2-way travel time of pulse). This traverse rate is one half the size of the footprint travel divided by the time for the acoustic pulse to reach the target and return. This traverse rate is based on the standoff calculated above and is limited by the speed of sound. The traverse rate should be calculated using the size and range of both the minimum and maximum width footprints, with the smaller of these two resulting values being the maximum allowable traverse rate.



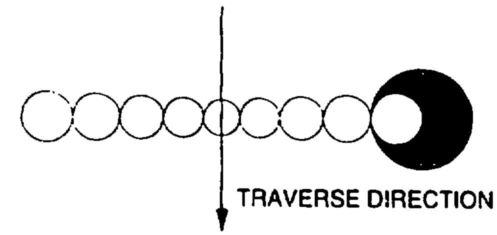
3. Calculate the required pulse repetition rate based on the traverse rate calculated in 2 above. This required pulse rate is the traverse rate (from 2 above divided by the width of the minimum footprint). If the actual sensor pulse repetition rate is less than this required pulse rate, recalculate the traverse rate as the smallest footprint diameter travel divided by the time between pulses (or pings). This traverse rate is limited by the update rate of the sensor and will eliminate the risk of "holidays".
NOTE: At short ranges as required to detect small holes, the sensor update rate will dictate the maximum traverse rate.



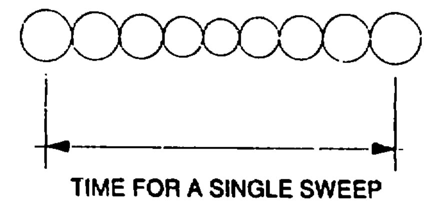
4. The inspection rate is the traverse rate times the width of the swath.

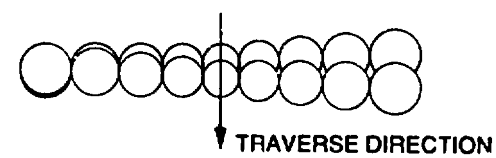
INSPECTION RATE CALCULATION - PROFILING SONAR

1. Calculate the standoff range at which the largest footprint dimension equals one half the desired hole detection size. The largest footprint is the one at the outermost scan angle as shown.
NOTE: Footprint elongation effects as a function of scan angle must be accounted for in calculating footprint dimensions.

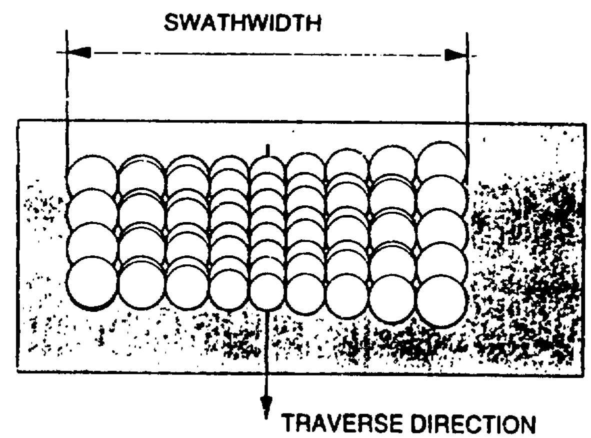


2. Calculate the time for a single sweep of the sonar at the standoff calculated above. The traverse rate is equal to one half the size of the largest footprint travel divided by the time for two sweeps of the sonar head. This traverse rate will prevent "holidays" in the area coverage.

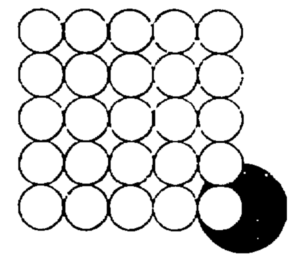




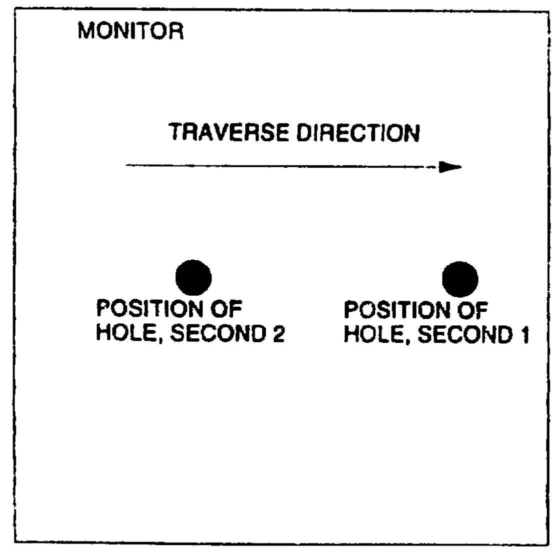
3. The inspection rate is the traverse rate times the swath width of the scanning profile sonar.



INSPECTION RATE CALCULATION - 3D MAPPING SONAR



1. Calculate the standoff range at which the largest footprint dimension equals one half the desired hole detection size. The largest footprint is the one at the outermost position of the field of view of the planar array as shown.
NOTE: Footprint elongation effects as a function of scan angle must be accounted for in calculating footprint dimensions.



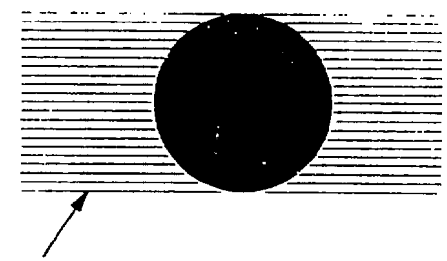
2. Calculate the field of view of the planar array at the standoff range calculated in 1 above. Determine the image pulse repetition rate and calculate the traverse rate which will allow the hole damage to appear on the imaging monitor for at least 2 seconds. This traverse rate is the horizontal field of view of the array divided by two seconds. The sketch shows the appearance of the hole in two successive images for a system with a pulse repetition rate of 1 pulse per second.
NOTE: This approach only works if the image pulse repetition rate is at least 1 pulse every 2 seconds. If the pulse repetition rate is less than one pulse every 2 seconds, the traverse rate should be calculated as the horizontal field of view divided by the time between pulses.

3. The inspection rate is the traverse rate times the vertical field of view.

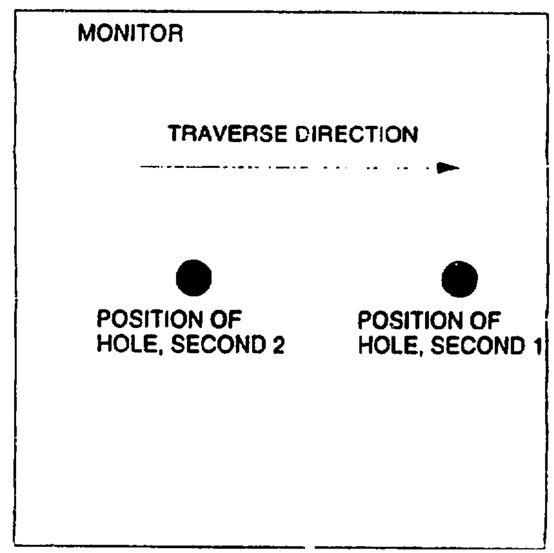
INSPECTION RATE CALCULATION - TELEVISION CAMERAS/RANGE GATED LASER

1. Calculate the standoff range possible to obtain a useful image in 1 meter water. Calculate the field of view at this standoff.

2. Calculate the number of horizontal lines creating the image of a 3 inch diameter hole. This number is the 3 inch hole divided by the vertical field of view (from 1 above) multiplied by the number of horizontal lines over the entire field of view. Twenty lines was selected as the number needed to create a useful image of the damage regardless of monitor size. If the number of horizontal lines with the field of view calculated in 1 above is less than 20, decrease the standoff and field of view until at least 20 lines are used to image a 3 inch hole.
NOTE: This results in the image occupying about 4 % of the total image area for a high resolution video (525 lines resolution) and about 6 % of the total image area for lower resolution color video (about 350 lines resolution).



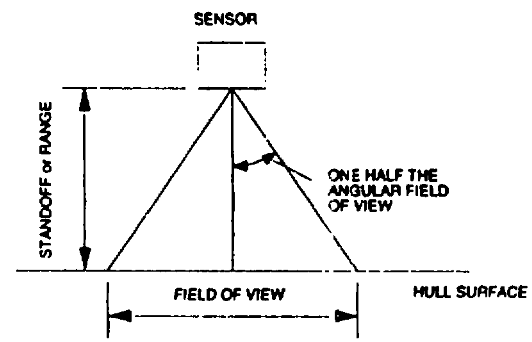
3. Calculate the traverse rate as the horizontal field of view (from the original value in 1 above or the value in 2 if a revision was necessary according to the guidelines in 2) divided by two seconds. This assures that the damage will appear on the monitor for at least 2 seconds.



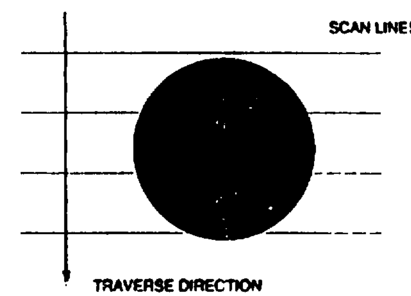
4. The inspection rate is the traverse rate times the vertical field of view.

INSPECTION RATE CALCULATION - SHORT-RANGE LASER LINE SCAN

1. Calculate the field of view at the appropriate range. The range is equal to two attenuation lengths. The field of view is twice the product of the range times the tangent of one half the angular field of view.



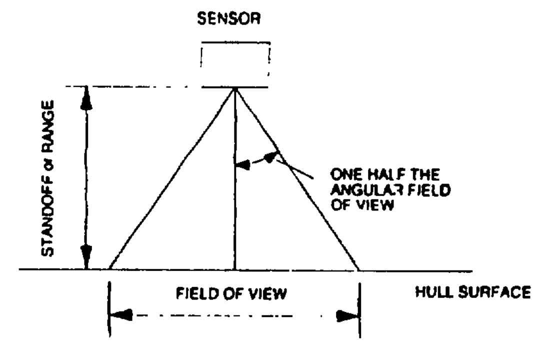
2. Calculate the traverse rate as the desired distance between scan lines times the scan line display update rate. For a 3 inch diameter hole, the scan lines should be about one inch apart to assure detection and characterization.



3. The inspection rate is the traverse rate times the field of view.

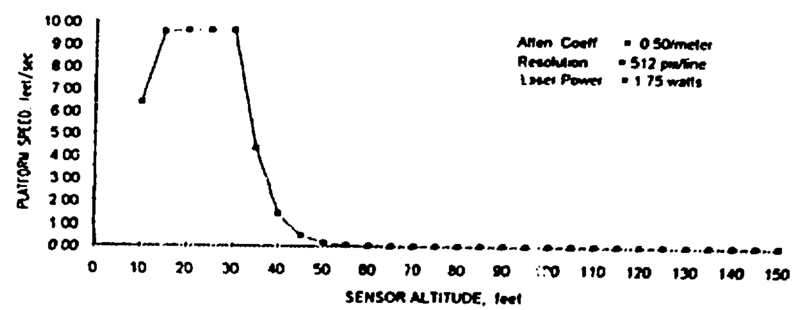
INSPECTION RATE CALCULATION - LONG-RANGE LASER LINE SCAN

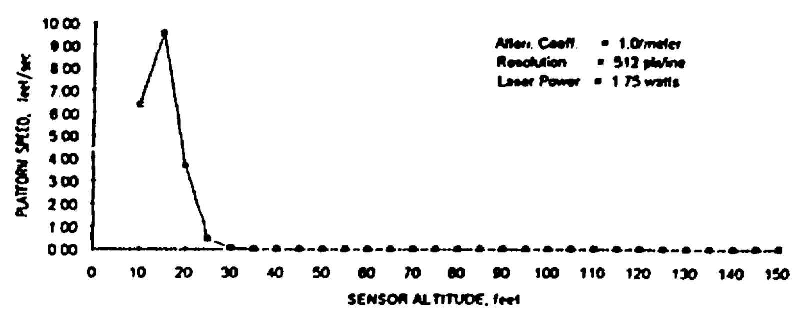
1. Calculate the field of view at the appropriate range. The range is equal to five attenuation lengths. The field of view twice the product of the range times the tangent of one half the angular field of view.



2. Use the graph for laser line scan system operating envelope to determine the traverse rate.

LASER LINE SCAN SYSTEM OPERATING ENVELOPE

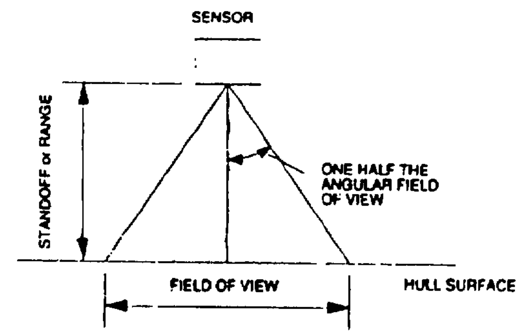




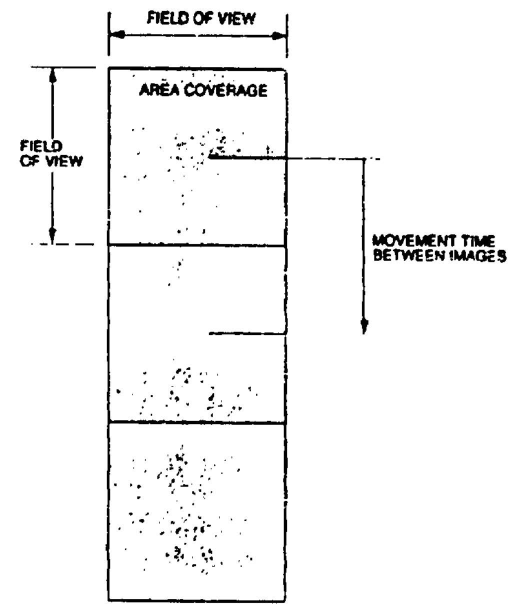
3. The inspection rate is the traverse rate times the field of view.

INSPECTION RATE CALCULATION - 3D IMAGING SYSTEMS

1. A stop and go crawling vehicle must be assumed. The standoff is 5 feet and the angular field of view is 40 degrees. Calculate the field of view as twice the product of the standoff times the tangent of one half the angular field of view. The area coverage per image is the field of view squared.



2. The time between images is the image generation time plus the time to move between images. A five second time to move betv'een images is assumed.



3. The inspection rate is the area coverage per image divided by the time between images.

U/W VEHICLE SENSOR SYSTEM: Side Scan Sonar	Levels / Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. INSPECTION RATE	sf/hour	50	0		1	12000	20000	H	20,000
2.0. SENSOR PRESENTATION REQUIREMENTS	1 to 9	50	0		1	5	9	H	2
3.0. SENSOR OUTPUT INTERPRETATION	1 to 9	50	0		1	5	9	H	1
4.0. CRACK DETECTION CAPABILITY	1 to 9	25	0		1	5	9	H	3
5.0. DENT DETECTION CAPABILITY		25	150						
5.1. Large Scale/Small Slope	1 to 9		100	0	1	5	9	H	1
5.2. Small Scale/Large Slope	1 to 9		50	0	1	5	9	H	3
SYSTEM LEVEL SUMMARY RATING		200							0.32

NOTES:

1.0. What is max. area that can be covered per unit time.

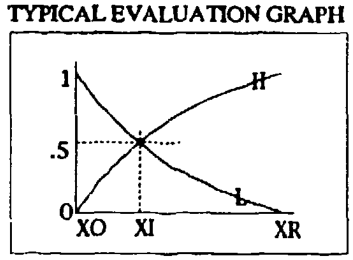
2.0. How sensitive is the system to the scene/sensor relationship, and the stability of the platform?

3.0. How easily and accurately can the information be interpreted?

4.0. How well can cracks be interpreted?

5.0. How well can dents of different aspect ratios be detected?

TYPICAL EVALUATION GRAPH



U/W VEHICLE SENSOR SYSTEM: Multiple Beam Bathymetric	Levels / Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. INSPECTION RATE	sf/hour	50	0		1	12000	20000	H	20,000
2.0. SENSOR PRESENTATION REQUIREMENTS	1 to 9	50	0		1	5	9	H	2
3.0. SENSOR OUTPUT INTERPRETATION	1 to 9	50	0		1	5	9	H	5
4.0. CRACK DETECTION CAPABILITY	1 to 9	25	0		1	5	9	H	3
5.0. DENT DETECTION CAPABILITY		25	150						
5.1. Large Scale/Small Slope	1 to 9		100	0	1	5	9	H	1
5.2. Small Scale/Large Slope	1 to 9		50	0	1	5	9	H	7
SYSTEM LEVEL SUMMARY RAT...		200							0.47

NOTES:

1.0. What is max. area that can be covered per unit time.

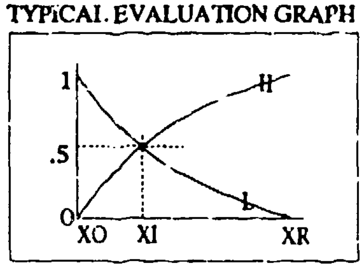
2.0. How sensitive is the system to the scene/sensor relationship, and the stability of the platform?

3.0. How easily and accurately can the information be interpreted?

4.0. How well can cracks be interpreted?

5.0. How well can dents of different aspect ratios be detected?

TYPICAL EVALUATION GRAPH



U/W VEHICLE SENSOR SYSTEM: Profiling Sonar	Levels Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. INSPECTION RATE	sf/hour	50	0		1	12000	20000	H	2,300
2.0. SENSOR PRESENTATION REQUIREMENTS	1 to 9	50	0		1	5	9	H	1
3.0. SENSOR OUTPUT INTERPRETATION	1 to 9	50	0		1	5	9	H	5
4.0. CRACK DETECTION CAPABILITY	1 to 9	25	0		1	5	9	H	3
5.0. DENT DETECTION CAPABILITY		25	150						
.1. Large Scale/Small Slope	1 to 9		100	0	1	5	9	H	1
5.2. Small Scale/Large Slope	1 to 9		50	0	1	5	9	H	7
SYSTEM LEVEL SUMMARY RATING		200							0.20

NOTES:

1.0. What is max. area that can be covered per unit time.

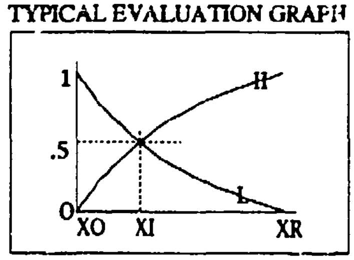
2.0. How sensitive is the system to the scene/sensor relationship, and the stability of the platform?

3.0. How easily and accurately can the information be interpreted?

4.0. How well can cracks be interpreted?

5.0. How well can dents of different aspect ratios be detected?

TYPICAL EVALUATION GRAPH



U/W VEHICLE SENSOR SYSTEM: Multibeam Fwd Look	Levels Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. INSPECTION RATE	sf/hour	50	0		1	12000	20000	H	10,900
2.0. SENSOR PRESENTATION REQUIREMENTS	1 to 9	50	0		1	5	9	H	3
3.0. SENSOR OUTPUT INTERPRETATION	1 to 9	50	0		1	5	9	H	5
4.0. CRACK DETECTION CAPABILITY	1 to 9	25	0		1	5	9	H	3
5.0. DENT DETECTION CAPABILITY		25	150						
5.1. Large Scale/Small Slope	1 to 9		100	0	1	5	9	H	1
5.2. Small Scale/Large Slope	1 to 9		50	0	1	5	9	H	1
SYSTEM LEVEL SUMMARY RATING		200							0.33

NOTES:

1.0. What is max. area that can be covered per unit time.

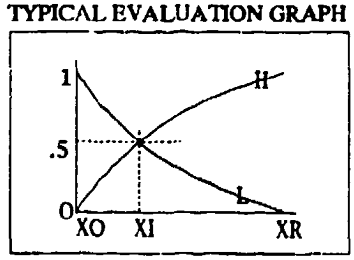
2.0. How sensitive is the system to the scene/sensor relationship, and the stability of the platform?

3.0. How easily and accurately can the information be interpreted?

4.0. How well can cracks be interpreted?

5.0. How well can dents of different aspect ratios be detected?

TYPICAL EVALUATION GRAPH



U/W VEHICLE SENSOR SYSTEM: 3D Mapping Sonar	Levels / Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. INSPECTION RATE	sf/hour	50	0		1	12000	20000	H	20,000
2.0. SENSOR PRESENTATION REQUIREMENTS	1 to 9	50	0		1	5	9	H	5
3.0. SENSOR OUTPUT INTERPRETATION	1 to 9	50	0		1	5	9	H	5
4.0. CRACK DETECTION CAPABILITY	1 to 9	25	0		1	5	9	H	3
5.0. DENT DETECTION CAPABILITY		25	150						
5.1. Large Scale/Small Slope	1 to 9		100	0	1	5	9	H	3
5.2. Small Scale/Large Slope	1 to 9		50	0	1	5	9	H	7
SYSTEM LEVEL SUMMARY RATING		200							0.58

NOTES:

1.0. What is max. area that can be covered per unit time.

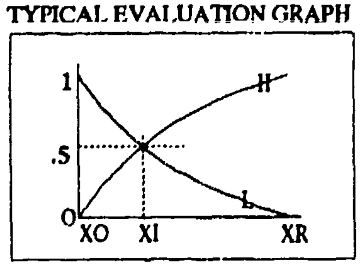
2.0. How sensitive is the system to the scene/sensor relationship, and the stability of the platform?

3.0. How easily and accurately can the information be interpreted?

4.0. How well can cracks be interpreted?

5.0. How well can dents of different aspect ratios be detected?

TYPICAL EVALUATION GRAPH



U/W VEHICLE SENSOR SYSTEM: Color CCD Camera	Levels Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. INSPECTION RATE	sf/hour	50	0		1	12000	20000	H	20,000
2.0. SENSOR PRESENTATION REQUIREMENTS	1 to 9	50	0		1	5	9	H	7
3.0. SENSOR OUTPUT INTERPRETA~ION	1 to 9	50	0		1	5	9	H	7
4.0. CRACK DETECTION CAPABILITY	1 to 9	25	0		1	5	9	H	7
5.0. DENT DETECTION CAPABILITY		25	150						
5.1. Large Scale/Small Slope	1 to 9		100	0	1	5	9	H	1
5.2. Small Scale/Large Slope	1 to 9		50	0	1	5	9	H	7
SYSTEM LEVEL SUMMARY RATING		200							0.75

NOTES:

1.0. What is max. area that can be covered per unit time.

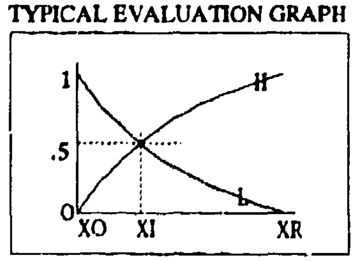
2.0. How sensitive is the system to the scene/sensor relationship, and the stability of the platform?

3.0. How easily and accurately can the information be interpreted?

4.0. How well can cracks be interpreted?

5.0. How well can dents of different aspect ratios be detected?

TYPICAL EVALUATION GRAPH



U/W VEHICLE SENSOR SYSTEM: Range Gated Laser	Levels Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. INSPECTION RATE	sf/hour	50	0		1	12000	20000	H	14,500
2.0. SENSOR PRESENTATION REQUIREMENTS	1 to 9	50	0		1	5	9	H	7
3.0. SENSOR OUTPUT INTERPRETATION	1 to 9	50	0		1	5	9	H	7
4.0. CRACK DETECTION CAPABILITY	1 to 9	25	0		1	5	9	H	7
5.0. DENT DETECTION CAPABILITY		25	150						
5.1. Large Scale/Small Slope	1 to 9		100	0	1	5	9	H	1
5.2. Small Scale/Large Slope	1 to 9		50	0	1	5	9	H	7
SYSTEM LEVEL SUMMARY RATING		200							0.66

NOTES:

1.0. What is max. area that can be covered per unit time.

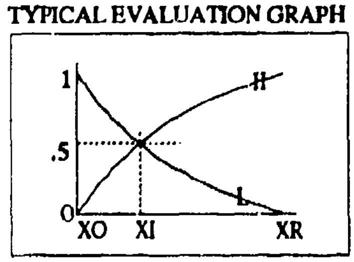
2.0. How sensitive is the system to the scene/sensor relationship, and the stability of the platform?

3.0. How easily and accurately can the information be

4.0. How well can cracks be interpreted?

5.0. How well can dents of different aspect ratios be detected?

TYPICAL EVALUATION GRAPH



U/W VEHICLE SENSOR SYSTEM: Laser Line Scan (Long Range)	Levels / Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. INSPECTION RATE	sf/hour	50	0		1	12000	20000	H	20,000
2.0. SENSOR PRESENTATION REQUIREMENTS	1 to 9	50	0		1	5	9	H	3
3.0. SENSOR OUTPUT INTERPRETATION	1 to 9	50	0		1	5	9	H	8
4.0. CRACK DETECTION CAPABILITY	1 to 9	25	0		1	5	9	H	5
5.0. DENT DETECTION CAPABILITY		25	150						
5.1. Large Scale/Small Slope	1 to 9		100	0	1	5	9	H	5
5.2. Small Scale/Large Slope	1 to 9		50	0	1	5	9	H	7
SYSTEM LEVEL SUMMARY RATING		200							0.67

NOTES:

1.0. What is max. area that can be covered per unit time.

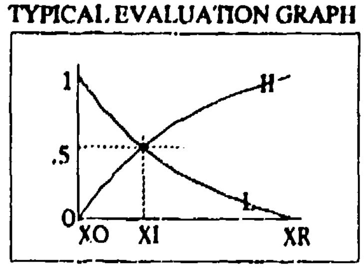
2.0. How sensitive is the system to the scene/sensor relationship, and the stability of the platform?

3.0. How easily and accurately can the information be interpreted?

4.0. How well can cracks be interpreted?

5.0. How well can dents of different aspect ratios be detected?

TYPICAL EVALUATION GRAPH



U/W VEHICLE SENSOR SYSTEM: Laser Line Scan (Short Range)	Levels Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. INSPECTION RATE	sf/hour	50	0		1	12000	20000	H	2,000
2.0. SENSOR PRESENTATION REQUIREMENTS	1 to 9	50	0		1	5	9	H	3
3.0. SENSOR OUTPUT INTERPRETATION	1 to 9	50	0		1	5	9	H	5
4.0. CRACK DETECTION CAPABILITY	1 to 9	25	0		1	5	9	H	3
5.0. DENT DETECTION CAPABILITY		25	150						
5.1. Large Scale/Small Slope	1 to 9		100	0	1	5	9	H	1
5.2. Small Scale/Large Slope	1 to 9		50	0	1	5	9	H	8
SYSTEM LEVEL SUMMARY RATING		200							0.27

NOTES:

1.0. What is max. area that can be covered per unit time.

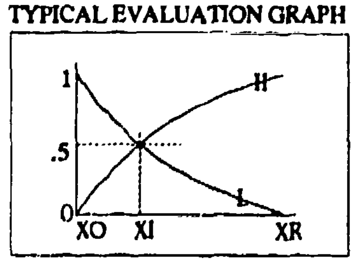
2.0. How sensitive is the system to the scene/sensor relationship, and the stability of the platform?

3.0. How easily and accurately can the information be interpreted?

4.0. How well can cracks be interpreted?

5.0. How well can dents of different aspect ratios be detected?

TYPICAL EVALUATION GRAPH



U/W VEHICLE SENSOR SYSTEM: 3D Mapping Laser	Levels Measure	1 WT	2 WT	3 WT	XO	XI	XR	BIAS	Scores
1.0. INSPECTION RATE	sf/hour	50	0		1	12000	20000	H	4,700
2.0. SENSOR PRESENTATION REQUIREMENTS	1 to 9	50	0		1	5	9	H	1
3.0. SENSOR OUTPUT INTERPRETATION	1 to 9	50	0		1	5	9	H	5
4.0. CRACK DETECTION CAPABILITY	1 to 9	25	0		1	5	9	H	7
5.0. DENT DETECTION CAPABILITY		25	150						
5.1. Large Scale/Small Slope	1 to 9		100	0	1	5	9	H	1
5.2. Small Scale/Large Slope	1 to 9		50	0	1	5	9	H	8
SYSTEM LEVEL SUMMARY RATING		200							0.29

NOTES:

1.0. What is max. area that can be covered per unit time.

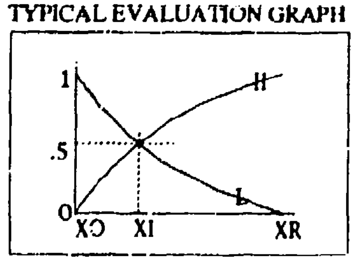
2.0. How sensitive is the system to the scene/sensor relationship, and the stability of the platform?

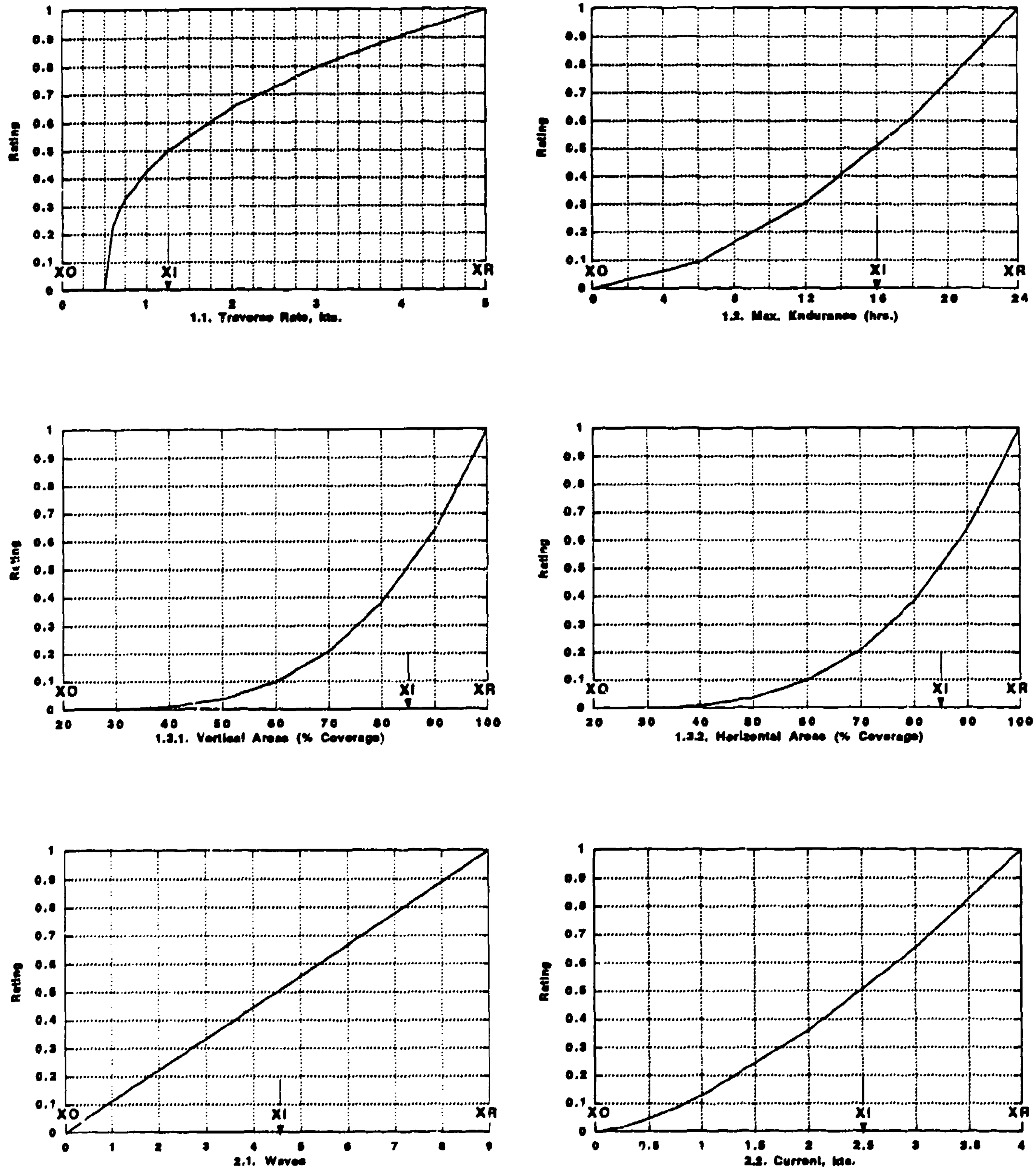
3.0. How easily and accurately can the information be interpreted?

4.0. How well can cracks be interpreted?

5.0. How well can dents of different aspect ratios be detected?

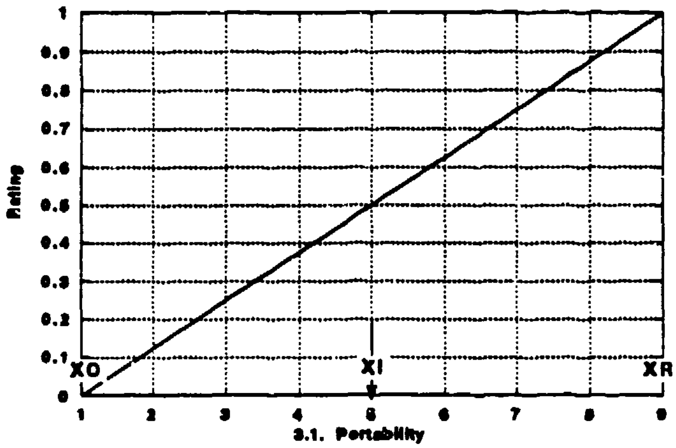
TYPICAL EVALUATION GRAPH

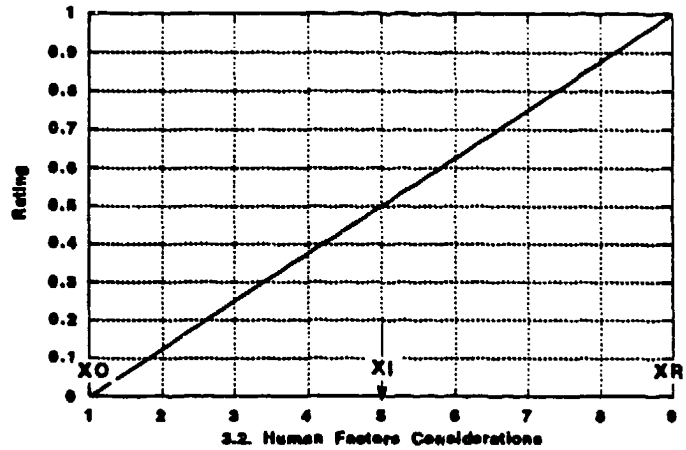


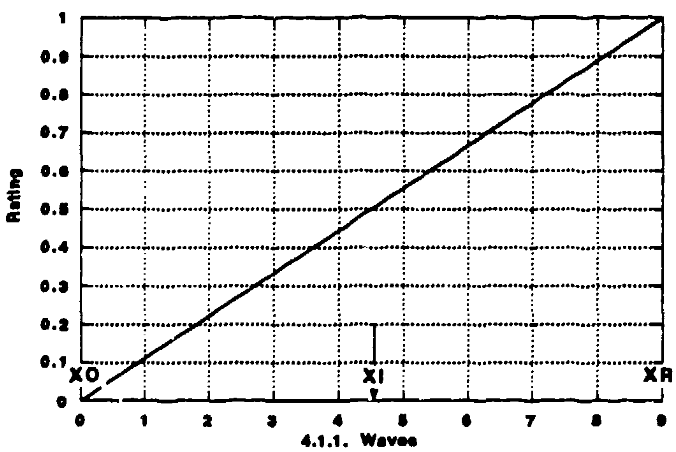


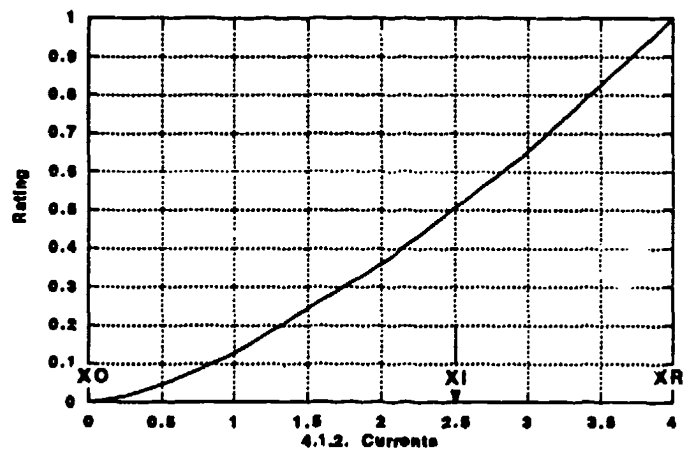
DELIVERY SYSTEM ATTRIBUTE RATING GRAPHS

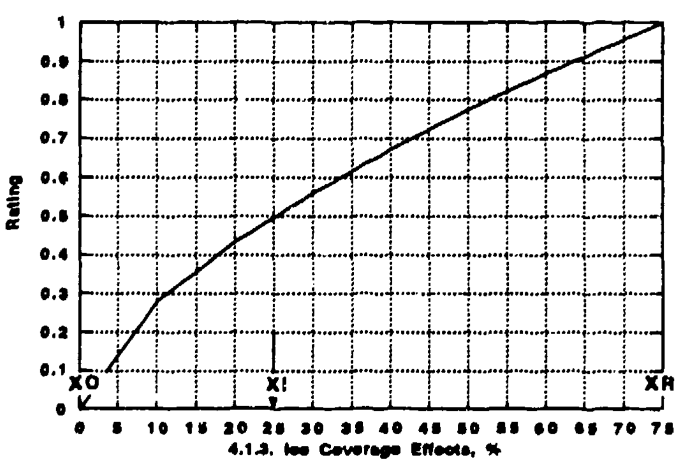
C-29



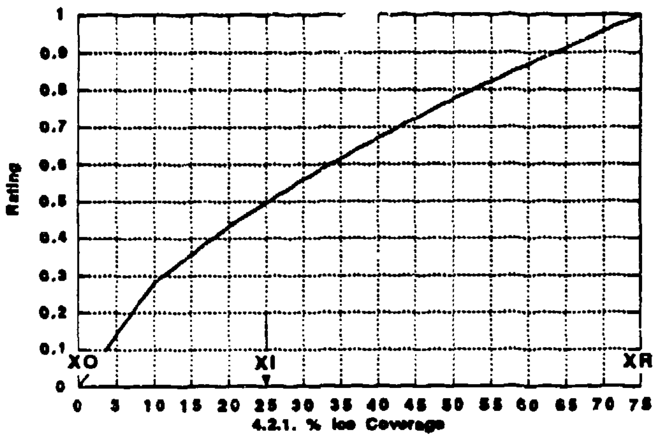


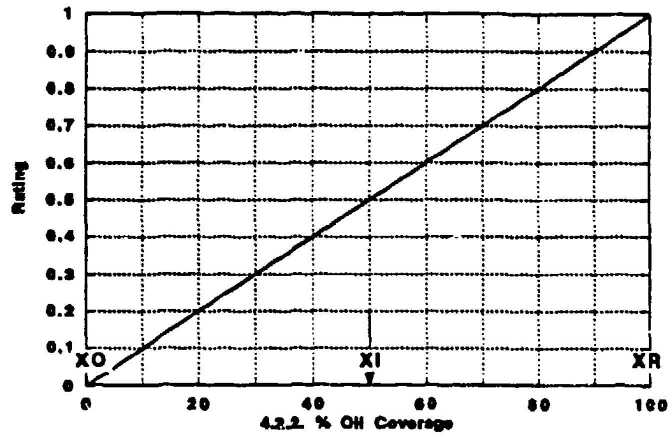


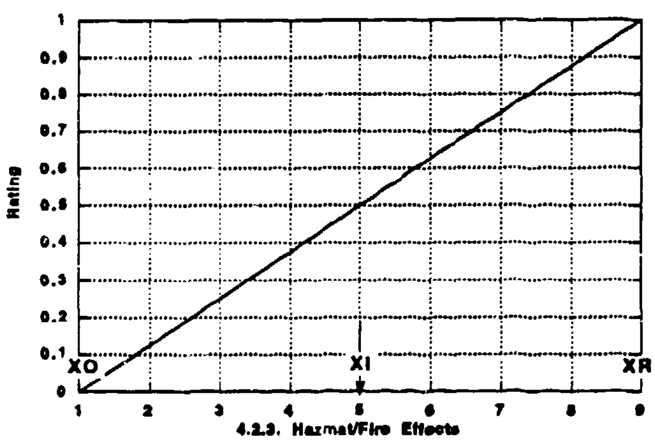


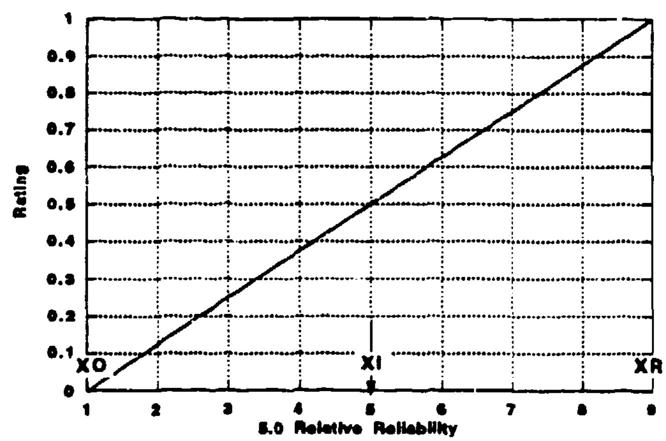


DELIVERY SYSTEM ATTRIBUTE
RATING GRAPHS

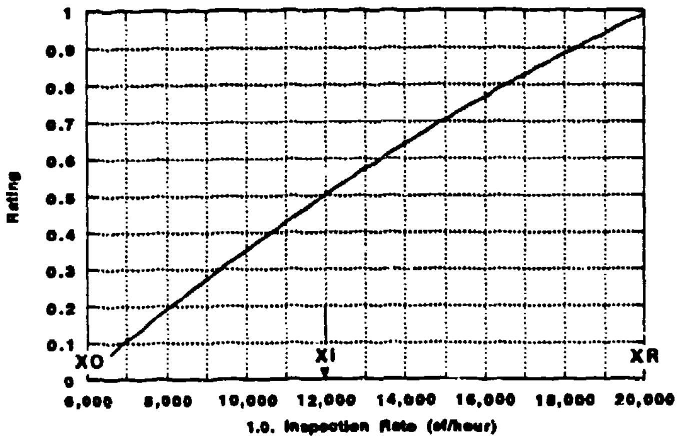


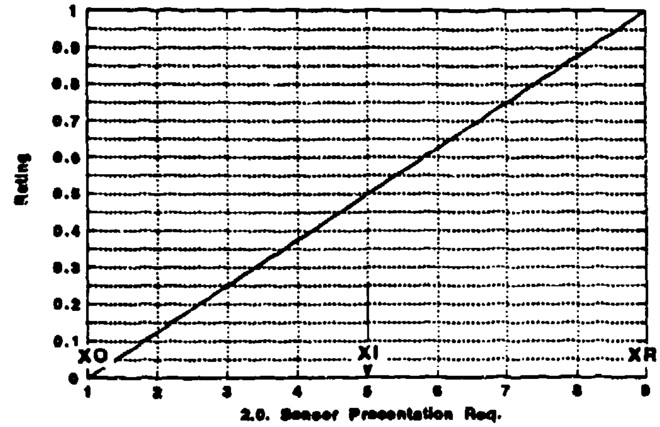


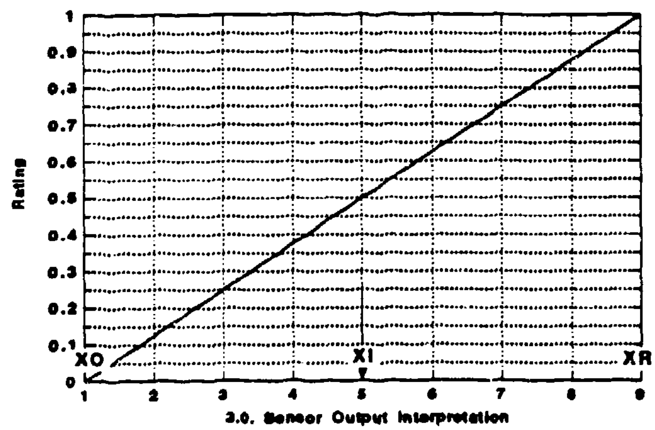


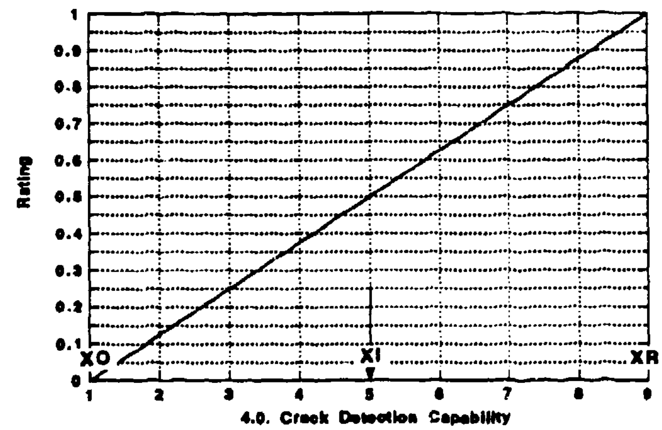


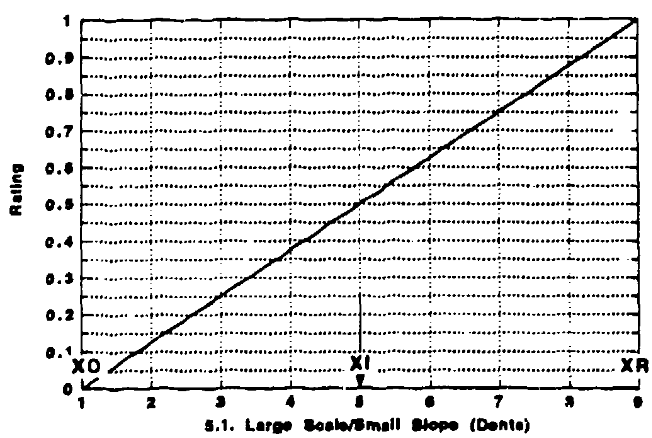
DELIVERY SYSTEM ATTRIBUTE
RATING GRAPHS

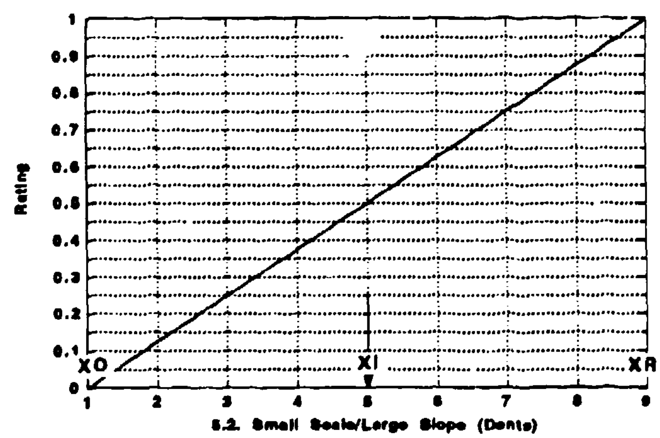












SENSOR SYSTEM ATTRIBUTE RATING GRAPHS

APPENDIX D

VEHICLE SYSTEMS DATABASE

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ROVs

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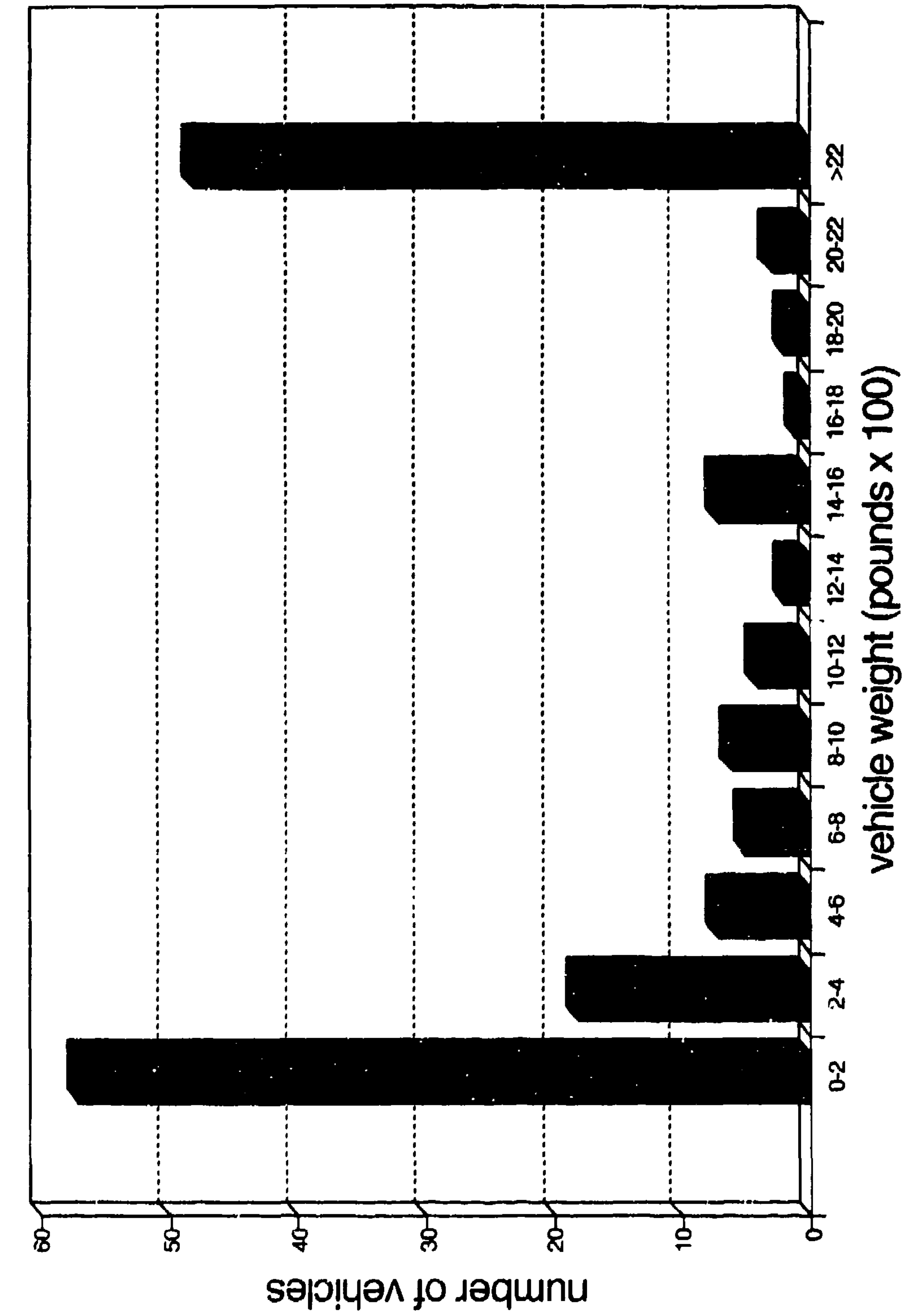
Manufacturer	Vehicle	Weight (lb)	Electrical Power (KVA)	Propeller Power (hp)	Maximum Speed (knots)	Frontal Area (sq ft)	Maximum Depth (ft)	Operational Volts (volts)	Lift Capacity (lbm)	Teather Length (ft)	Teather Strength (lbf)	Bouyancy Ballast (type)
Hydro Products	Adrov	227	15.0		3	6.3	328	460	64			PB+Thrust
Allseas Engineering	ALLSEAS											
Heriot-Watt University	ANGUS 002	1540	20		1.5							
Heriot-Watt University	ANGUS 003	2860		12	3.5	22.6	985	240				PB
Ketema	ASD/620	1000	23.0	21	3	8.9	3000	480				PB+Thrust
Naval Ocean Systems Center	ATV	11000	60			80.7	19684	2800				PB
Remotely Operated Vehicle	Bluey	40	1.0		1	1.2	131	240		460	550	PB+Thrust
ROVTECH A/S	Buster	176	1.5		2	7.8	1640	220		820	1100	PB+Thrust
ROVTECH A/S	BUSTER MK II											
Underwater Systems Aust.	C'CAT	26			3	1.1	164	12				PB+Dive Planes
Sonat Subsea Services	Challenger	3200		50		16.4	5000	480	114			PB+Thrust
Slingsby Engineering Ltd.	Cirrus	6600	200.0		3	38.8	3281	415				PB+Thrust
British Aircraft Corp.	CONSUB 1	2994	53	20	3.5	28.6	2001	240				PB+Thrust
BUE Subsea	CONSUB 201	8800	125	50	2.5	42.6	2001	380				PB+Thrust
Ocean Systems Engineering	CRE 1800 HYDRA AT											
Ocean Systems Engineering	CRS 1850	8900		150		34.5	4921	2500	500	5900		PB+Thrust
Naval Undersea Warfare Eng	CURV IIA	4500	100.0	30	3	34.3	5000	440	9900	6000	15000	PB+Thrust
Naval Ocean Systems Center	CURV IIC	6900	50.0		4	36	6000	400				PB+Thrust
Naval Ocean Systems Center	CURV III	5538	50	30	4	45.5	1000	400				PB+Thrust
International Sub. Eng.	Cyclone	2550				21.7	2000	440	100			PB+Thrust
International Sub. Eng	Dart	70	4.0		1.3	1.5	1200	240				PB+Thrust
Ketema	Deep Drone	1600	35.0	21	3.5	21	5400	480		7000		PB+Thrust
QI Inc.	Delta-100	35	2.0		2.5	1.3	328	100				NB+Thrust
QI Inc.	Delta-500	112	2.0		2	3.6	1640	440				NB+Thrust
QI Inc.	DLT-300C	104	1.2	1	2	2.9	656	220				PB+Thrust
Mitsui Eng. & Shipbuild	Dolphin 3K	8155		67	3.9	39.7	10800	2500	330	16400	33000	PB+Thrust
SUTEC	DOUBLE EAGLE											
OSEL Group	Dragonfly	3500	15.0		3	21.1	6000	1000	990			PB+Thrust
CERTSM	Eric	6600	60.0		4	43.1	1640	440				PB+Thrust
Gay Underwater Instrument	Filippo	190			1	4.5	1300			1640	400	PB+Thrust
Deep Ocean Engineering	Firefly	6				0.3	98			150		PB+Thrust
International Sub. Eng.	FMV	2000				17	3000	440				PB+Thrust
Swedish National Defense	FOA-Sub	1322	18.0	13	2	18.8	820	220				Ballast Pump
SUTEC	FORCE I	2200	135	56	2.6	21.5	3280	440				PB+Thrust
Ketema	Gemini	4500		80	2	25	5000	440	300			PB+Thrust
Eastport International	Gemini II	9200		70		43.1	20000	440		22000	120000	PB+Thrust
Taylor Diving & Salvage Co.	HARVEY	348	8.8	2	2	7.1	1000	220				PB+Thrust
Hitachi Zosen	HI-ROV-15	350		0.6	3.3	1.8	492	100	3.5			PB+Thrust
Sumitomo Heavy Ind.	Hornet 500	265	3.0	1.1	2.7	7.2	1640	1100	22	1640	2100	PB+Thrust
Hydrovision Ltd.	Hyball	86	2.5	2	2.5	2.6	984	100	10			PB+Thrust
International Sub. Eng.	Hydra	2645		40	2.5	17.6	8200	460				PB+Thrust
ISE. Ltd.	HYDRA (Type 40)											
Oceaneering International	HYDRA 50 AT	3806	150		2.8	22.6	5971	460				PP+Thrust
International Sub. Eng.	Hydra AT 1850	2600				17.1	6000	460	200			PB+Thrust
Hydrobots Eng. Canada	Hydrobot	75	1.5		2.5	1.3	984	240		500	600	PB+Thrust
International Sub. Eng.	Hysub 250					66.7	328	1200	6614	1969	200000	Air Ballast
International Sub. Eng.	Hysub 5000	4600		30		27.1	16400	460	80	16400	121000	PB+Thrust
International Sub. Eng.	Hysub ATP 10	650	7.5	10		6.4	3000	480				
International Sub. Eng.	Hysub ATP 150	9600		150		43.8	6000	2300	803			PB+Thrust
International Sub. Eng.	Hysub ATP 20	2200				18.8						
International Sub. Eng.	Hysub ATP 25	2000	60.0	25		12.8	5000	480	174			PB+Thrust
International Sub. Eng.	Hysub ATP 40	3718	125.0	40		20.6	6068	480	160			PB+Thrust
International Sub. Eng.	Hysub ATP 50	3800	100.0	60		22.6	6000	480	200			PB+Thrust

Manufacturer	Vehicle	Weight (lb)	Electrical Power (KVA)	Propeller Power (hp)	Maximum Speed (knots)	Frontal Area (sq ft)	Maximum Depth (ft)	Operational Volts (volts)	Lift Capacity (lbm)	Teather Length (ft)	Teather Strength (lbf)	Bouyancy Ballast (type)
International Sub Eng	Hysub ATP 60	3800		64		24.2	610					PB+Thrust
International Sub. Eng	Inspector	120		2		3.3	1200	240				PB+Thrust
Intersub	Iris	66	1.0		2	1.5	656	220	2.2	328		PB+Thrust
BUE Sub Sea Ltd	IZE I	441	40.0	6	2.5	7.8	984	440	132			PB+Thrust
Deep Submergence Lab.	Jason	2400			1	10.8	19680					PB+Thrust
Deep Submergence Lab.	JJ	260	1.5		1.5	4.6	13120	120				PB+Thrust
Kawasaki Heavy Industries	Kawasaki ROV-1	88	4.0		3	4.1	328	110		656	1320	PB+Thrust
Kowa	Kowa 100	51	1.8		3	2.3	328	110			990	PB+Thrust
Kowa	Kowa 150	77	2.0		4	4	492	100				Bouyancy tanks+Thrust
Lowa Co.	KOWA 300											
Seametrix	LADYBIRD											
Fluid Energy Ltd.	LR 300	88				2.5	984					PB+Thrust
Academy of Sciences USSR	Manta 1.5	2645	10.0	6	2	17.3	4920	380	22			PB+Thrust
KDD Laboratories	Marcas	1322	30.0		2.5	16.6	656	200				PB+Thrust
KDD Laboratories	Marcas-2500	7934	52.0		4	36.8	8200	2250		11483	20000	PB+Thrust
Platinum Industries	Merlin	55			2	1.4	164	12				Open Pressure System
American Marine Consultants	MICRO SUB 2000						151	12				
Osel Group	Microv	331		4	7.6	6.5	656					PB+Thrust
Benthos	MicroVer	14				0.2	98			150		PB+Thrust
SUTEC	Midas			0.3		0.67	98					PB+Thrust
SMIN Consortium	MIN	2865			5	16.2	492		264			PB+Thrust
Benthos	MiniROVER	55	1.0		3.2	1.6	853	220				PB+Thrust
Benthos	MiniROVER MK II	75	1.0		3	2.1	1000	240	11			PB+Thrust
Benthos	MiniROVER MK IV	110	0.8		2.5	2.4	3280	240	12	125	850	PB+Thrust
Marconi Underwater Ssytem	Minnow	870			5	11.6	656		277			PB+Thrust
Slingsby Engineering Ltd.	MMiM		133.0	19	3	64.5	1312	415				Open Pressure System
Honeywell Marine Systems	MNS	2500	108.0	60	6	8.7		2400				PB+Thrust
Mediterraneenne Ind. e.	Modexa	617					1312					
Mitsui Ocean Development	MURS-300	5730	60.0		3	41	984	220				PB+Thrust
Mitsui Ocean Development	MURS-300 MKII	441			1.8	4.8	984		88			PB+Thrust
OSEL	NUFO	231	15.0		3.5	3	984		11			PB+Thrust
Slingsby Engineering Ltd.	Observer	286	5.0		3	6.2	1968	440				PB+Thrust
Aqua Air Industries	ORCA	221		6		2.7	1000					PB+Thrust
ISE, Ltd.	ORION (Maxi-Dart)											
Slingsby Engineering Ltd	ORV	198	2.5	1.5	2.4	7	656	415				PB+Thrust
Societe ECA	PAP 104 - MK IV	1543			5.5	18.2	984	30				
Deep Ocean Engineering	Phantom 300	46.3	2.0		2	2.5	350	120				PB+Thrust
Deep Ocean Engineering	Phantom 500	57	1.5		3.1	3.1	500	110				PB+Thrust
Deep Ocean Engineering	Phantom HD	85	1.5		3.6	2.9	1000	110				PB+Thrust
Deep Ocean Ingineering	Phantom HD2	132	3.5		3.5	3.8	1000	230		2000		PB+Thrust
Deep Ocean Engineering	Phantom HVS4	180			4	1.5	1000	400	31			PB+Thrust
Geologinen Tutkimuslaitos	Phocas II	500	5.0			6.9	984	220				Variable Ballast
Slingsby Engineering Ltd.	PIC	7714	75.0	80	3	32.3	3280	1000				PB+Thrust
MBB, GmbH	PINGUIN B3	2970			8	22.6	328					Thrust
Sub Sea Offshores Ltd.	Pioneer	3000	42.0	50	3	33.1	5000	1000	220			PB+Thrust
Ametek	Piper	1600	35.0			19	2000	460	100			PB+Thrust
Naval Ocean Systems Center	PIV	18260	200	150	2	241.5	850	460				Variable Ballast
Gaymarine S.r.l.	Pluto	310		4.5	4	3.9	1300		88	1640	660	PB+Thrust
Society ECA	Pope	882	5.0		5	11.6	492	380	154			Ballast Tanks
Remuscraft Ltd.	Prove	216	3.0	1.6	4	4.8	1640	440	16	6562		Ballast Tanks
Offshore Syst. Eng. Ltd.	R3000LF	3000			3	17.7	3000	440	100			
International Sub. Eng.	RASCL	119	3.0	2	3	2.6	1180	220				PB+Thrust
ISE, Ltd.	RASCL 1											

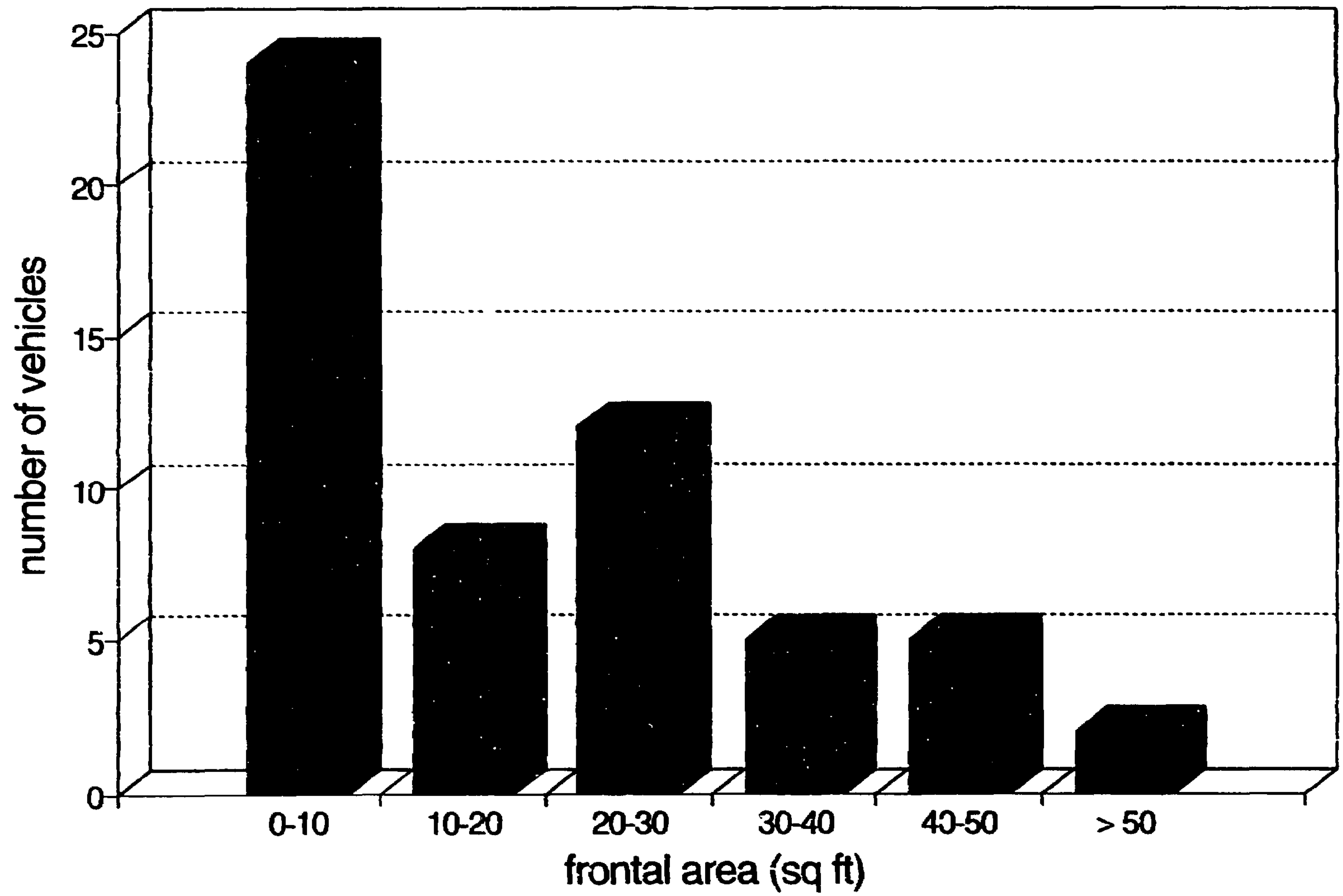
Manufacturer	Vehicle	Weight (lb)	Electrical Power (KVA)	Propeller Power (hp)	Maximum Speed (knots)	Frontal Area (sq ft)	Maximum Depth (ft)	Operational Volts (volts)	Lift Capacity (lbm)	Teather Length (ft)	Teather Strength (lbf)	Bouyancy Ballast (type)
ISE. Ltd	RASCL MK II											
Hydro Products	RCV-150	1060	100.0		2	23.3	1968	440				PB+Thrust
Hydro Products	RCV-225	180	5.0		1.7	3.6	1312	440				PB+Thrust
Hydro Products	RCV-425	200	15.0	10	5	6.3	1200	460				PB+Thrust
Perry Offshore	RECON III											
Perry Offshore	Recon III-B	500	48.0		2	6.1	1000	440		1700	7500	PB+Thrust
Perry Offshore	RECON III-C											
Perry Offshore	Recon IV	904	35.0		3	8	1500	220	253			PB+Thrust
Perry Offshore	Recon IV S	900	80.0	4	3	8.2	1500	460	250			PB+Thrust
OSEL Group	RINGWORKER	2200	175	300	3	21.4	3001	440				PB+Thrust
Intersub	Robin	286			1	4.1	19680	600		230		PB+Thrust
RICO Mikroeleknotronik	ROMIS I	110	1.0		0.7	3.9	1300	220	11	1300	220	PB+Thrust
RICO Mikroeleknotronik	ROMIS II											
International Sub. Eng.	ROSS	480	3.0		3.5	3.7	1640	460	24			PB+Thrust
Benthos	RPV	358			2	9.9	1968	480	20			PB+Thrust
Benthos Corp.	RPV-2000											
Benthos Corp.	RPV-430											
Mitsui Engineering	RTV-100	55	1.0	0.9	2.7	2.1	328	120		492	550	PB+Thrust
Mitsui Engineering	RTV-100S	48	1.0		3	2.1	328	100		328	550	PB+Thrust
Mitsui Engineering	RTV-300											
Mitsui Engineering	RTV-500	132	4	2.14	3.7	3.4	1640	100				PB+Thrust
Mitsui Engineering	RTV-KAM	191	7	2.14	3	4	98	100		3936		PB+Thrust
Hydrobotics Eng. Canada, Inc.	SCAMP	33			2.5	1.5	98	24		108		Variable Ballast
Ketema	SCARAB	4990	150	37	3	29.9	6000	480		10000		PB+Thrust
Naval Ocean Systems Center	SCAT											
International Sub. Eng.	Trail Blazer - Type 1	144		0.625		2.8						
International Sub. Eng.	Trail Blazer - Type 10	750		10		5.2						
International Sub. Eng.	Trail Blazer - Type 30	1700		30		5.3	1200	440				
Ketema	Scorpi	700			3.5	6.46	3000	1000	30		4500	PB+Thrust
Ketema	Scorpio	1500	50		2	21.4	3000	440				PB+Thrust
Hydrobotics	SEACLOPS	48				2.2	250					PB+Thrust
SUTEC	Sea Eagle	200	5	2.8	2.5	4.7	820	440	22			PB+Thrust
Seaeyemarine	SEAEYE 600	84	2		3	3.6	600	115				PB+Thrust
Perry Offshore	SEA GRANT 1	847	100		2.5	7.44	1200	240		1500	1995	PB
SUTEC	SEA HAWK	275	3	2.8	2.5	5.6	1640	800		1148	5000	PB+Thrust
Inst. of Offshore Eng.	SEA HORSE	2640		32	2.7	38.4	1968					PB+Thrust
Rebikof Underwater Prod.	SEA INSPECTOR	280	4	2	5	7.87	656	230				PB+Thrust
Deep Ocean Robotics Ltd.	SEAKER	30				1	656					PB+Thrust
RSI Research Ltd.	SEAMOR	17.6			2	0.66	151	120				PB+Thrust
J.W. Fishers Mfg. Inc.	SEA OTTER	65			2.6	2.1	499	110				Thrust
SUTEC	Sea Owl MKII	187	5	2.8	2.5	4.8	1150	220	17.6	1150		PB+Thrust
Underwater & Marine Equip. Lt	Sea Pup II	170	2	1.5	3	4.3	1500	240		656		PB+Thrust
Underwater & Marine Equip. Lt	Sea Pup III	170	2	1.5	3	6	2000	240		656		PB+Thrust
Deep Sea [illegible]t. International	SeaROVER Mark II	88	5	3	4	3.4	820	440	33			PB+Thrust
Sea Scan [illegible]hnology	Sea Scanner	30	0.5		1.2	1.2	500	120	6.6	600	640	PB+Thrust
Sea Scan [illegible]chnology	Sea Whip	110	3		2.5	2.7	1000	240	81	1000	640	PB+Thrust
Underwater Syst. Austrailia	SEKA	92.4	1			1.8	328	110				PB+Thrust
Bennico Ltd.	SKATE	4620	50			43	2952	440				PB, Variable
Skadoc Submersibles	SMIT-SUB	1540	150			37.9	3281	380				PB+Thrust
Naval Ocean Systems Center	SNOOPY	300	1.2		2	4.66	1500	115				PB
Continental Shelf Inst.	SNURRE 1	3960	70		2	39	1640	220				PB+Thrust
Myerns Verksted A/S	SNURRE 2	3080	35		2.5	29.3	2953	380				PB+Thrust
Slingsby Engineering, Ltd.	SOLO	4400	75	40	4	57.2	4921	380				PB+Thrust

Manufacturer	Vehicle	Weight (lb)	Electrical Power (KVA)	Propeller Power (hp)	Maximum Speed (knots)	Frontal Area (sq ft)	Maximum Depth (ft)	Operational Volts (volts)	Lift Capacity (lbm)	Teather Length (ft)	Teather Strength (lbf)	Bouyancy Ballast (type)
Skadoc Submersibles	SOP	3960	65		3.2	30.1	3280	440				NB+Cable
Stolt-Nielsen Seaway	SPIDER	7260			n/a	43	1640	440				NB+Cable
Robertson Tritech	Sprint 101	150	11	2.5	2	4.6	2000	220				PB+Thrust
Innovative Engineering	SUB 300	1100	35	36.9		13.5	984	380				PB+Thrust
Underwater Systems Australia	SUPER C'CAT	77	1.4		1.8	1.8	328	110		328	1980	NB+Thrust
ISE, Ltd.	SUPERDART	748		7	2.5	16.8	1181	440				PB+Thrust
Deep Ocean Engineering	Super Phantom 2	150	4.5		3	5.2	1000	230		2000		PB+Thrust
Deep Ocean Engineering	Super Phantom 4	180	6		4	5.2	1000	230		2000		PB+Thrust
Ketema	Super Scorpio	3500	45		2.5	22.6	3280	3000	450			PB+Thrust
Ketema	Super 2006	4000	45		2.5	24.2	8200	3000	3300			PB+Thrust
Euro Submersibles Ltd.	TAXI											
Remote Ocean Systems, Inc.	TELESUB	550		4	2.3	5.86	2001	220				PB+Thrust
Taylor Diving & Salvage	TIV	95	5			3.9	1000	220				PB+Thrust
Oceanwide U.K. Services	TOM THUMB	33		1.47		1.64	328	220				Variable Ballast
Naval Systems Warfare	TONGS I				2.9							NB+Cable
Naval Systems Warfare	TONGS II											
ISE, Ltd.	TRAPR	24000	300			79.3	5577	460				Var. Ballast+Syn. Foam
ISE, Ltd.	TREK	350	8	6	2	9.3	1200	120		1500		NB+variable ballast
Taylor Diving & Salvage	TRIDENT	1496	100		3	17	4000	440				PB+Thrust
Skadoc Submersibles	TRIGLA		0.4			0.0156	115	24				NB+Variable Ballast
Perry Offshore Inc.	Triton	4200	38		3	20.2	3280	2400	500			PB+Thrust
Slingby Engineering Limited	Trojan	4000	70		2.5	27.6	3280	440				PB+Thrust
ISE, Ltd.	Trov	1130		10.4	3	28.7	1200	460	100			ballast tanks
ISE, Ltd.	TROV-N	4490	100	40	3	24.9	5232	440		4500	39916	PB+Thrust
J.W. Fisher: Mfg. Inc.	TURTLE											
OSEL Group	UFO-300	315	20		2	4	1400	440				PB+Thrust
K.B.A. Subsea	VICTOR	403				6.1	600					PB+Thrust
ISE, Ltd.	Viking	1100	10	7	2	17.5	1200	500	50			PB+Thrust

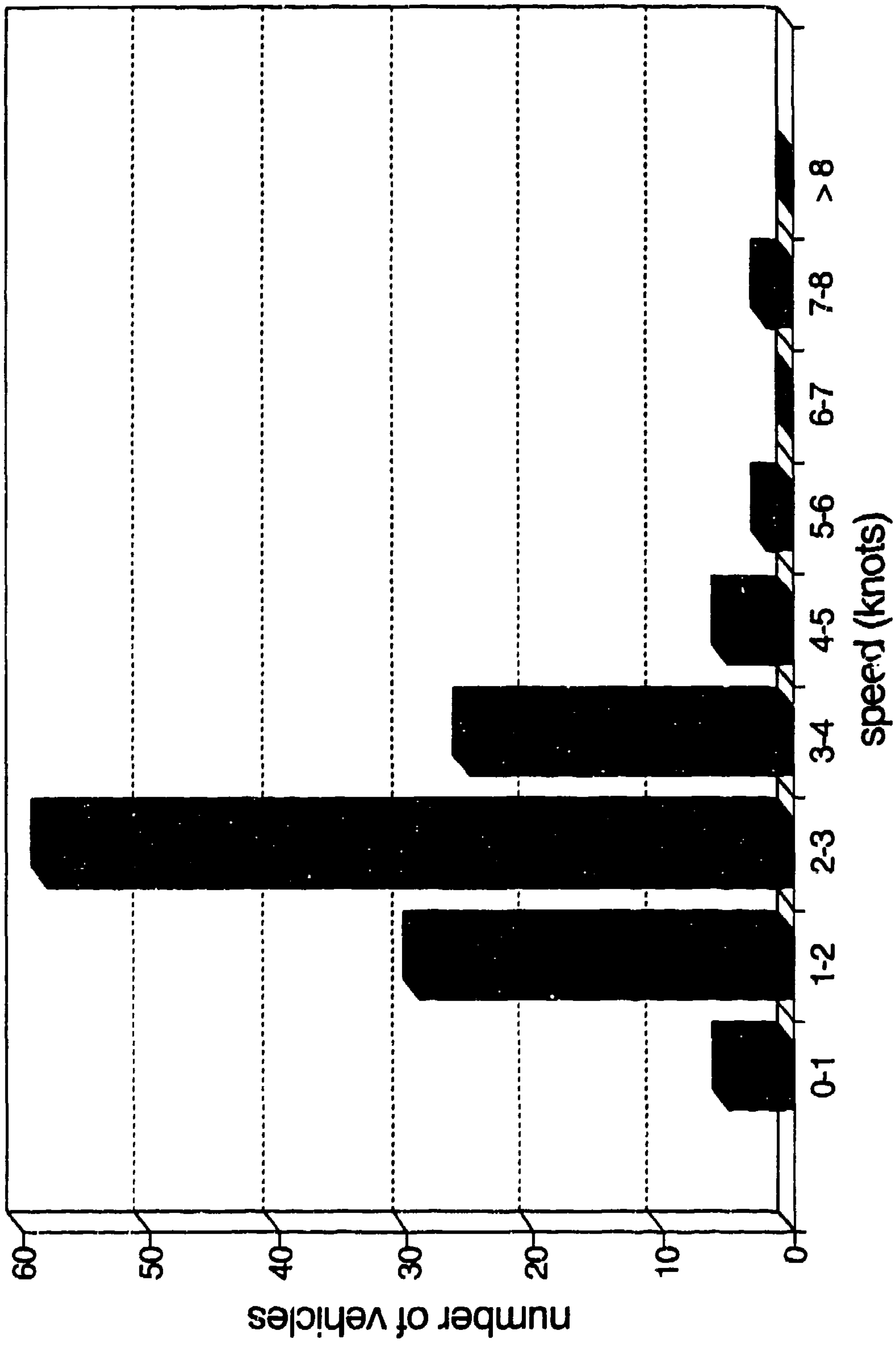
Frequency Distribution for ROVs
Vehicle Weight



Frequency Distribution for ROVs
Vehicle Size



Frequency Distribution for ROVs
Maximum Vehicle Speed



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AUVs

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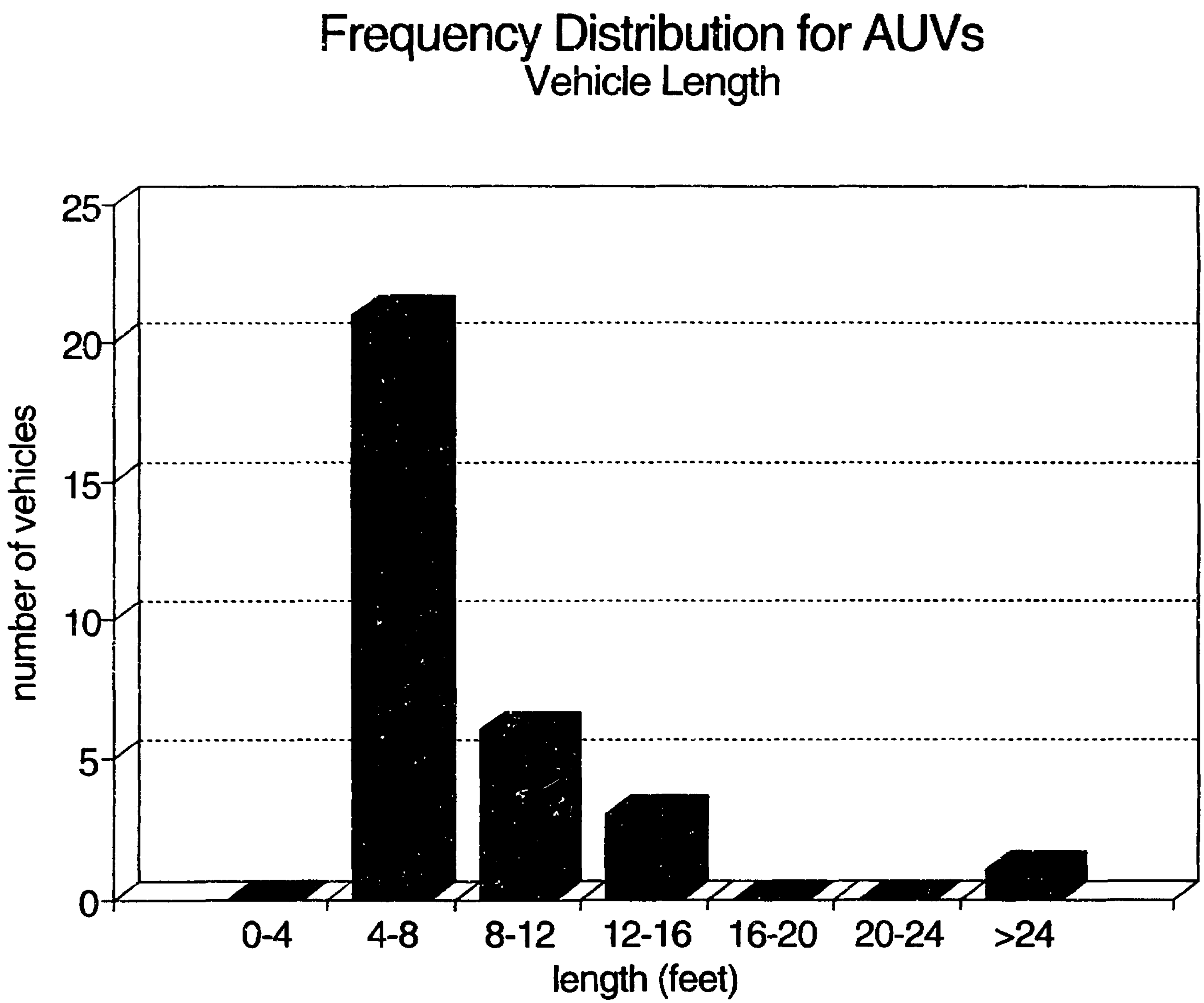
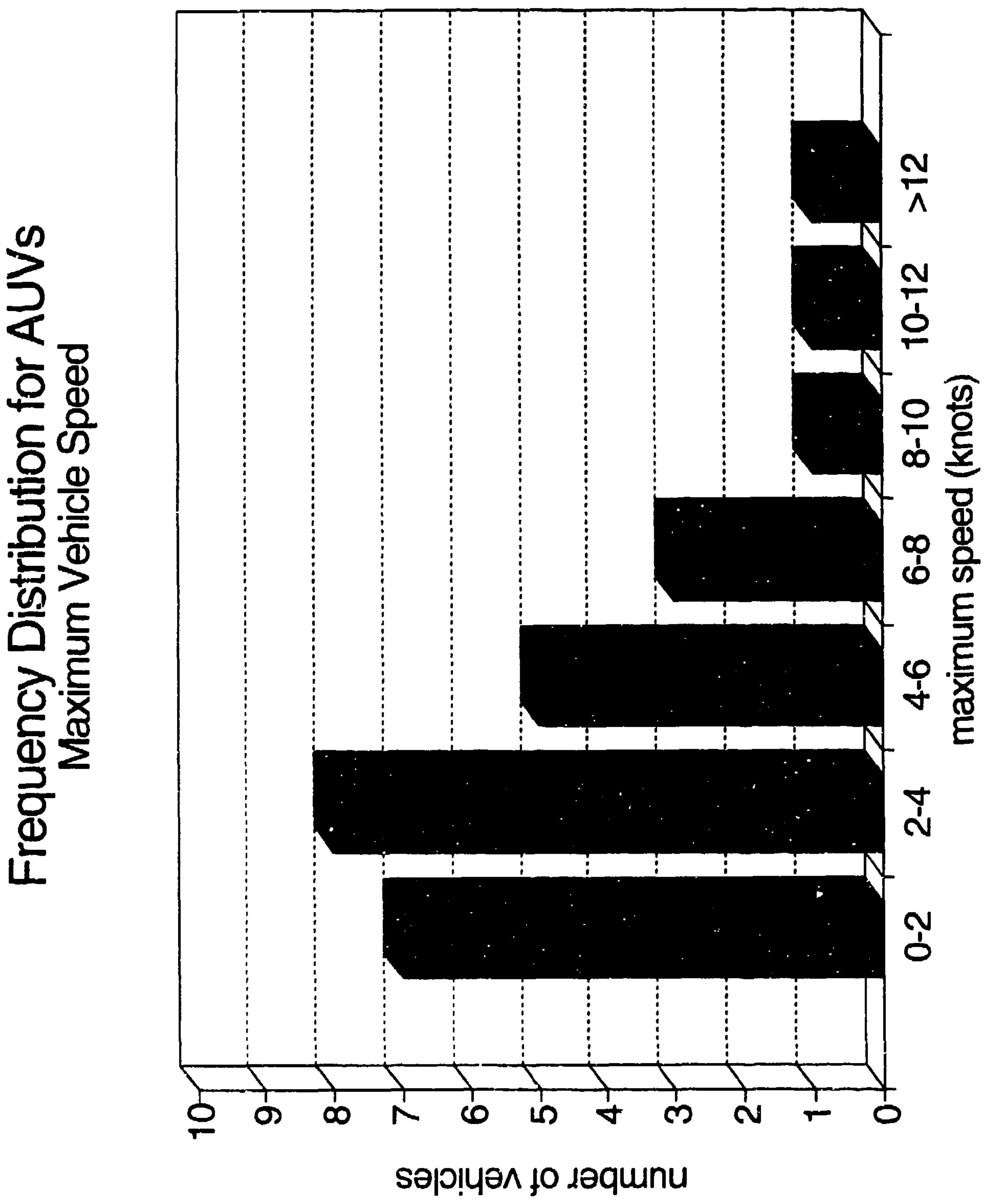
Vehicle Name	Developer/ Operator	Location	Purpose	Date Launched	Status	Maximum Depth (feet)	Dimensions Length (ft) Length (ft)	Width (ft) Diam. (ft)	Height (ft)
ACTV	Applied Physics Lab.	Univ. of Wahington, USA	Conductivity and temp. data	1989	Oper	820	5.35	0.29	
ADVANCED MARINE ROBOT	MITI	Tokyo, Japn	Struct. Inspect. and Repair		Const	656	10.50	8.86	8.86
ARCS	ISE, Ltd.	Port Moody, BC, Canada	Under Ice Mapping	1984	Oper	1312	22.96	2.30	
AROV	SUTEC	Linkoping, Sweden	Search and Mapping		Const				
ARUS	Various Orgs	Italy, British	Bottom Survey	1993	Const	19680	19.68	4.26	
AUSS	NOSC	San Diego, CA, USA	Search/ Identification	1983	Proto	19995	14.01	2.56	
AUV	U.S. Defense Advncd Rsrch. Proj. Ag.	Wash., DC, USA	Low Drag Studies		Proto				
B-1	Naval Underwater Systems Center	Newport RI, USA	Laminar Flow Data	1982	Const	298	9.02	2.33	
CSTV	Naval Coastal Systems Center	Panama City, FL, USA	Submarine Control testing	1980	Oper		29.85		
DOGGIE	Yard Ltd.	Glasgow, Scotland	Bottom sub-bottom survey		Const				
DOLPHIN	Yard Ltd.	Glasgow, Scotland	Temp./Sal./Depth monitoring		Const				
EAVE III	Univ. of New Hampshire	Durham, NH, USA	Pipeline/Struct. Inspection	1979	Proto	298	4.23	4.43	5.08
EAVE WEST	NOSC	San Diego, CA, USA	Pipeline/Struct. Inspection		Proto	2198	8.86	1.84	1.84
ELIT	IFREMER/COMEX	France	Pipeline/Struct. Inspection	1990	Const	3280	6.56	4.59	
EPAULARD	IFREMER	Toulon, France	bottom photgraphy/topography	1983	Oper	1968	13.12	3.61	6.56
FSMNV	Naval Ocn Sys. Cntr.	San Diego, CA, USA	Mine neutralization		Const				
LSV	Naval Coastal Systems Center	Panama City, FL, USA	Model Testing	1987	Oper		87.90	9.84	
MINI MOBILE TARGET	Hazeltine Corp.	Braintree, MA	Acoustic Device training	1982	Oper	348	4.26	0.29	
MT-88	Institute of Marine Tech.	Vladivostok, USSR	Bottom Surveys/ Water	1989	Oper	19680	12.46	3.61	3.61
MUST	Martin Marietta	Baltimore, MD, USA	Gen. Purp. Testbed	1989	Oper	2001	29.85	4.59	
OSRV	Japn Soc. Promotion Machine Ind.	Tokyo, Japan	Ocean Research		Inact				
PINGUIN A1	MBB GmbH	Bremen, Germany	Route Survey		Oper				
PLA 2 6000	C.E.A. & IFREMER	France	Manganese Nodule Collection	1985	Proto	16400	18.04	10.82	8.53
PTEORA	Inst. of Ind. Science	Tokyo, Japan	Bottom photography/ feasibility	1989	Proto	19680	4.92	2.46	1.48
ROBOT II	MIT	Cambridge MA, USA	Bottom Surveys	1982	Proto	298	7.71	1.15	
ROVER 01	Heriot-Watt Univ.	Edinburgh, Scotland	Structure inspection	1982	Const	328	4.40	2.07	1.77
RUMIC	Naval Coastal Systems Center	Panama City, FL, USA	Mine Countermeasures		Const				
RUV	Applied Physics Lab., Univ. of Wash.	Seattle, WA, USA	Krill census	1988	Oper	820	4.26	0.23	
SEA SQUIRT	MIT Sea Grant	Cambridge, MA, USA	Testbed		Const	200	2.82	0.72	
SKAT	Institue of Oceanology	Moscow, USSR	Ocean research		Proto				
SPAT	Westinghouse Oceanics Div.	Cleveland, OH, USA	Acoustic Target training	1980	Oper	787	10.76	0.83	
SPURV I	Applied Physics Lab.	Seattle, WA, USA	Mid-water research	1967	Oper	11998	10.17	1.64	
SPURV II	Applied Physics Lab.	Seattle, WA, USA	Mid-water research		Oper	4999	10.17	1.64	
SUB MARINE	JAMSTEC	Yokosuka, Japan	Testbed/ hydro daynamic flow		Inact				
TELEMINE	Teksea	Laguna, Switzerland	Vessel destruction	1983	Oper	492	16.40	1.64	
TM 308	Tecnomare S.p.A.	Venice, Italy	Structure Inspection		Concpt	1312			
UFSS	naval REsearch Lab.	Wash. DC, USA	Search	1979	Proto	1499	19.68	3.94	
UROV 2000	JAMSTEC	Yokosuka, Japan	Bottom Survey		Const	6560	6.56	2.62	3.28
UUV	Draper Laboratory	Cambridge, MA, USA	Military missions	1990	Const		35.98	3.67	
WIR	EUREKA	European	Struct. Inspection		Const	9840	6.56	3.94	3.94
XP-21	Applied Remote Tchnology	San Diego, CA, USA	Testbed	1988	Oper	2001	15.84	1.75	
WATER BIRD	Sasebo High Tech Co.	Sasebo, Japan	Survey		Const				
no name	JAMSTEC	Yokosuka, Japan	Testbed		Const				
no name	Simrad Subsea A/S	Horten, Norway	Feasibility	1985	Const	328	5.25	3.94	1.31

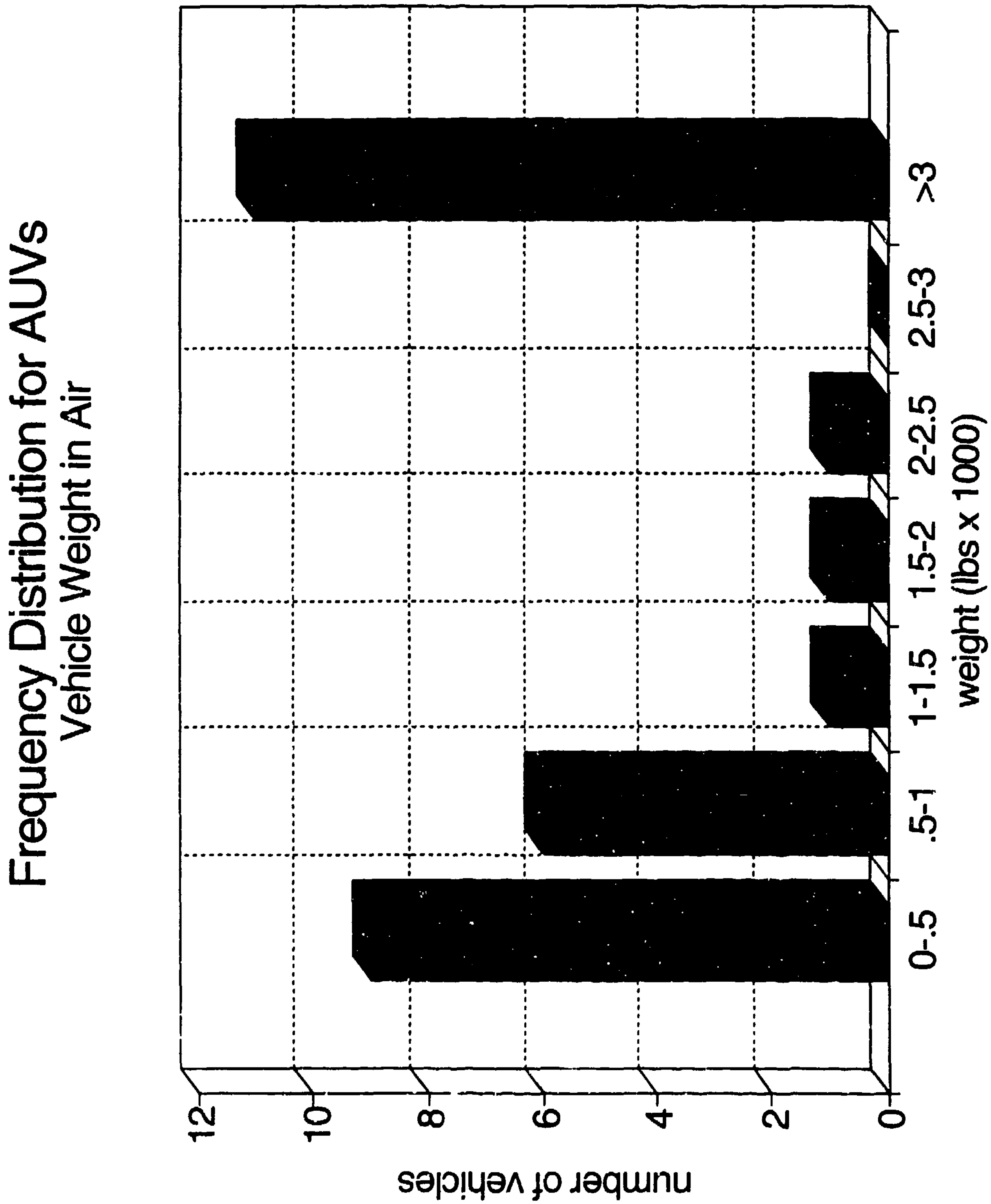
Vehicle Name	Weight in Air (lbs)	Speed (knots)	Buoyancy Control	Power	Propulsion
ACTV	22	4		battery pack	
ADVANCED MARINE ROBOT	11000	2	Neu	battery Ag-Zn	3 thrusters
ARCS	3322	6	N/A	battery Ni-Cad	2 Props
AROV					
ARUS	13200	6		.igine	
AUSS	1995	7	Neg/Neu	battery Ag-Zn	4 Props
AUV					
B-1	924				
CSTV	8980	5		battery Ag-Zn	25 hp motor
DOGGIE					
DOLPHIN					
EAVE III	598	1.5	Pos	battery Lead-acid	6 thrusters
EAVE WEST	449	1.8	Pos	battery Lead-acid	3 thrusters
ELIT	20[illegible]	1.5	Pos/Neu	battery	2 thrusters
EPAULARD	6600	2	Pos	battery lead-acid	1 thruster
FSMNV					
LSV	308000			battery	
MINI MOBILE TARGET	17	4		battery lithium	1 prop
MT-88	2200	2	N/A	battery	thrusters
MUST	8140	8	Neu	battery lead-acid	1 prop, 3 thrusters
OSRV					
PINGUIN A1					
PLA 2 6000	35200		Neg	battery	2 trains ..chemedian srews
PTEGRA	484	4	Neg	battery Ni-Cd	2 thrusters
ROBOT II		3	Neu	battery lead acid	1 prop
ROVER 01	264	NA		battery lead acid	5 thrusters
RUMIC					
RUV	20	4	Pos	battery Li-SO2	1 prop
SEA SQUIRT	62	3		battery Ag-Zn	3 thrusters
SKAT					
SPAT	330	12		battery	1 prop
SPURV I	999	7	Pos	battery Ag-zn	1 prop
SPURV II					
SUB MARINE					
TELEMINE	1320	20	Pos	battery Li	2 props
TM 308		2.4		anerobic engine	
UFSS	5408	5		battery lead acid	1 prop
UROV 2000	880	1		battery Ni-Zn	5 thrusters
UUV	14960	10	Ballast	battery Ag-Zn	1 prop
WIR	4400	3		umbilical	
XP-21	997	6	elevators	battery lead acid gel	4 thrusters
WATER BIRD					
no name					
no name	528		bladder	battery lead acid	3 thrusters



Frequency Distribution for AUVs
Vehicle Length
number of vehicles
0
5
10
15
20
25
0-4
4-8
8-12
12-16
16-20
20-24
>24
length (feet)



Frequency Distribution for AUVs
Maximum Vehicle Speed
number of vehicles
0
1
2
3
4
5
6
7
8
9
10
0-2
2-4
4-6
6-8
8-10
10-12
>12
maximum speed (knots)


Frequency Distribution for AUVs
Vehicle Weight in Air
number of vehicles
0
2
4
6
8
10
12
0-.5
.5-1
1-1.5
1.5-2
2-2.5
2.5-3
>3
weight (lbs x 1000)

D-19

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CRAWLERS

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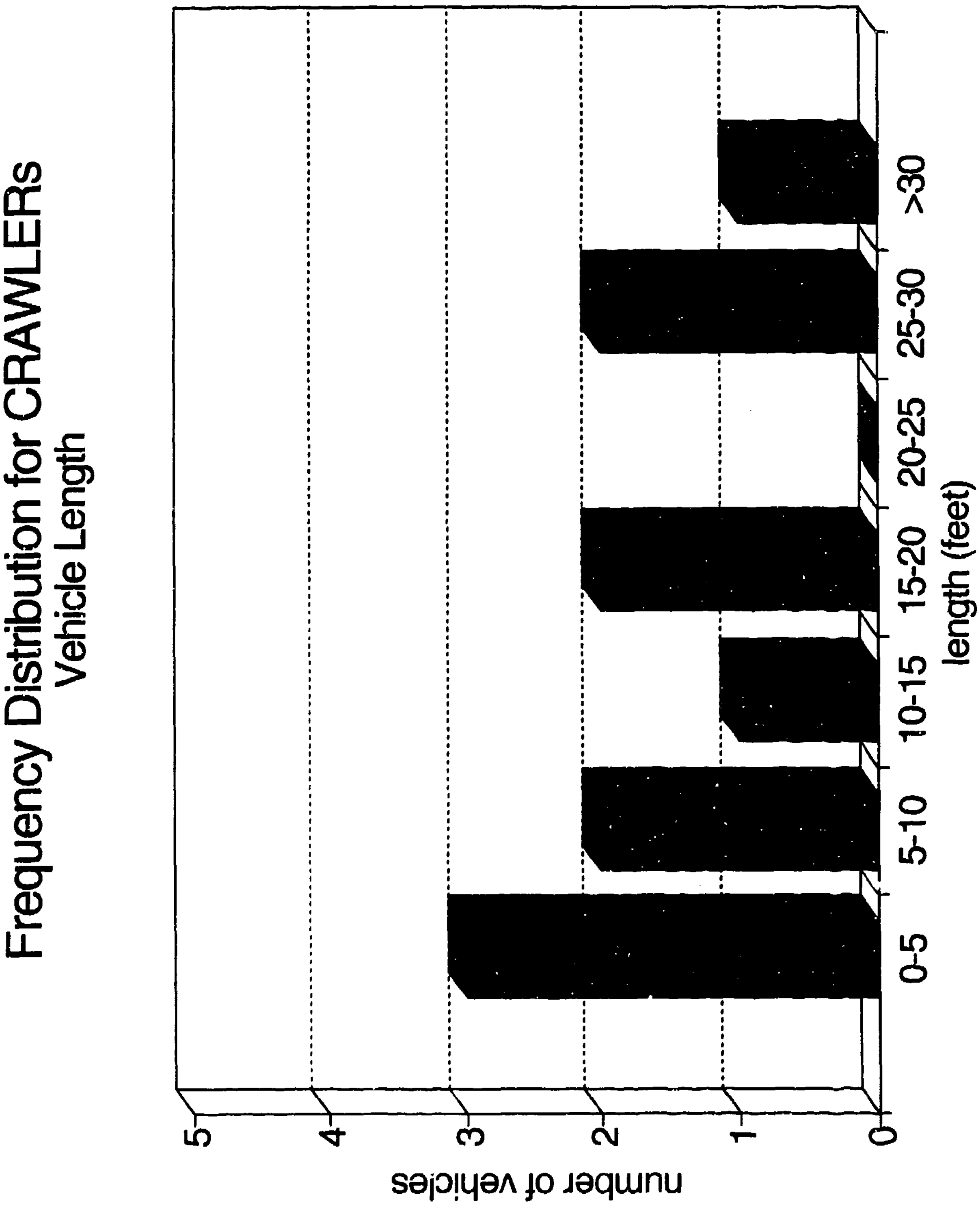
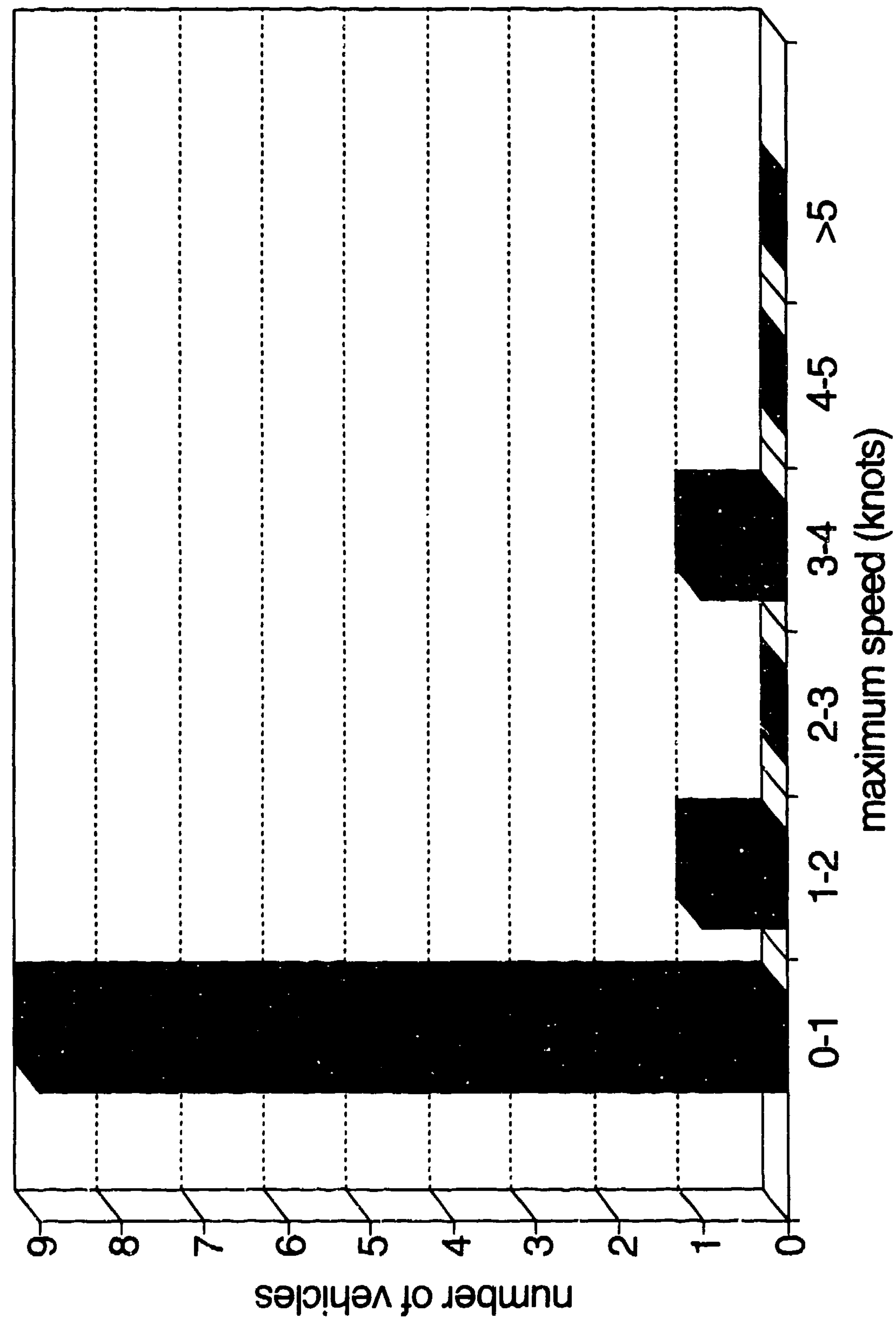
Vehicle Name	Developer/ Operator	Location	Purpose	Date Launched	Status	Maximum Depth (feet)	Dimensions Length (ft) Length (ft)	Width (ft) Diam (ft)
ASTROS 200	Travocean	Marseille, France	Inspection	1986	Oper	656	4.92	4.26
BANDIT	Deep Ocean Technology	San Diego, CA USA	Wellhead Maintenance	1983	Oper	1181	2.36	6.10
GRANSEOLA	Incop	Anacona, Italy	Pipeline Trenching	1978	Oper	151	26.24	19.68
MMS	Exxon Company	Houston, TX USA	Subsea Prod. Sys. Maintenance	1976	Oper	2001		
NORMAN MUDBUG	Norman Offshore Pipeline Contractors	Lafayette, LA USA	Pipeliine Trenching	1987	Oper			
PBM	Sub Sea Oil Services S.p.A	Milan, Italy	Pipeline Trenching	1978	Oper	2132	19.68	5.90
ROCIS	ASEA Oil and Gas	Vasteras, Sweden	Pipe Crack Inspection		Oper	984	2.62	3.28
SCAMP	Butterworth Systems Inc.	Floral Park, NJ USA	Hull Cleaning	1970	Oper	115		5.90
SCAN	Underwater Maintenance Co., Ltd.,	Eastleigh, Hamps., England	VLCC Hull Inspection	1974	Oper	115		5.90
SCIMITAR	Woodside Offshore Petroleum	Perth, Australia	Structure Cleaning	1988	Oper	410		10.50
SEA ROVER	Bedford Inst. of Oceanography	Dartmouth, NS, Canada	Oil Tank Soundings	1975	Inact	328	8.53	8.20
TALPA	Incop	Anacona, Italy	Pipeline Trenching		Unk	151	26.24	26.24
TALPETTA	Incop	Anacona, Italy	Cable Trenching		Unk	151	16.40	9.84
TIM	ELF Aquitaine	Paris, France	Subsea Prod. Sys. Maintenance	1979	Oper	2001	13.78	7.54
Unnamed	Kaiyo Kiki Co. Ltd.	Tokyo, Japan	Waterway (Aquaduct) Inspection	1986	Oper		8.53	3.74
Unnamed	Kaiyo Kiki Co. Ltd.	Tokyo, Japan	Underwater Cleaning Equipment	1986	Oper	492		
Unnamed	Myrens Verksted A/S	Oslo, Norway	Pipeline Trenching	1977	Oper	1640	30.50	31.82

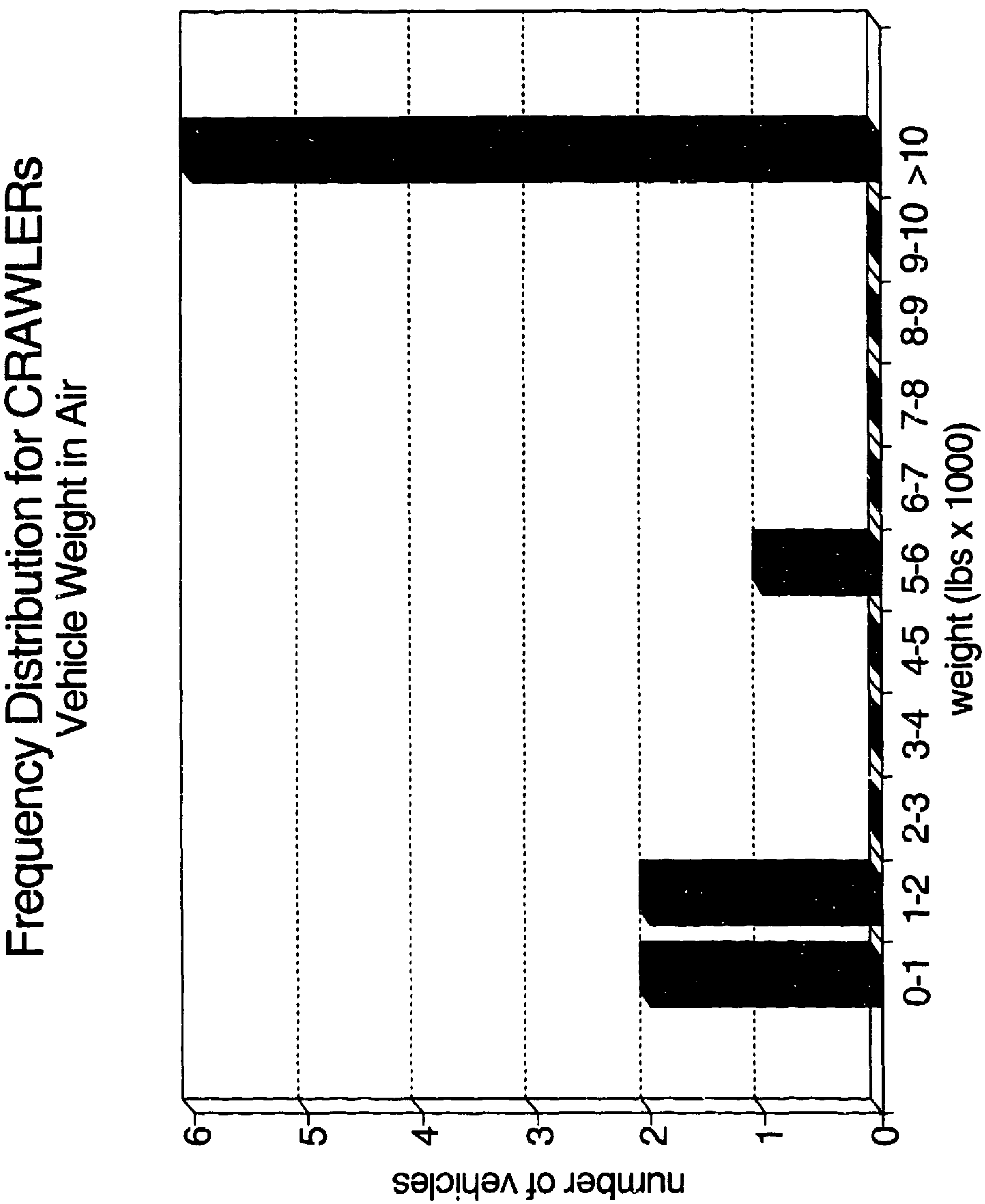
Vehicle Name	Hieght (ft)	Weight in air (lbs)	Speed (knots)	Buoyancy Control	Power	Operating Voltage (volts)
ASTROS 200	1.97	286	4	Pos	8kW	380
BANDIT	9.45	1696		Neg		240
GRANSEOLA	18.70	19800	0.08		2 450 hp diesel generator	
MMS		71720		Neg		
NORMAN MUDBUG						
PBM	11.48	11000	0.03	Air Ballast		
ROCIS	1.31					
SCAMP	1.64	1496	0.5	Pos	15 hp, shipboard generat	
SCAN	2.49	598	0.5	Pos	7 KVA	420
SCIMITAR				Neg	tethered	
SEA ROVER	3.94		2	Neg	shipboard	
TALPA	17.38	37400	0.04			
TALPETTA	4.92	5500	0.08			
TIM	18.04	26400	0.5	Neg		
Unnamed	2.85		0.81	Neg/Pos	8 kW	200
Unnamed						
Unnamed	26.90	198000	0.3	4 ballast tanks	500 kW	


Frequency Distribution for CRAWLERs
Vehicle Length
number of vehicles
0
1
2
3
4
5
0-5
5-10
10-15
15-20
20-25
25-30
>30
length (feet)

D-25

Frequency Distribution for CRAWLERs
Maximum Vehicle Speed




Frequency Distribution for CRAWLERs
Vehicle Weight in Air
number of vehicles
0
1
2
3
4
5
6
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
>10
weight (lbs x 1000)

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TOWED VEHICLES

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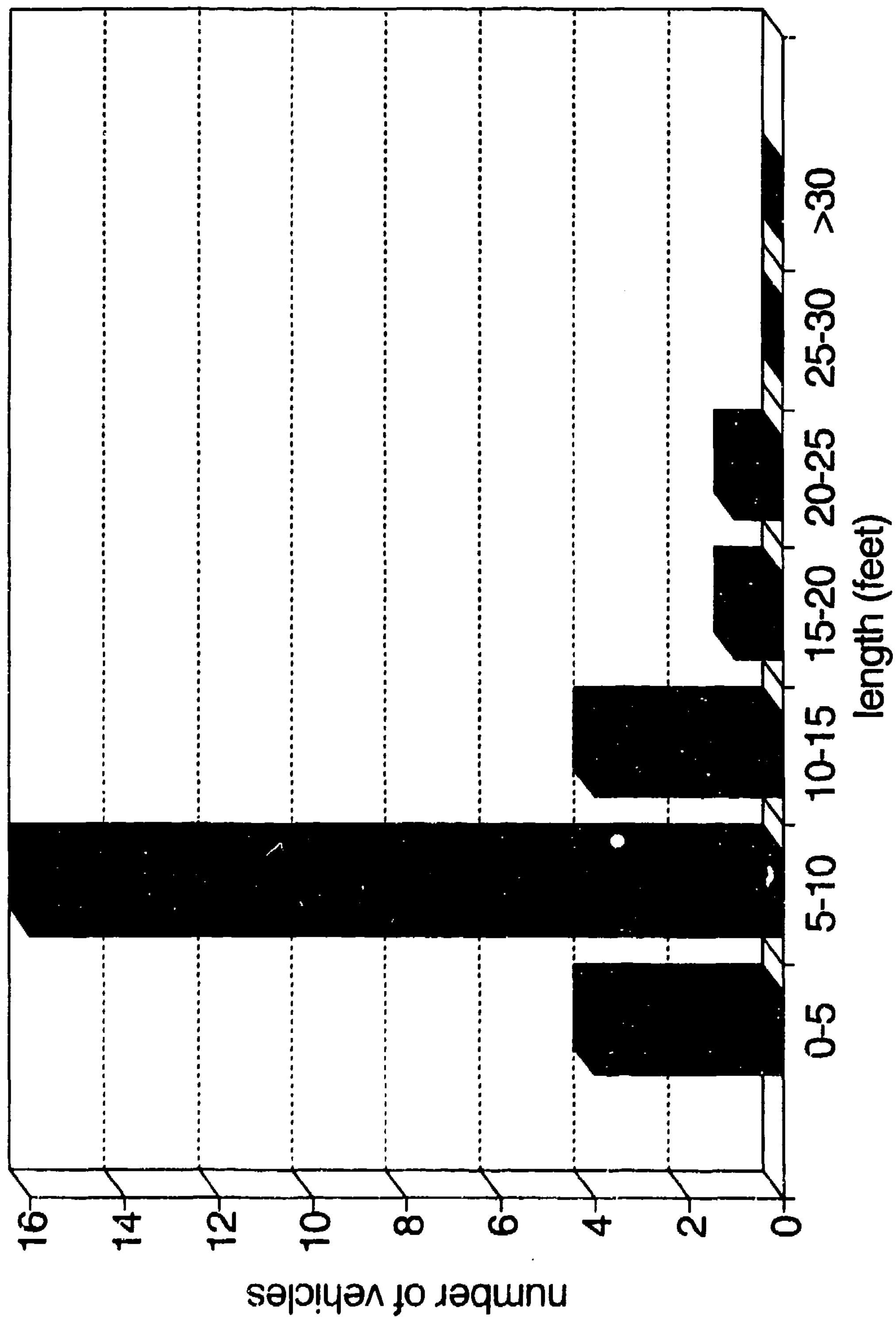
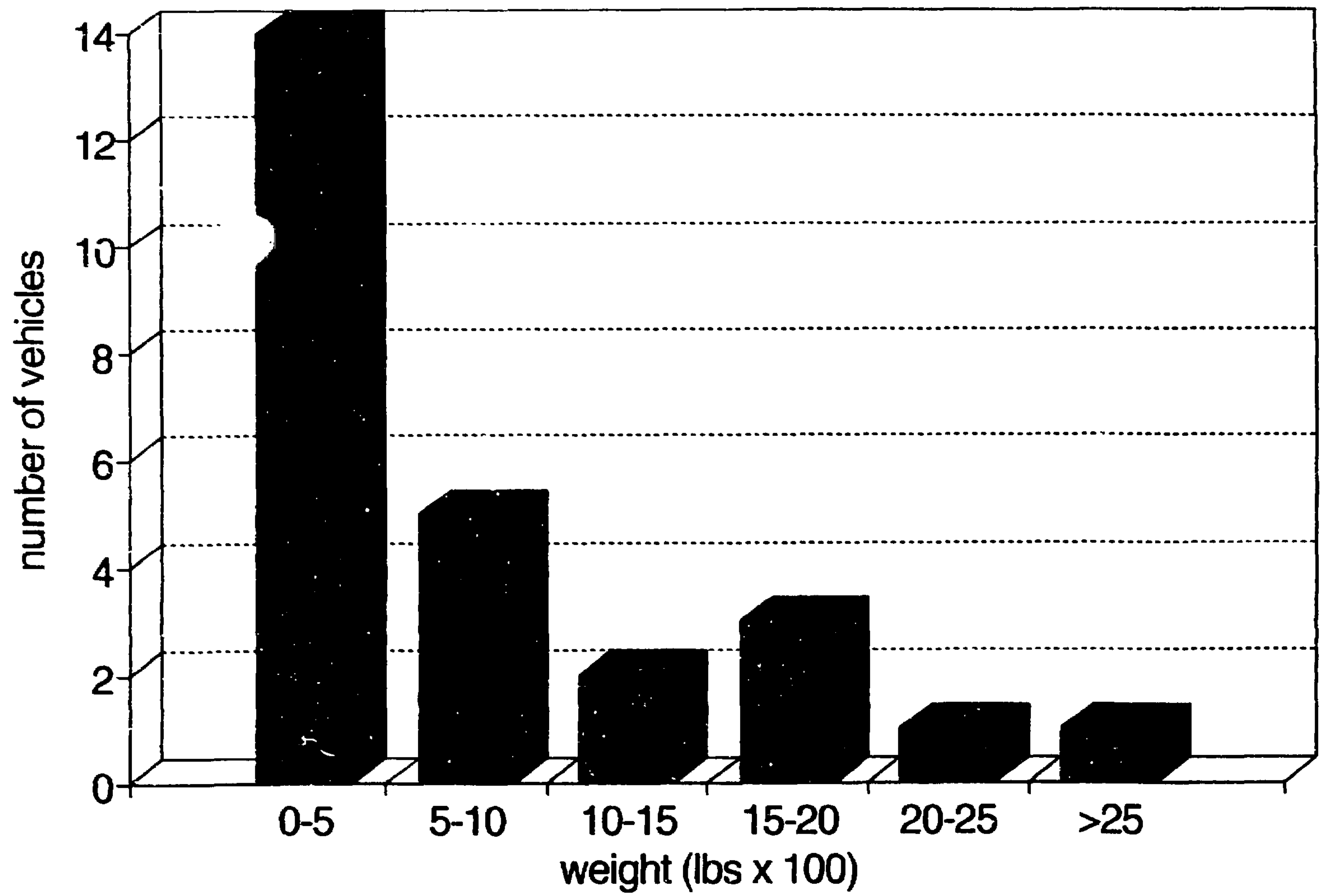
Vehicle Name	Developer/ Operator	Location	Purpose	Date Launched	Status	Max. Depth (m)	Dimensions Length (ft) Length (ft)
ANGUS	Woods Hole Oceanographic Inst.	Woods Hole, MA USA		1980	Oper	19680	14.10
ARGO	Woods Hole Oceanographic Inst.	Woods Hole, MA USA	Used to Identify RMS TITANIC	1985	Oper	19680	15.09
BRUTIV	Biological Station, St. Andrews	New Brunswick, Canada	Versions MK I, MK II, and MK III	1977	Oper	899	9.84
COSMO I	Seametrix	Aberdeen, Scotland			Const	984	6.56
CSA/STCS	Continental Shelf Assoc.	Jupiter, FL USA		1976	Oper	1148	7.15
CSA/UTTS	Continental Shelf Assoc	Jupiter, FL USA			Oper	1000	
DEEP CHALLENGER	Japan Marine Science and Tech Center	Yokosuka, Japan		1978	Oper	19680	9.84
DEEP TOW	Marine Physical Lab., Scripps Inst. of Oceanography	La Jolla, CA USA		1960	Oper	19680	6.56
DEEP TOW SURVEY SYS	Lockheed Ocean Laboratory	San Diego, CA USA		1981	Oper	20008	22.96
DSS-125		Japan Germany		1974		19680	7.54
MAKO	Remotely Operated Vehicles, Ltd	West Perth, Australia			Oper	131	2.01
MANTA	National Marine Fisheries Service	NOAA, Bay St. Louis, MS		1981	Oper	1115	7.87
NODULE COLLECTION VEHICLE	National Research Inst. for Resources and Pollution	Japan		1979	Proto	115	5.58
OCEAN ROVER MK3	Seametrix	Aberdeen, Scotland		1984	Oper	1312	6.56
OCEAN SURVEYOR	Seametrix	Aberdeen, Scotland		1985	Oper	1968	6.23
OFOS	Preussag Meerestechnik	Hannover, Germany		1985	Oper	19680	11.48
ORION	U.S. Navy Supervisor of Salvage	Wash., D.C. USA		1986	Oper	9997	7.87
RAIE II	IFREMER	Brest, France		1978	Oper	19680	9.84
RCT[illegible]	Dept. of Agriculture & Fisheries	Aberdeen, Scotland	designed to observe fishing gear	1982	Oper	328	6.79
SMA SEA[illegible]	S.E.A.	La Mesa, CA USA			Oper	492	4.36
SEA SE[illegible]	S.E.A.	La Mesa, CA USA		1988	Oper	2624	6.36
S[illegible]UND	Instituteof Oceanology	Moscow, USSR		1981	Oper	13120	
STSS	Submarine Development Group One	San Diego, CA, USA		1981	Oper	20008	13.78
TELEPROBE	Naval Oceanographic Office	Bay St. Louis, MS USA		1970	Oper	19680	9.84
TSS-1000	Deep Sea Systems Int.	Falmouth, MA		1989	Oper	1000	7.05
TUGOS	Center for Fisheries Engineering Research	Cambridge, MA USA		1987	Oper	1000	3.00
TUMS	Royal British Navy			1982	Oper	19680	12.63
USV	JAMSTEC	Yokosuka, Japan		1978	Oper	328	1.97
ZVUK	USSR Instit. of Oceanoology	Moscow, USSR				NA	

Vehicle Name	Width (ft) Diam. (ft)	Height (ft)	Weight in Air (lbs)	Speed (knots)	Buoyanc Control	Power	Propulsion
ANGUS	16.40	5.90	4789	1	Neg	30V 150 A-h Pb-acid battery	towed
ARGO	3.28	3.28	3960	71	Neg	Elect. from ship	towed
BRUTIV	7.87	2.49	499	6	Pos	28V 15 A-h Pb-acid battery	towed
COSMO I	3.94	2.23	286	6	Neg	220 VAC at 50 VA	towed
CSA/STCS	3.74	3.58	299	3	Neg		towed
CSA/UTTS				6			towed
DEEP CHALLENGER	4.59	4.92	2200	3	Neg	115V 10kva	towed
DEEP TOW	2.46	3.28	2200	2.1	Neg	120V, 60 Hz, 20 A	towed
DEEP TOW SURVEY SYS	13.12	9.84	2495	1.5	Neg	400VAC	towed
DSS-125	4.26	3.94	3692	1.5	Neg	115VAC, 60 Hz, 20 A or 220VAC, 50Hz, 10 A	
MAKO	1.48	1.78	26	2		12 or 24 VDC battery, 90 W	towed
MANTA	4.92	4.92	1397	5		12 VDS internal	towed
NODULE COLLECTION VEHICLE	4.59	3.94	440	2		220V, 60 HZ, 1.5kW	towed
OCEAN ROVER MK3	4.59	4.59	660	5		115/230VAC, 3.5 KVA	towed
OCEAN SURVEYOR	6.07	6.23	880	6		115/230VAC, 3.5 KVA	towed
OFOS	4.92	4.92	0	3		onboard batteries	towed
ORION	2.95	2.95	792	3		440 VAC	towed
RAIE II	3.28	3.28	1320	1.5	Neg	onboard batteries	towed
RCTV	6.04	6.56	515		Neg	240V, 5A	towed
SMA SEARCH MK III			40	6			towed
SEA SEARCH MK V			117	6			towed
SOUND			880	4		27V, 1.5kW	towed
STSS	1.97	1.97	2495	1.5		440VAC, 60Hz	towed
TELEPROBE	3.94	5.25	3494	2.5		120VAC, 30A	towed
TSS-1000	2.98	5.48	1386	2.5		120/240 VAC, 2.5kW	
TUGOS	3.50	1.83	120	4.5		125VAC, 10A	towed
TUMS	5.08	4.59	6292	2		3000VAC, 30 KVA	towed, thrusters
USV	1.31	1.31	11	8		6 adn 13VDC	towed
ZYUK							

Frequency Distribution for TOWED ROVs
Vehicle Length

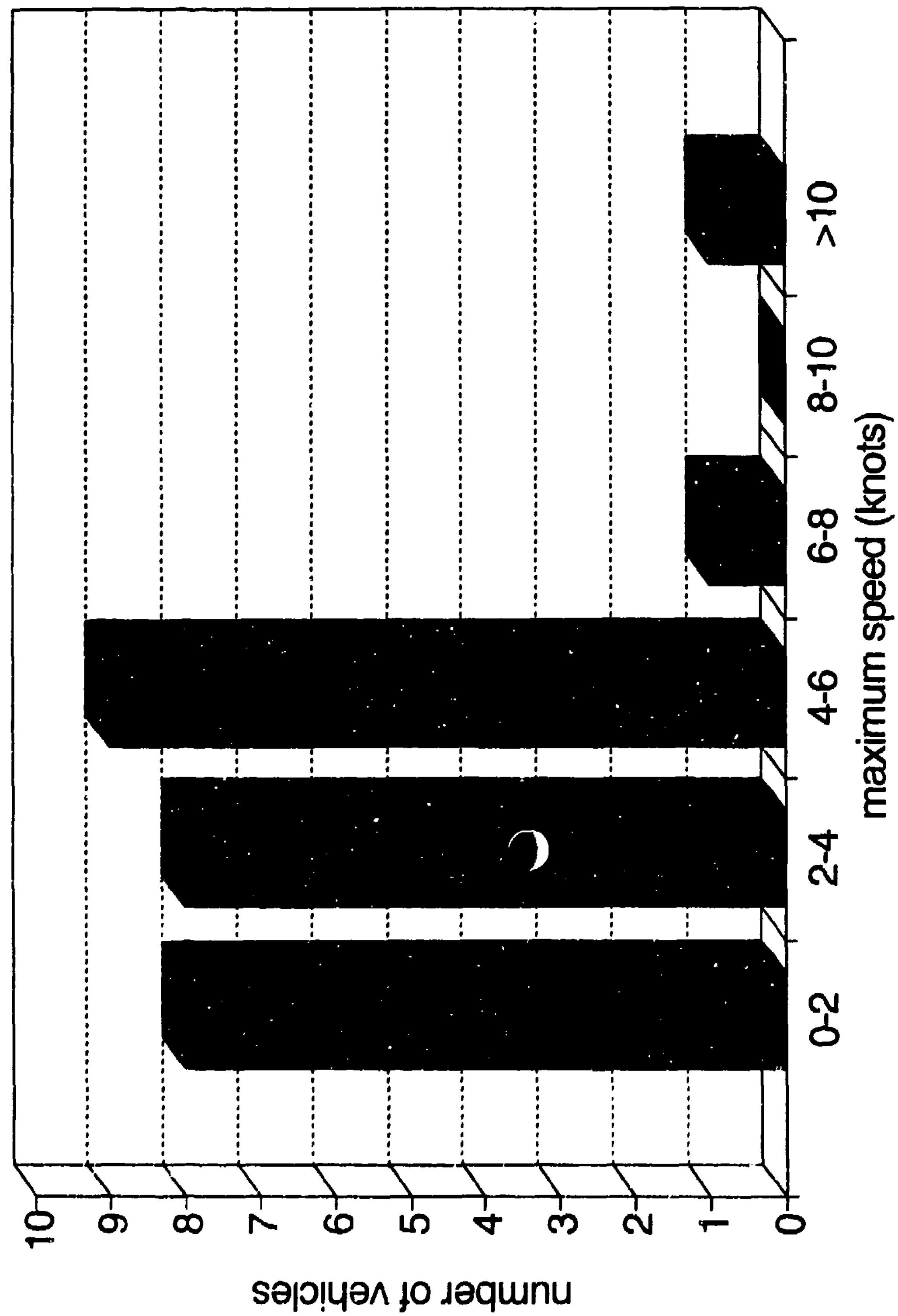


Frequency Distribution for TOWED ROVs
Vehicle Weight in Air



Frequency Distribution for TOWED ROVs

Maximum Tow Speed



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APPENDIX E

ENVIRONMENTAL ANALYSIS

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STATISTICS AND DATA SOURCES

In mid- to high-latitudes, the severity of oceanographic and weather conditions will depend strongly on the season. Generally, conditions at sea will be less favorable for navigation, safe operation of small boats, deck equipment, and rigging from late fall to early spring. Conditions for these activities improve during the summer. Scenarios were developed to distinguish two general situations that one could expect with during fair (summer) and inclement (winter) conditions at sea.

Oceanographic and climate statistics for each zone were extracted from readily available data such as climate and oceanographic atlases, NOAA National Data Buoy Center (NDBC) data summaries, and the U.S. Coast Pilots. Whenever possible, statistics for currents, waves, and winds were derived from multi-year records to avoid bias resulting from year-to-year variability. Surface current statistics are the most unreliable in this regard because long-term, near-surface measurements are not routinely made.

The basic statistical procedures for selecting wind speeds, current speeds, and wave heights for most zones are the same. Cumulative frequency distributions (CFDs) for these parameters were generated from observations at fixed locations central to each zone. For example, Figure E-1 shows wave height CFDs for the Gulf of Alaska and the gulf of Mexico. When several current meter records from several locations over a multiyear period were available, the current speed CFDs were constructed from near-surface current meter records ranging from a few months to 6 months. The CFDs for individual meters were weighted by record length and combined to form a single CFD for the zone. The combined CFDs thus represent a spatial and temporal average surface current for the entire zone.

Summer (fair) conditions were represented by the 50th percentiles of the CFDs, and winter (inclement) conditions were represented by the 90th percentiles. The 50th percentile is the wind/current speed, or wave height, that was exceeded during half of the observations. The 90th percentile is the value that was exceeded during 10% of the observations. CFDs provide a good base function for evaluating success and failure. For example, based on engineering data, a threshold parameter value can be selected for a piece of equipment which if exceeded will cause it to fail or become ineffective. The CFD for that parameter can then be used to estimate the percent of time the failure condition or inefficient operation will likely occur.

Wind Speed: Cumulative frequency distributions for winds recorded by NDBC buoys (NOAA 1990a) were used to estimate probable winter and summer wind speeds. Summer wind speeds were estimated by the 50th cumulative percentile. Because buoy data were not available for

January and February for the Great Lakes, annual CFDs could not be generated. Winter and summer wind and wave statistics were, therefore, estimated with the 50th percentiles for December and August data, respectively.

Wave Height: cumulative frequency distributions for significant wave heights recorded by NDBC buoys in offshore waters were used to estimate probable summer and winter wave heights for eact .:one. Significant wave height is the average height of the one-third largest waves in a sea. Summer wave heights were estimated by the 50th cumulative percentile, and winter wave heights were estimated by the 80th cumulative percentile. Wave date of the sort used to develop the offshore scenarios are not routinely measured in protected waters and were not readily available. The wave heights in the Zone 9 scenario are, therefore, based on personal ol :ervations.

Surface Currents: Cumulative current-speed frequency distributions were developed form multi-year, near-surface current meter records. Summer current speeds were estimated by the 50th cumulative percentile, and winter current speeds were estimated by the 90th percentile.

Surface current data of the type used to analyze offshore and tidal current speed statistics are limited for the Great Lakes. It was, therefore, not possible to generate CFDs. Surface circulations in the Great Lakes differ from offshore waters because there are no density gradient s caused by salinity variations or significant astronomical tides. Surface currents in the Great Lakes are driven mainly by the wind. Therefore, surface currents strong enough to hinder self-help measures rarely occur in the absence of strong winds, stormy weather, and moderate wind waves. During storms, surface current velocities will be approximately 2% to 3% of the local wind velocity. For example, when the average wind speed is 15 knots, the surface current will be the range form 0.15 to 0.23 m/s (0.29 to 0.45 knots). The current speeds given in the scenario for zone 8 were estimated in this way with wind statistics form NDBC Buoy data.

River currents flow in one directions, and current speed increases with river stage dependent on the surface water hydrology of headwater and tributary rivers and streams. In general, the higher the river stage the higher the average current speed will be. Very large changes in stage and current speed can occur within a period of days when storms cause severe runoff and flooding. Variations in surface currents from one location to another are tremendous along a river navigation channel. The values given in the scenarios for Zone 9 represent 50% and 100% bank-full surface current estimates obtained from the U.S. Army Corps of Engineers measurements at Greenville, Mississippi. The station is upstream from tidal influences during low-flow.

Tidal Current speed statistics at harbor entrances leading to oil terminal locations were with the program TIDE 2 (Micronautics 1991). Because the year-to-year variation of tidal forces is very small, one year of predicted data is sufficient to characterize current speeds for all years. TIDE 2 was run to make hourly predictions for 1991, and a CFD was calculated from the resultant 8,760 speeds. The 50th percentiles for each location with heavy tanker and barge traffic were determined from the CFDs and used in the scenario descriptions. Although the analysis was not made for the Intracoastal Waterway, tidal current speeds for the Waterway can be expected to fall within the range of values for Zones 1 through 3.

Sea Ice NASA satellite passive-microwave observations were used to assess sea ice coverage (Parkinson et al. 1987). Ice thickness data were also used (Bilello 1980; Bauer and Martin 1980).

Air and Sea-Surface Temperatures The mean monthly temperatures recorded by NDBC buoys for January (March for Lake Michigan) and August were used to estimate winter and summer values, respectively.

Visibility, Precipitation, Superstructure Icing. The climatological tables in the U.S. Coast Pilots were used to determine if low visibility (fog) and precipitation are likely conditions in each zones. These conditions were considered likely if either occur more than 50% of the days in December, January, and February (winter), or July, August, September (summer). For example, frequent summertime precipitation is common in the Gulf of Mexico (Zone 3). It rains more than 0.01 inches in 24 hours 52 out of 92 days at Fort Myers, Florida, during an average summer according to the Coast Pilot Climatological summary. Therefore, precipitation was included in the summer scenario for Zone 3. Likewise, fog is common in the Alaskan Bering Sea, Zone 7. Saint Paul Island has fog 69 out of 92 days during an average summer; therefore, fog is included in the summer scenario. There are no climatological data for superstructure icing in the Coast Pilots. However, the Coast Pilots indicate that it should be of concern to mariners in the Bering Sea and northern Great Lakes. For this reason, superstructure icing is included in Zones 7 and 8.

Water-Level Fluctuations: TIDE 1 software was used to generate tidal range statistics. The values given in the scenarios are the maximum tidals at locations for each scenario. In the case of Zones 1 and 3, the minimum and maximum tidal ranges for inlets with significant tanker traffic are given. In the case of Zone 2 and 7, there are no tidal inlets with significant tanker traffic; therefore, no tidal ranges are given. The remaining zones have only one inlet with significant tanker traffic.

SCENARIO DESCRIPTIONS

This section presents the scenario descriptions developed from oceanographic and weather statistics discussed above (see Tables E-1 through E-9). The descriptions for each zone are divided into winter and summer conditions. Conditions that have a low probability of occurring in a zone, such as sea ice, superstructure icing, and low visibility, are not listed.

The tables presented in this section list water and oceanographic conditions that are considered likely for U.S. navigable waters. They provide a way to factor physical conditions into analyses of the effectiveness of damage assessment technologies.

It is important to know the limitations of these tables. First, the numbers for wind and current speeds, wave heights, etc., do not represent forecasts for a particular location or time. Second, winter and summer are generic scenarios because it is generally true that inclement weather and sea conditions occur in winter, and milder conditions occur in summer in the mid latitudes. Hurricanes, persistent dense fog, and torrential rains are three obvious exceptions to the generic association of summer with mild conditions. The main utility of the tables is for the selection of parameter ranges for analyzing how well a particular damage assessment technology might perform in a particular geographic area.

E-3 Discussion

Environmental scenarios for U.S. offshore, inland, and intracoastal waters represent a wide range of environmental conditions that can be factored into evaluations of damage assessment technologies. Wind, waves, currents, sea ice, and superstructure icing could have the most significant influence on damage assessment technology effectiveness. The ranges of primary conditions for U.S. waters (all zones and all seasons) are shown in Table E-10.

Upper values of the ranges for winds, waves, and currents have about a 10% chance of occurring in certain zones based on the data analyzed. The minimum values for these conditions will be exceeded about 50% of the time in the U.S. waters.

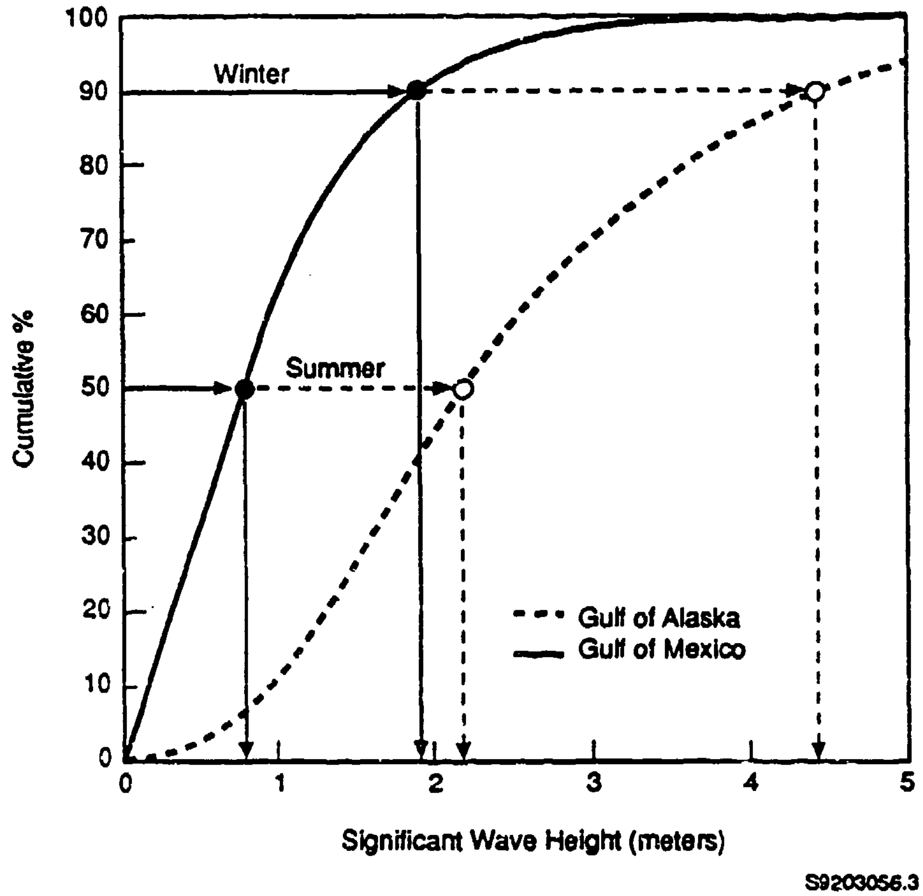

FIGURE E-1. Wave Height Cumulative Frequency Distributions for the Gulf of Alaska and the Gulf of Mexico

TABLE E-1. Zone 1, Eastport, Maine to Cape Hatteras

	Winter	Summer
Primary Conditions		
Wind Speed[a]	24 kn	13.5 kn
Sea State (H_s)[a]	3.57 m	1.5 m
Current Speed[b]	0.46 m/s (0.89 kn)	0.22 m/s (0.43 kn)
Secondary Conditions		
Air Temperature[a]	7.5°C	23.8°C
Sea Surface Temperature[a]	14.8°C	25.5°C
Daylight[c]	9.3 h/d	15.0 h/d
Tidal Range[c]	1.3 - 4.2 m	
Tidal Current Speed[c]	0.33 - 0.64 m/s (0.64 - 1.24 kn)	

(a) NDBC Buoy No. 44004 (NOAA 1990a).
(b) 106-mile Site. Battelle Ocean Sciences. Draft. Winter Survey of Selected Areas in the New York Night in Support of Designation of an Alternative Mud Dump Site.
(c) TIDE 1 and 2 (Micronautics 1991).

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Centimeter

Inches

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TABLE E-2. Zone 2, Cape Hatteras to Key West, Florida

	Winter	Summer
Primary Conditions		
Wind Speed[a]	18 kn	9.7 kn
Sea State (H_s)[a]	2.6 m	1.3 m
Current Speed[b]	No Data	0.33 m/s (0.64 kn)
Secondary Conditions		
Air Temperature[a]	19.5°C	27.9°C
Sea Surface Temperature[a]	23.0°C	28.9°C
Daylight[c]	10 h/d	14 h/d
Precipitation[d]	-	>0.01 in. in 24 h

(a) NDBC Buoy No. 41006 (NOAA 1990a).
(b) Battelle Ocean Sciences. Draft Final Report. The Physical Oceanography of the U.S. Atlantic and Eastern Gulf of Mexico. Volume II.
(c) TIDE 1 (Micronautics 1991).
(d) NOAA 1989a.

TABLE E-3. Zone 3, Key West, Florida to Brownsville, Texas

	Winter	Summer
Primary Conditions		
Wind Speed[a]	19 kn	10 kn
Sea State (H_s)[a]	1.9 m	0.7 m
Current Speed[b]	0.40 m/s (0.78 kn)	0.26 m/s (0.51 kn)
Secondary Conditions		
Air Temperature[a]	20.5°C	28.7°C
Sea Surface Temperature[a]	23.8°C	29.6°C
Daylight[c]	10.3 h/d	14 h/d
Precipitation[d]	-	>0.01 in. in 24 h
Tidal Range[c]	0.7 - 1.0 m	
Tidal Current Speed[c]	0.34 - 0.46 m/s (0.66 - 0.89 kn)	

(a) NDBC Buoy No. 42001 (NOAA 1990a).
(b) SAIC (1986, 1987, 1988, 1989).
(c) TIDE 1 and 2, Houston & New Orleans (Micronautics 1991).
(d) NOAA 1989b.

TABLE E-4. Zone 4, San Diego to Eureka, California

	Winter	Summer
Primary Conditions		
Wind Speed[a]	17.5 kn	8.5 kn
Sea State (H_s)[a]	3.0 m	1.6 m
Current Speed[b]	0.61 m/s (1.19 kn)	0.36 m/s (0.70 kn)
Secondary Conditions		
Air Temperature[a]	11.1°C	13.7°C
Sea Surface Temperature[a]	11.9°C	14.4°C
Daylight[c]	9.5 h/d	15.0 h/d
Tidal Range[c]	2.7 m	
Tidal Current Speed[c]	0.81 m/s (1.57 kn)	

(a) NDBC Buoy No. 46012 (NOAA 1990a).
(b) EG&G (1989, 1990a, 1990b).
(c) TIDE 1 and 2, Golden Gate, CA, (Micronautics 1991).

TABLE E-5. Zone 5, Eureka, California to Ketchikan, Alaska

	Winter	Summer
Primary Conditions		
Wind Speed[a]	23.5 kn	13.5 kn
Sea State (H_s)[a]	4.4 m	2.1 m
Current Speed	No Data	No Data
Secondary Conditions		
Air Temperature[a]	8.9°C	15.3°C
Sea Surface Temperature[a]	10.0°C	16.1°C
Daylight[b]	8.4 h/d	16.2 h/d
Tidal Range[b]	3.3 m	
Tidal Current Speed[b]	0.36 m/s (0.70 kn)	

(a) NDBC Buoy No. 46005 (NOAA 1990a).
(b) TIDE 1 and 2, Strait of Juan de Fuca, WA (Micronautics 1991).

TABLE E-6. Zone 6, Ketchikan to Dutch Harbor, Alaska

	Winter	Summer
Primary Conditions		
Wind Speed[a]	27 kn	17 kn
Sea State (H_s)[a]	4.5 m	2.2 m
Current Speed	No Data	No Data
Secondary Conditions		
Air Temperature[a]	3.3°C	12.4°C
Sea Surface Temperature[a]	4.7°C	12.9°C
Daylight[b]	6.8 h/d	18 h/d
Tidal Range[b]	5.4 m	
Tidal Current Speed[b]	0.31 m/s (0.60 kn)	

(a) NDBC Buoy No. 46001 (NOAA 1990a).
(b) TIDE 1 and 2, Prince William Sound entrance, Cape Bear, Alaska (Micronautics 1991).

TABLE E-7. Zone 7, Dutch Harbor to Demarcation Bay (Alaskan Beaufort Sea)

	Winter	Summer
Primary Conditions		
Wind Speed[a]	23 kn	13 kn
Sea State (H_s)[b]	No Data	2.2 m
Current Speed[b]	No Data	0.25 m/s (0.49 kn)
Superstructure Icing	Yes	No Data
Sea Ice[c]	1 m/60%	No Data
Secondary Conditions		
Air Temperature[a]	-14.1°C	7.4°C
Sea Surface Temperature[d]	2.5°C	11.0°C
Daylight[e]	4 h/d	22 h/d
Visibility[d]	-	Fog
Precipitation[d]	-	>0.01 in. in 24 h
Snow	Yes	-

(a) NDBC Buoy No. 46016 (NOAA 1990a).
(b) EG&G. 1985. Meteorological and Oceanographic Monitoring in St. George Basin, Summer-Fall 1984 RAT No. 1 Well. ARCO Alaska, Inc., Anchorage, Alaska. NORTEC. 1985. Meteorological & Oceanographic Data Acquisition Program. OCS-Y-586, Package #1 Navarin Basin, Bering Sea, Alaska ARCO Alaska, Inc., Anchorage, Alaska.
(c) Parkinson et al. 1987.
(d) NOAA 1989c.
(e) TIDE 1 (Micronautics 1991).

TABLE E-8. Zone 8, Great Lakes

	Winter	Summer
Primary Conditions		
Wind Speed[a]	13.4 kn	8.2 kn
Sea State (H_s)[a]	1.1 m	>0.5 m
Current Speed[b]	0.20 m/s (0.29 kn)	0.12 m/s (0.23 kn)
Superstructure Icing	Yes	-
Ice[c]	0.3 m/20%	-
Secondary Conditions		
Air Temperature[a]	2.3°C	21.5°C
Water Temperature[a]	2.6°C	22.0°C
Daylight[d]	9 h/d	13.5 h/d
Snow[e]	Yes	-

(a) NDBC Buoy No. 46007 (NOAA 1990a).
(b) Average Wind Speed X 0.03.
(c) NOAA 1983.
(d) TIDE 1 (Micronautics 1991).
(e) NOAA 1991b.

TABLE E-9. Zone 9, Intracoastal Waterways and Rivers

	Winter	Summer
Primary Conditions		
Wind Speed[a]	13.4 kn	8.2 kn
Sea State (H_s)[b]	>0.5 m	>0.25 m
Current Speed[c] (m/s)	0.50 m/s (2.4 m/s[d])	0.50 m/s (2.4 m/s[d])
Current Speed[c] (kn)	0.97 kn (4.66 kn[d])	0.97 kn (4.66 kn[d])
Secondary Conditions		
Air Temperature[a]	0.8°C	23.8°C
Water Temperature[a]	2.3°C	26.0°C
Daylight[c]	9.4 h/d	13.1 h/d

(a) NOAA 1991a.
(b) Personal Observations.
(c) TIDE 1 & 2, Wilmington, Delaware (Micronautics 1991).
(d) Median surface current speed of the lower Mississippi River; Ron Wooley, WES, Personal communication.

TABLE E-10. The Ranges of Primary Conditions for U.S. Waters

Primary Conditions	Ranges
Wind Speed	8.2 to 27 kn
Sea State (H_s)	<0.5 to 4.5 m
Current Speed	0.12 to 2.4 m/s (0.23 to 4.66 kn)
Sea/Lake Ice	None to 60% coverage of 1-m ice
Superstructure Icing	None to 50% chance of occurrence

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APPENDIX F

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