

FROM COUSTEAU TO CAMERON: A QUADRANT MODEL FOR UNDERSEA
MARINE RESEARCH INFRASTRUCTURE ASSESSMENT

by

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George Mason University
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From Cousteau to Cameron: A Quadrant Model For Undersea Marine Research
Infrastructure Assessment

A Dissertation submitted in partial fulfillment of the requirements for the degree of
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DEDICATION

This is dedicated to all who struggle with evaluating the complex and the intangible.

And to Mom, who has believed in me every step of the way.
Everyone should be as fortunate to have such love and support.

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LIST OF ACRONYMS

Advanced Research Instrumentation and Facilities	ARIF
<i>Alvin</i> Review Committee.....	ARC
American Bureau of Shipping	ABS
Assistant Secretary of Defense (Research & Engineering)	ASD (R&E)
Association for Computer Machinery	ACM
Autonomous Underwater Vehicle	AUV
Bureau of Ocean and Energy Management.....	BOEM
Code of Federal Regulations	CFR
Cognitive Task Analysis.....	CTA
Committee on Science, Engineering and Public Policy (NAS)	COSEPUP
Cooperative Institute for Ocean Exploration, Research and Technology	CIOERT
Critical Infrastructure for Ocean Research and Societal Needs	CIORSN
Decadal Survey of Ocean Sciences	DSOS
<i>Deep Discoverer</i> ROV	D2
Deep Sea Coral	DSC
DEep Submergence Science Committee	DESSC
Deep Submergence Vehicle	DSV
Department of the Interior	DOI
DEveloping Submergence SCienceE for the Next Decade.....	DESCEND

Division of Ocean Sciences (NSF).....	OCE
Dynamic Positioning	DP
Environmental Protection Agency	EPA
Federal Oceanographic Fleet Coordinating Council	FOFCC
Florida Atlantic University	FAU
Florida International University	FIU
French-American Mid-Ocean Undersea Study	FAMOUS
Government Performance and Results Act	GPRA
Harbor Branch Oceanographic Institution.....	HBOI
Hawai'i Undersea Military Munitions Assessment	HUMMA
Hawaii Undersea Research Laboratory	HURL
Human Occupied Vehicle.....	HOV
Human Occupied Vehicle Safety Standards (UNOLS).....	HOVSS
Human-Robot Interaction	HRI
Institute of Electrical and Electronics Engineers.....	IEEE
Interagency Committee on Oceanography	ICO
Interagency Working Group on Infrastructure and Facilities	IWG-FI
International Decade of Ocean Exploration	IDOE
<i>Johnson Sea Link</i>	<i>JSL</i>
Journal of Human-Robot Interaction.....	JHRI
<i>KA 'IMIKAI-O-KANALOA</i>	<i>KOK</i>
Launch, Recovery and Transport Platform	LRT
Manned Underwater Vehicle.....	MUV
Marine Technology Society	MTS

Memorandum of Understanding.....	MOU
Monterey Bay Aquarium Research Institute	MBARI
Multiple Criteria Decision Making	MCDM
NASA Extreme Environment Mission Operations	NEEMO
National Academy of Sciences.....	NAS
National Advisory Committee on Oceans and Atmosphere.....	NACOA
National Aeronautics and Space Administration	NASA
National Deep Submergence Facility	NDSF
National Marine Sanctuary Program	NMSP
National Ocean Council	NOC
National Oceanic and Atmospheric Administration.....	NOAA
National Research Council	NRC
National Science Foundation.....	NSF
Naval Sea Systems Command.....	NAVSEA
NOAA Undersea Research Program	NURP
NOAA's Observing System Integrated Analysis.....	NOSIA
Nuclear Research Submarine 1	NR-1
Occupational Safety and Health Administration	OSHA
Ocean Drilling Program	ODP
Ocean Studies Board	OSB
Oceanographic Instrumentation (NSF OCE).....	OI
Oceanographic Research Vessel.....	ORV
Oceanographic Technical Services (NSF OCE).....	OTS
Office of Exploration and Research	OER

Office of Management and Budget	OMB
Office of Naval Research	ONR
Office of Oceanic and Atmospheric Research	OAR
Office of Science and Technology Policy	OSTP
Office of Technology, Planning and Integration for Observation (NOAA)	TPIO
Other Facility Activities (NSF OCE)	OFA
Portfolio Analysis Machine	PALMA™
Pressure Vessel for Human Occupancy	PVHO
Public Value Account	PVA
Public Value Scorecard	PVS
Remotely Controlled Vehicle	RCV
Remotely Operated Vehicle	ROV
Research and Development	R&D
Research Vessel	RV or R/V
Research Vessel Act	RVA
Research Vessel Operators Committee (UNOLS)	RVOC
Research Vessel Safety Standards	RVSS
Scientific and Environmental ROV Partnership Using Existing Industrial Technology	SERPENT
Scientific Support Equipment (NSF OCE)	SSE
Ship Acquisition and Upgrade (NSF OCE)	SAU
Sustainable Seas Expedition (NOAA)	SSE
Technology Readiness Assessment	TRA
Technology Readiness Level	TRL

Tether Management System	TMS
Undersea Marine Research Infrastructure	UMRI
Underwater Safety Project (USCG)	USP
United States Geological Survey	USGS
United States Coast Guard	USCG
University National Oceanographic Laboratory System	UNOLS
University of North Carolina, Wilmington	UNCW
Woods Hole Oceanographic Institution	WHOI

ABSTRACT

FROM COUSTEAU TO CAMERON: A QUADRANT MODEL FOR UNDERSEA MARINE RESEARCH INFRASTRUCTURE ASSESSMENT

Karen M. Kohanowich, Ph.D.

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Dissertation Director: Dr. E.C.M. Parsons

The oceans are of great importance to society, but their visual opacity, corrosive chemical composition, and great pressure at depth make them one of the most challenging and hostile environments in which to conduct research. Many important marine science questions require data that is gathered *in situ*—much like that required for biological and geological fieldwork—to fully understand marine ecosystems and the interactions within them. This research, often referred to collectively as ‘submersible science,’ requires undersea systems (including human-occupied, robotic, and autonomous vehicles) that are beyond the ability of a single university or sponsor to support, but not costly enough to warrant the attention and rigor that is applied to more expensive systems such as ships or satellites. As a result, many U.S. scientists are faced with a challenging and distributed system for obtaining access to these tools, especially since a U.S. government marine research organization that supported many of these systems was discontinued in 2014. The U.S. marine research community has conducted numerous

studies to address these submersible science infrastructure needs, but the studies have focused on assessing scientific priorities and infrastructure value in addressing those priorities, and have not considered the causative dynamics of economic and societal contributions to infrastructure sustainment.

This study introduces a quadrant model that provides the framework to consider technical, operational, functional, and societal influences on the sustainment of U.S. undersea marine research infrastructure. It tests the model using the case of U.S. human-occupied submersibles which, from Jacques Cousteau's diving saucer *Denise* to James Cameron's *Deepsea Challenger*, have experienced practically a full technological lifecycle within our lifetime, and have been subject to a wide range of program influences. Results include a model that features a quasi-quantitative visualization tool; validation of the model for use in further study; demonstration of the importance of societal and behavioral factors on human-occupied research submersible sustainment, and insights into U.S. marine research infrastructure dynamics.

CHAPTER ONE : EVALUATING MARINE RESEARCH INFRASTRUCTURE

1.1 INTRODUCTION

When compared to research in terrestrial ecosystems and even outer space, science in the oceans has the distinction of presenting some of the most significant potential impacts to human well being combined with the greatest technical challenges for data collection. Many of the most substantial threats to society today involve the marine environment, and include overfishing, ocean acidification, coastal pollutants, and sea level rise. Increased pressure, opacity to light, corrosiveness of seawater, and often-unfriendly sea surface conditions make even simple research exploration and sampling tasks expensive and complicated. More so than many scientific disciplines, marine research requires expensive infrastructure to support both remote and *in situ* data collection and experimentation, with infrastructure requirements ranging from satellites and aircraft to ships, buoys, submersibles, and scuba divers.

Multi-million dollar, large infrastructure—such as satellites and vessel fleets—require national attention, and are subject to rigorous requirement and budget analyses, whereas on the other end of the spectrum, small infrastructure—low-cost capabilities such as scuba—are subject to less cooperative oversight and managed largely on an institutional level (National Science Board, 2003). Between these extremes, undersea *in*

situ research systems, termed ‘undersea marine research infrastructure’, or ‘UMRI’ for the purposes of this study, typically fall within a category of midsize infrastructure; equipment of intermediate cost for which assessment and support is a more complicated mixture of national, agency, and university involvement. Some of these systems, such as buoys, gliders, and shipboard support equipment and technologies, can be purchased and maintained at the university level, but benefit from national coordination of deployment and data collection. A particularly challenging subset of UMRI is the suite of equipment that provides mobile, real-time, responsive and manipulative underwater data collection capabilities. Often noted as a defining requirement of ‘submersible science’ (UNOLS 1982, 1990), these systems—such as human occupied vehicles (HOVs), remotely operated vehicles (ROVs), and, increasingly, autonomous underwater vehicles (AUVs)—provide unique and important data gathering capabilities, but are often beyond the resources of a single university to operate and support.

The success of a marine research system is not only influenced by functional performance of the equipment, but by a complex web of economic considerations, scientific drivers, organizational dynamics, and the forces of human nature. A conceptual diagram included in a recent National Academy of Sciences study on “Critical Infrastructure for Ocean Research and Societal Needs in 2030” (Ocean Studies Board, 2011) illustrates the complexity of the relationships between factors that impact assessment of national oceanographic research activity and the infrastructure that supports it.

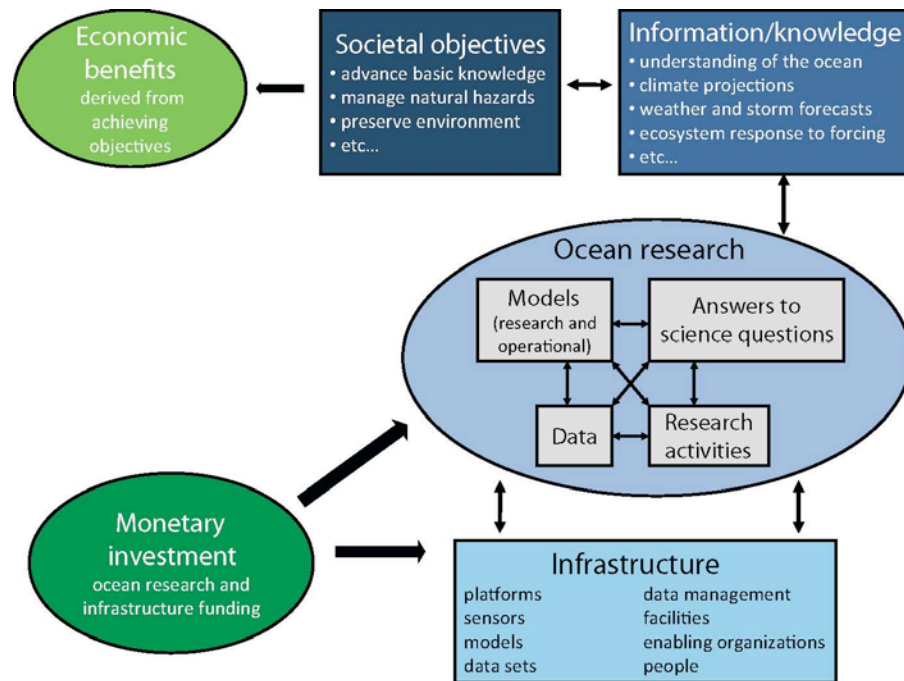


Figure 1-1 Conceptual diagram illustrating the variety of considerations of ocean research infrastructure assessment (Ocean Studies Board, 2011 p.9).

Ocean research infrastructure studies, whether focused on a broad ocean science theme (Ocean Studies Board, 2011, 2015) or specific infrastructure topic (Interagency Working Group on Facilities and Infrastructure, 2013; Ocean Studies Board, 2004; UNOLS, 2016), typically emphasize a requirements analysis, or a ‘top-down’ approach that identifies important research questions and activities prior to determining infrastructure needs. As yet, these studies have not fully examined infrastructure effectiveness from an equipment-focused, or ‘bottom up’ perspective that includes economic, organizational, social and other functional factors and impacts. Within the oceanography community, Briscoe (2003) has observed that “factors that might be

important ingredients in the success of a science or technology project” include people, money, serendipity, and external factors that are out of one’s control, such as “politics, opportunities/circumstances, other science and technology developments” (p. 6). Despite this reflection, and extensive literature on the relationships between society, science, and technology (Bijker, Hughes, & Pinch, 1987; Staudenmeir, 1985), social impacts in particular have been absent from past oceanographic infrastructure studies. Whereas requirements-based analysis is sound policy and should not be discarded, there is an opportunity to gain further insight into the dynamics of UMRI support through a broader scope of examination that begins with the technologies themselves.

The field of technology development and management provides a number of approaches—including the concepts of obsolescence, replaceability, and sustainment—that can be useful for such an examination. Managers of other types of infrastructure—such as computer hardware and software, aircraft electronics, and buildings—face complexities similar to those described above. Researchers at Delft University have examined the factors that influence obsolescence of residential buildings. Lkening the difficulties of assessment of building performance to those of “wicked problems—as inherent in policy science and planning—[which] are difficult or impossible to solve because of incomplete, contradictory, and changing requirements that are often difficult to recognize” (Thomsen, Nieboer, & van der Flier, 2015, p. 3), they have developed a conceptual model that categorizes causal factors into quadrants that reflect the degree of internal versus external, and physical versus behavioral origin of impact (Thomsen & van der Flier, 2011). Given the similarities in the nature of assessment challenges faced by

these researchers to those noted above for UMRI, this model offers an innovative perspective on UMRI assessment.

The development of a quadrant-based assessment model as described in this study is intended to be relevant for all types of oceanographic research infrastructure, and will possibly provide a useful approach for other research infrastructure as well. For the purposes of this study, however, a relatively small subset of tools—human-occupied research submersibles—was chosen in order to provide a wide range of impact factors while allowing for investigation at a beneficial level of detail.

The research presented here will therefore answer these questions:

(1) Does an assessment model exist, or can one be developed, that incorporates the full range of causative factors into the evaluation of undersea marine research infrastructure?

(2) How can such model be best illustrated and applied?

(3) What does a test of this model reveal about U.S. human-occupied research submersible sustainment?

This chapter first provides a brief review and status of *in situ* undersea research tools, and reviews infrastructure assessment efforts and techniques.

1.2 MARINE RESEARCH TECHNOLOGY BACKGROUND

1.2.1 OCEAN PROCESSES AND SCALES

Oceanographic research encompasses investigation into processes and ecosystems that occur on a wide range of time and space scales, from understanding global ocean

current regimes to determining the anatomy of plankton and coral polyps. Dimensional visualization of the scales of physical oceanographic processes was pioneered by Henry Stommel (Stommel, 1963) and translated thereafter into biological and ecological cross-scale illustrations (Peterson, 2010; Vance & Doel, 2010). An example of this type of diagram is seen in Figure 1-2, which describes processes of the upper ocean. Later researchers built on these concepts to include assignment of corresponding research sampling platforms (Dickey, 1990, 1991; Esaias, 1981) (Figure 1.2, 1.3, 1.4).

A third dimension—depth—significantly impacts marine research processes, as well as infrastructure characteristics for UMRI. The absorption of light with depth is a first order factor that determines the nature of marine ecosystems, and defines ocean zones (Figures 1-5, 1-6).

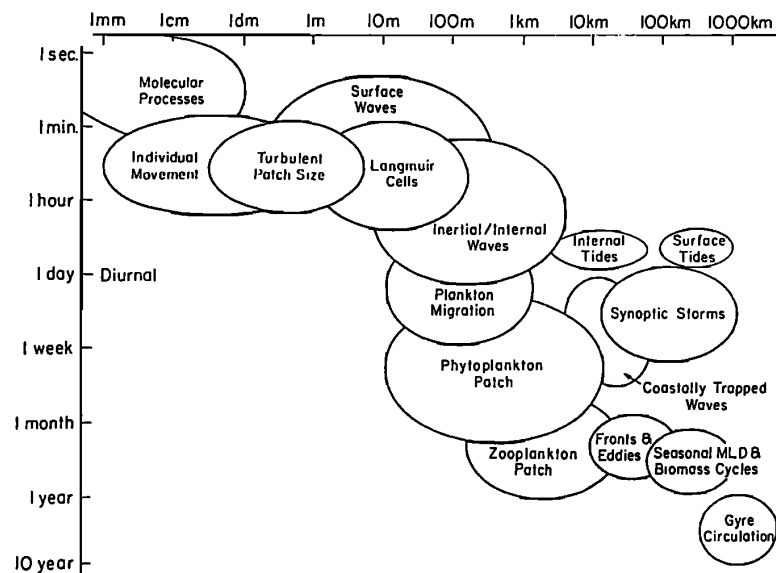


Figure 1-2 An illustration of scales of processes important to the ecosystems of the upper ocean (Dickey 1990).

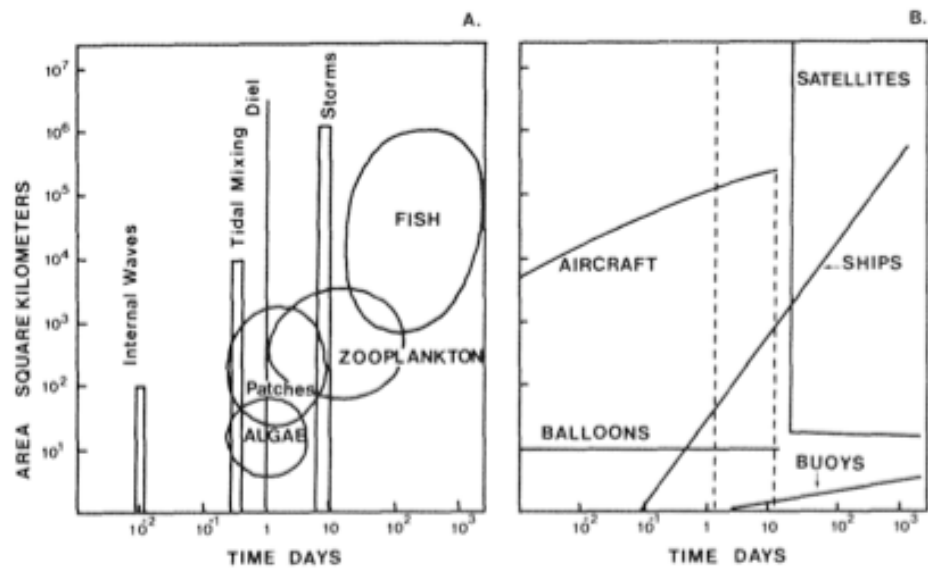


Figure 1-3 An illustration of space and time domains for some oceanic processes and sampling (Esaias 1981).

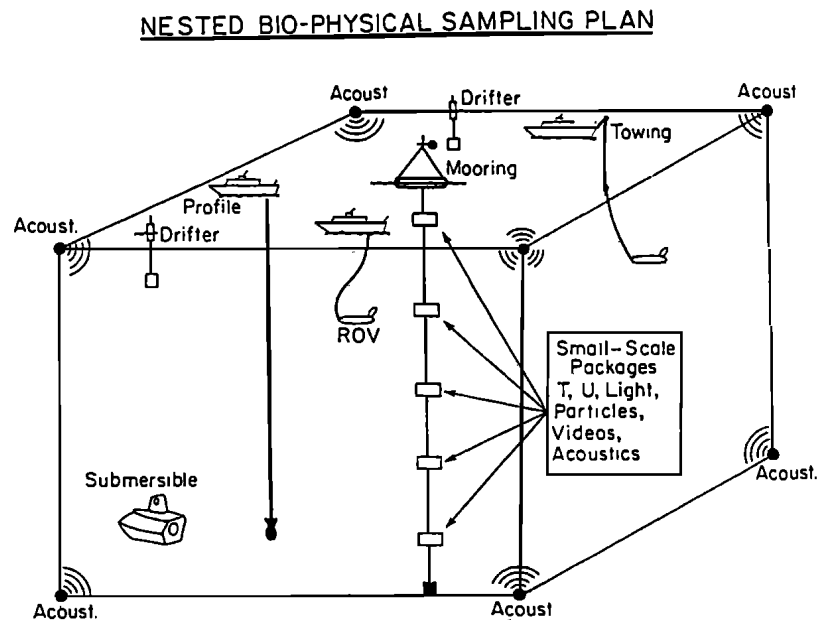


Figure 1-4 A conceptual illustration of a "nested" *in situ* bio-physical sampling configuration designed to sample processes with a broad range of temporal and spatial scales (Dickey 1991).

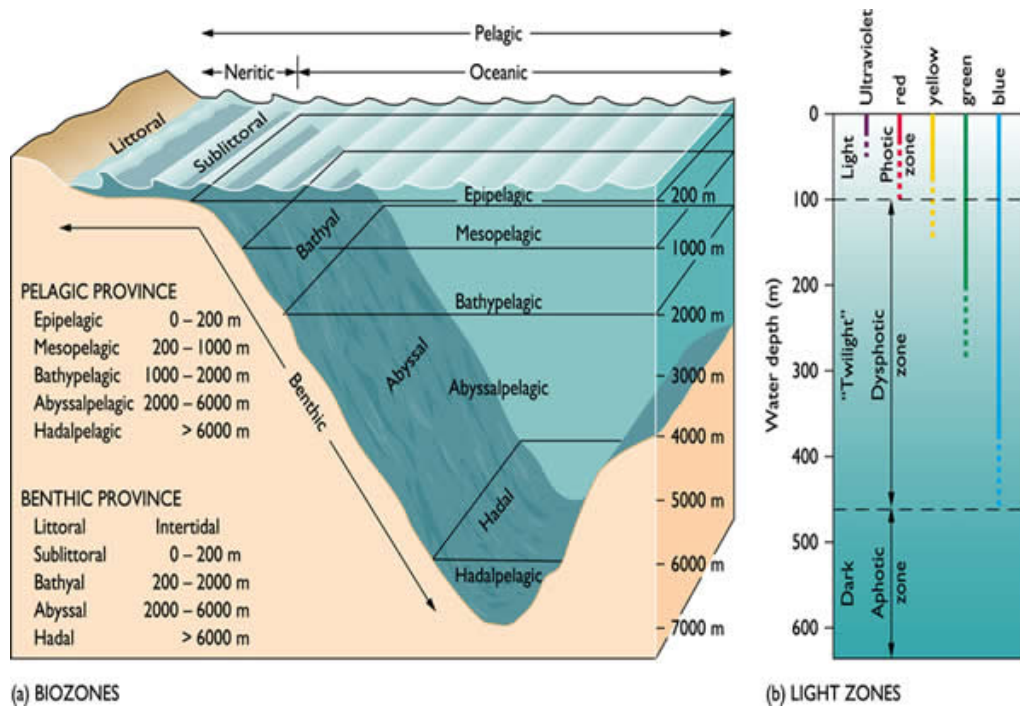


Figure 1-5 Ocean depth and light zones (retrieved from www.marinebio.org/oceans/light-and-color).

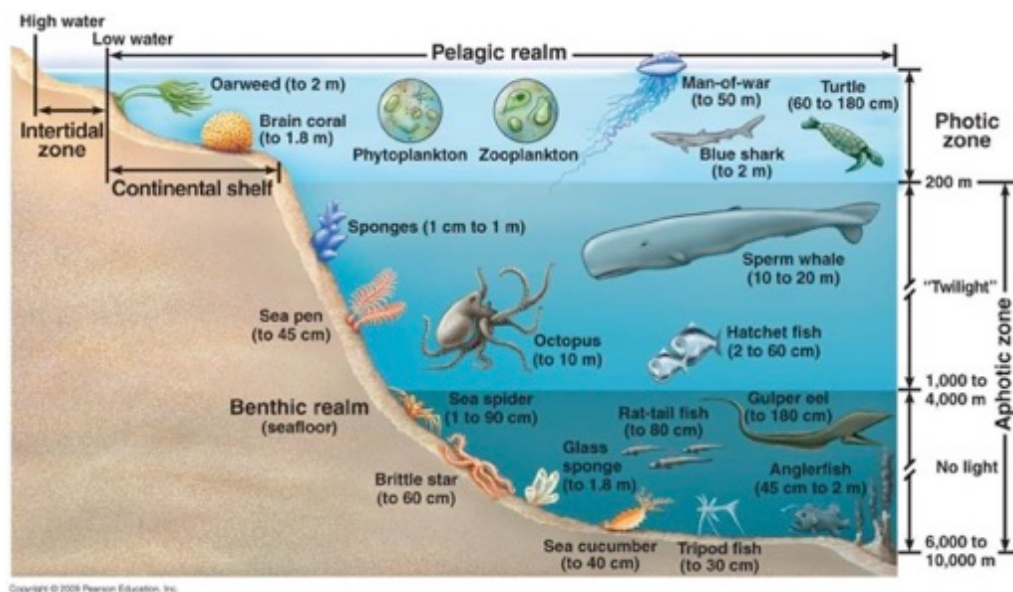


Figure 1-6 Ocean depth zones and associated representative fauna (© 2009, Pearson Education, Inc.).

Valuation of work at various depths must consider this variety of ecosystems, as well as the prevalence of particular zones, illustrated by the hypsographic curve of the earth's surface (Figure 1-7). The ocean depths also present engineering challenges, including pressure, salinity, and opacity to light, that impact the design of any undersea system.

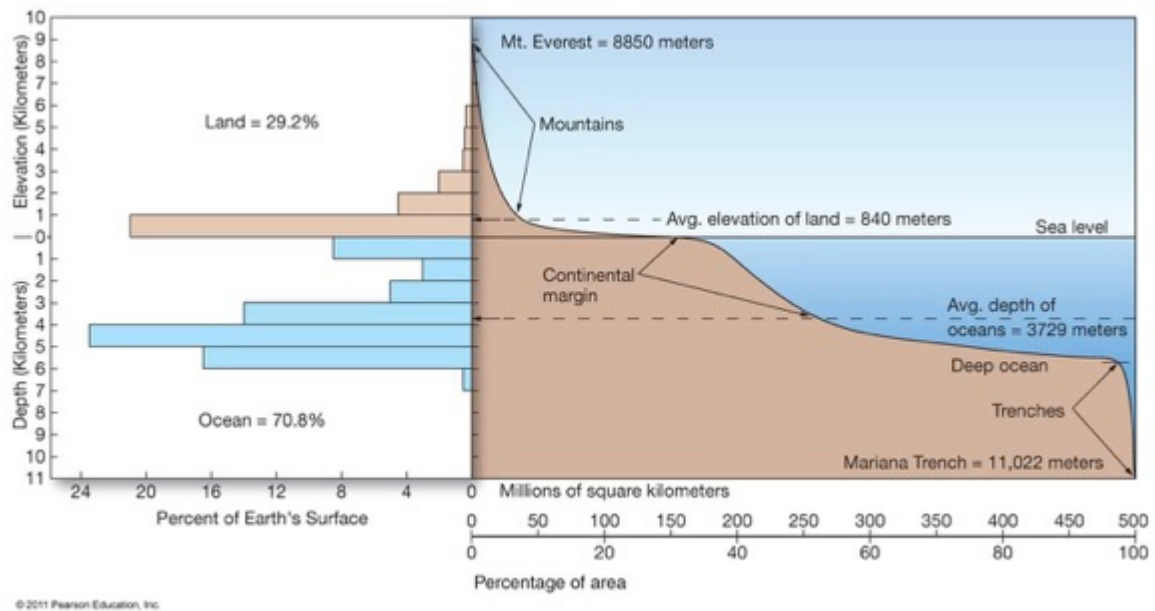


Figure 1-7 Hypsographic curve of earth's surface (© 2011, Pearson-Education, Inc.)

1.2.2 UNDERSEA MARINE RESEARCH INFRASTRUCTURE SYSTEMS

Undersea marine research infrastructure in its broadest sense is any device that collects data under the surface of a body of water, and includes a wide range of equipment that is referred to using a variety of terminology. The equipment may be

mobile or stationary, and be occupied by humans, remotely operated, or autonomous.

Figure 1.8 illustrates the types of systems and their general horizontal space and time limitations. Each category of system can be adapted to perform at various depths, with accompanying cost and performance differences and considerations (these will be discussed further throughout this study).

Undersea Marine Research Infrastructure

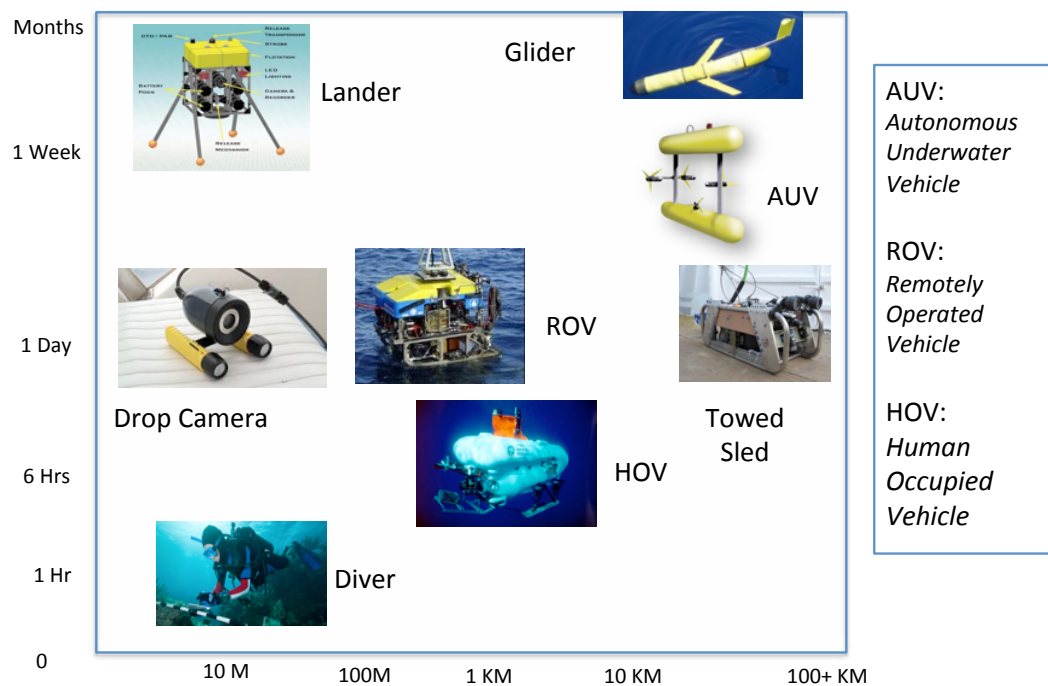


Figure 1-8 Examples of and typical operating scales for a variety of *in situ* undersea research systems.

The term ‘submersible’ may be used today to describe virtually any undersea system, but typically connotes a mobile undersea vehicle (manned or unmanned) (Mission Blue, 2013) that is used for research: “a small submersible boat or other craft, especially one designed for research and exploration” (Oxford English Dictionary, n.d.-b). Submersibles are distinguished from submarines in that submarines are larger and semi-autonomous (and often associated with military use) (Bluebird Marine Systems, 2013; Water Encyclopedia, n.d.). Historically, the term ‘submersible’ (and ‘submarine’) referred to human-occupied underwater vehicles; the evolution and variety of terminology for these vehicles merits some further discussion.

The terms ‘bathysphere’ and ‘bathyscaphe’ (“bathy” = deep, “scaphe” = ship) referred to early, less maneuverable submersibles - Beebe’s *Bathysphere* and *Trieste* (Forman, 1995). The U.S. Navy has applied ‘Deep Submergence Vehicle’, or DSV, to note a class of submersible (i.e. *Alvin* was officially DSV-2 (Naval Sea Systems Command, 2016)). The term ‘DSV’ is still occasionally used with respect to *Alvin*, but its supporting agencies implemented use of the term ‘human-occupied vehicle (HOV)’ as a conscientious effort to use more gender-neutral verbiage in the early 1990s (Managers B, C). The term ‘manned underwater vehicle’ or MUV, has been adopted by the Marine Technology Society (MTS) manned submersibles subcommittee because “HOV sounds like a car pool lane or any land/sea/air vehicle with people in it, which is in large part why MUV hasn’t gone to HOV” (Kohnen, 2016c); but this term is not frequently seen elsewhere. Since 2006, the NASA Style Guide has encouraged that “non gender-specific (e.g. human, piloted, un-piloted, robotic)” (Garber, 2015) references be used when

referring to the space program. The term “crewed” has begun to gain favor, but is resisted by some who note that it sounds like “crude” when spoken (Kohnen, 2016c; Plait, 2015).

Within this document, HOV will be used as the expression of choice because of its U.S. research origins, but historical descriptions in which the occupied sense is clear will retain the term ‘submersible.’

1.2.2.1 Human Occupied Vehicles

The history of human-occupied submersibles and their contributions to science is well documented in books and articles (Ballard & Hively, 2000; Busby, 1976; W. Forman, 1999; Geyer, 1977; Terry, 1966). Since 2000, the Marine Technology Society’s Manned Underwater Vehicle (MTS MUV) committee, which includes research, tourist, commercial, and private submersible interests, has maintained a database of international submersibles, hosted an annual series of manned submersible presentations at the MTS Underwater Intervention Conference, and published an annual summary of MUV activity (Kohnen, 2013, 2016a; MTS MUV Committee, 2016).

The temporal and spatial limits of HOV operations are typically less than 10 hours on site, and a few hundred meters of horizontal travel. With respect to depth, submersibles are typically divided into ‘deep’ and ‘shallow’ categories. A precise boundary between the two varies with the source – the Ocean Studies Board (2004) notes 1500 m as a technological divide, and uses 200 m to define “future needs in deep submergence science” (p.12).

After the introduction of Cousteau’s diving saucer *Denise* in 1959 and the Deep Submergence Vehicle (DSV) *Alvin* in 1964, submersible development and use expanded

through the 1970s to total more than 100 vehicles (Busby, 1975, Forman 1999). By the mid-1980s, industry had largely abandoned the use of manned submersibles, although a number of other countries developed research submersible capability at this time (France, Japan, Russia, Germany) (Walsh, 1990). Four U.S. research submersible operations were active in 1985, and continued to conduct marine science through 2010 and today. (Note: two U.S. Navy submersibles, the DSVs *Turtle* and *Seacliff*, and the Navy's nuclear powered submarine NR-1, were made available for research, but were all retired between 1997 and 1999 (W. Forman, 1999; Vyborny & Davis, 2004)). The four U.S. operations are:

- National Deep Submergence Facility (NDSF) at Woods Hole Oceanographic Institution (WHOI), which has operated *Alvin* since 1964 (Figure 1-9);
- Hawaii Undersea Research Laboratory (HURL), which has operated the *Pisces V* since 1985 and *Pisces IV* since 2000 (Figure 1-10);
- Harbor Branch Oceanographic Institution (HBOI), which operated the *Johnson Sea Link I/II* from 1971 and 1975, respectively, until 2009 (Figure 1-11); and
- Delta Oceanographics, which operated the *Delta* submersible from 1982 until 2009 (Figure 1-12).

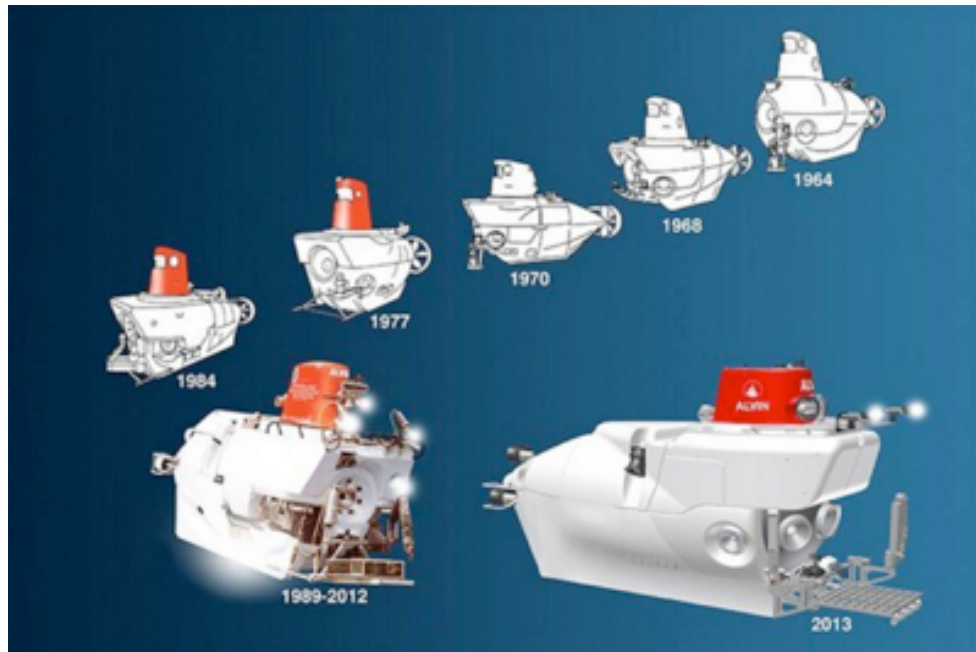


Figure 1-9 Evolution of the *Alvin* submersible (Illustration by E. Paul Oberlander, Woods Hole Oceanographic Institution).



Pisces IV



Pisces V

Figure 1-10 *Pisces IV* and *V* submersibles (Hawai'i Undersea Research Laboratory).



Figure 1-11 *Johnson Sea Link* submersible (Photograph by Liz Baird).

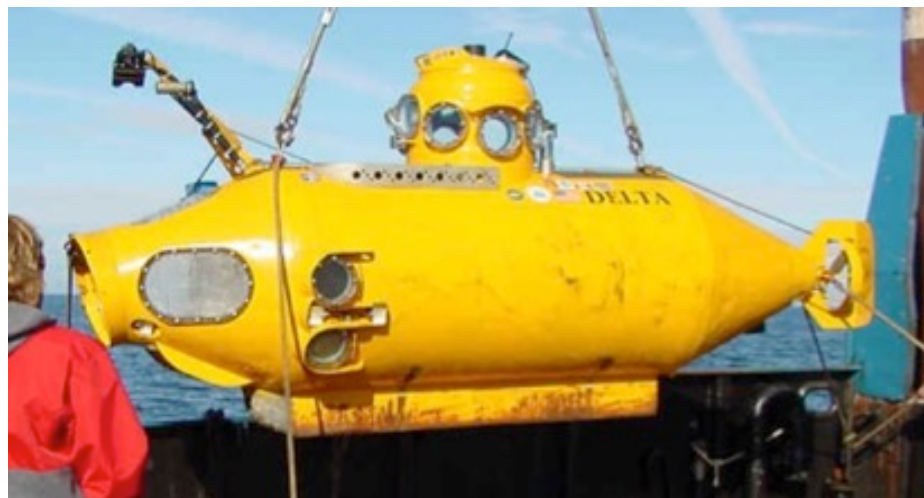


Figure 1-12 *Delta* submersible (NOAA Alaska Fisheries Center).

Internationally, four government-sponsored submersibles (German *Jago*, Japanese *Shinkai 6500*, French *Nautilus* and Chinese *Jialong*) still conduct marine research (Kohnen, 2016a). Canadian entrepreneur Phil Nuytten has been developing, building and operating small submersibles (including *Aquarius/Curasub*, *Deep Rover*, and one- or two-man *Deep Worker* models) and one-atmosphere diving suits (*Newtsuit*, *Exosuit*) for industry, research, and filmmaking for more than 40 years (Nuytco Research, Ltd., n.d.) (Figure 1-13).

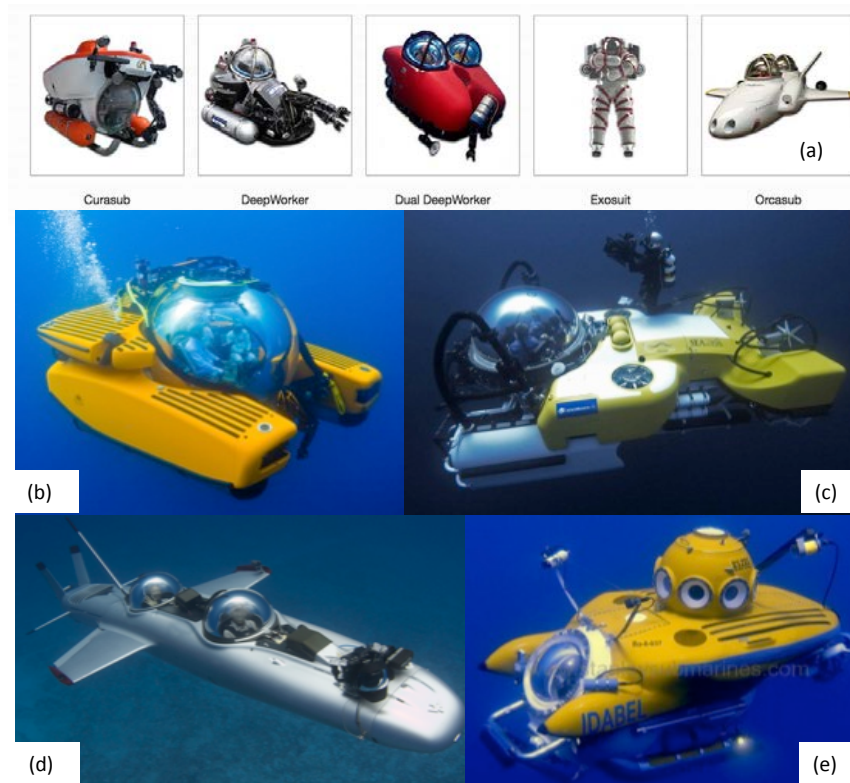


Figure 1-13 Examples of private submersibles: a) Nuytco submersibles (www.nuytco.com); b) Triton's *Triton 3300/3* (www.triton.com); c) SEAmagine's *Deepsee* (www.seamagine.com); d) DeepFlight's *Super Falcon Mark II* (www.deepflight.com); e) Stanley Submarine's *Idabel* (www.stanleysubmarines.com).

A number of privately owned submersibles are also active in conducting research missions. These include the *Idabel* in Roatan, Honduras (Stanley, 2016), SEAmagine's *Deepsee*, operated in Costa Rica by Undersea Hunter (Aburto-Oropeza, Caso, Eisman, & Ezcurra, 2011; Undersea Hunter, n.d.-b), and Triton submersibles used during private expeditions sponsored by Project Baseline, the Nekton Mission, and onboard the private vessel *M/V Alucia* (with *Deep Rover 2*) (Alucia, 2016; Global Sub Dive, 2015; Nekton Mission, 2016). Innovative 'flying submersibles,' developed by engineer Graham Hawkes, are available from his DeepFlight company and from Nuytco Research Ltd, but as yet have seen limited scientific use (DeepFlight, n.d.; Nuytco Research, Ltd., 2016; Nuytten, 2009; The Engineer, 2012) (Figure 1-13).

1.2.2.2 Remotely Operated Vehicles

Like HOVs, remotely operated vehicles, or ROVs, were initially developed primarily by the U.S. Navy, and used extensively in the oil and gas industry for inspection, construction and repair. Today, more than 50 companies produce hundreds of ROV models (Borne, 2015; Ocean News and Technology, 2016). ROVs are classified by size, depth, power, and purpose, and categories vary (Borne, 2015; Christ & Wernli, 2013; MTS ROV Committee, 2016b). Christ & Wernli (2013) describe "Observation Class" (<200 lbs., 300 m depth, low voltage), "Mid Size" (>200 lbs., >1000 m depth, medium voltage), and "Work Class" (>200 lbs., >3000 m, high voltage) vehicles; the Unmanned Vehicles Buying Guide lists "Light", "Medium", "Heavy", and "Inspection/Observation Workclass" ROVs with no specified limits for each classification.

The science community began using ROVs in the mid-late 1980s, with International Submarine Engineering, Ltd. (ISE)'s *ROPOS* (purchased by Canada's Department of Fisheries and Oceans in 1986 (Shepherd & Juniper, 1997)) and *Ventana* (purchased by the Monterey Bay Aquatic Research Institute in 1988 (MBARI, 1997)) ROVs. The first ROV to be developed and built at an academic institution, the *Jason*, launched at Woods Hole in 1988 (Ballard & Hively, 2000) (Figure 1-14).

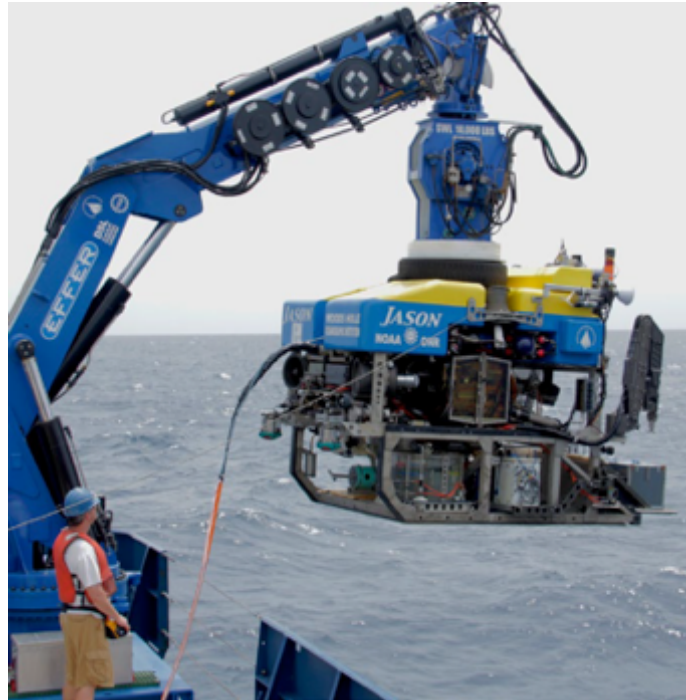


Figure 1-14 The *Jason* Remotely Operated Vehicle (Woods Hole Oceanographic Institution).

Today, new versions of each of these ROVs continue to operate for research, and are joined by the *Hercules* ROV of the Nautilus Exploration Program, the National

Oceanic and Atmospheric Agency (NOAA)'s Office of Ocean Exploration's *Deep Discoverer (D2)*, the University of Connecticut's *Kraken2* (Figure 1-15), and the University of Hawaii's *Lu'ukai*.

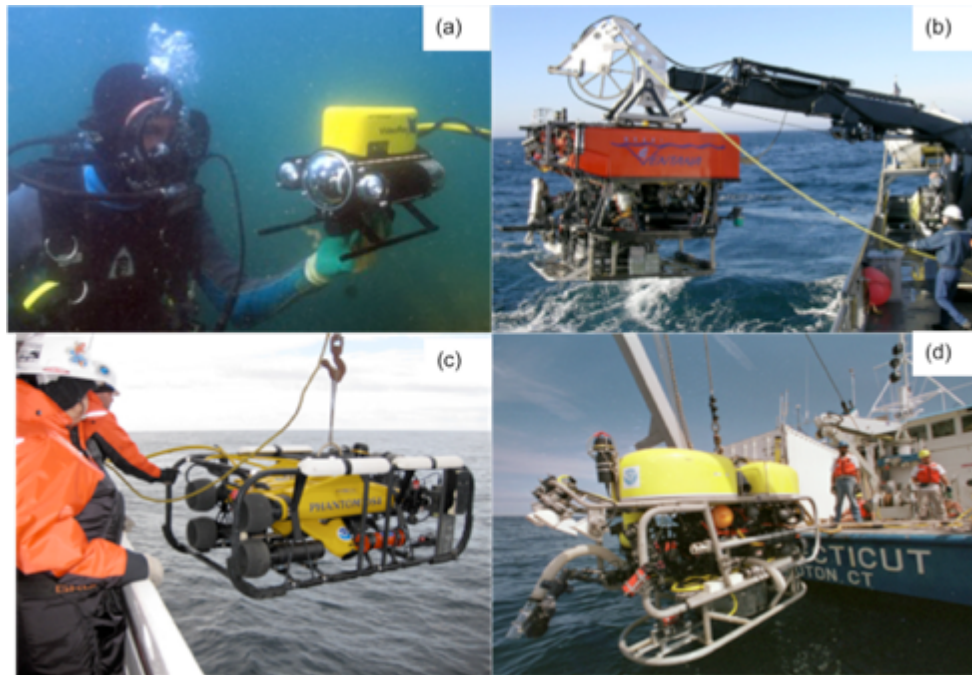


Figure 1-15 Examples of ROVs used for science: a) a small Video Ray ROV (www.PRWeb.com); b) MBARI's *Ventana* (www.mbari.org); c) an observation class *Phantom* ROV used by NOAA fisheries (www.swfsc.noaa.gov); d) the University of Connecticut's *Kraken 2* (www.uconn.edu).

NOAA's Undersea Research Program (NURP) began supporting use of observation class ROVs for research in the late 1980's. Overall, research ROVs began to become operationally established in the late 1990's and have continued to mature in capability (Auster, 1997; MBARI, n.d.-a; Shepherd & Juniper, 1997; Wagner, Randall, & Albaugh, 2000; Woods Hole Oceanographic Institution, 2016d). Small and medium

observation-class ROVs are found in numerous academic and federal marine research centers. Several small ROV manufacturers have estimated that 10% of their vehicle sales are for scientific use (Video Ray, Outland, SeaBotix, & Shark Marine Technologies, 2013) (Figure 1-15).

1.2.2.3 Other undersea technologies

Autonomous undersea vehicles have become extremely capable since they began commercial operations in the 1990s (Blidberg, 2001). The typical commercially available AUV is a torpedo-like vehicle programmed to ‘fly’ a specific course underwater, collecting sonar bathymetry and other low-powered sensor data (Borne, 2015; Wynn & Linley, 2013). Within the data collection niche, AUVs, especially the *Seabed* and *Sentry* AUVs built at Woods Hole Oceanographic Institution (Singh et al., 2004; Woods Hole Oceanographic Institution, n.d.), have been used to regularly collect visual data in slow survey modes (Marouchos, Muir, Babcock, & Dunbabin, 2015; Wynn et al., 2014), but the use of AUVs for the on-site sampling or stationary work enabled by HOVs and ROVs has not yet become common (Figure 1-16). New autonomous intelligence and optical technologies are beginning to provide more capability in this realm (Farr, 2013; Kantor, Fairfield, Jonak, & Wettergreen, 2008).

Other means of retrieving biological and geological information from the undersea environment include the use of towed vehicles such as dredges or camera sleds; drop-corers and cameras, which remain tethered to the ship, and are deployed while the ship is stationary; and a device known as a lander, which is deployed from a ship untethered, and rests on the bottom unattended until it is recovered (Figure 1-17).

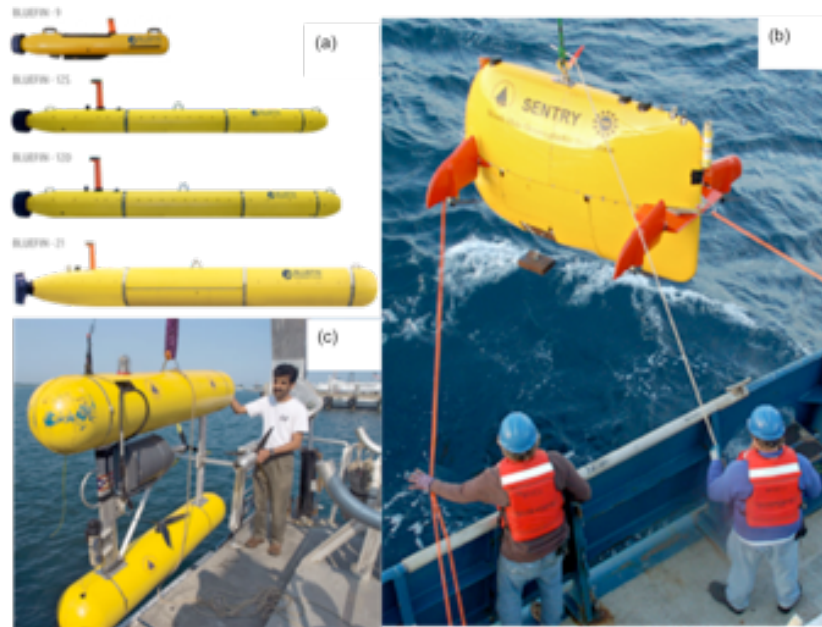


Figure 1-16 Autonomous Underwater Vehicles: a) Bluefin Robotics AUVs (www.cpmas.com/auv/bluefin-auvs); WHOI's b) *Sentry* (www.whoi.edu/main/sentry); and c) *Seabed* (www.whoi.edu/main/seabed) vehicles.

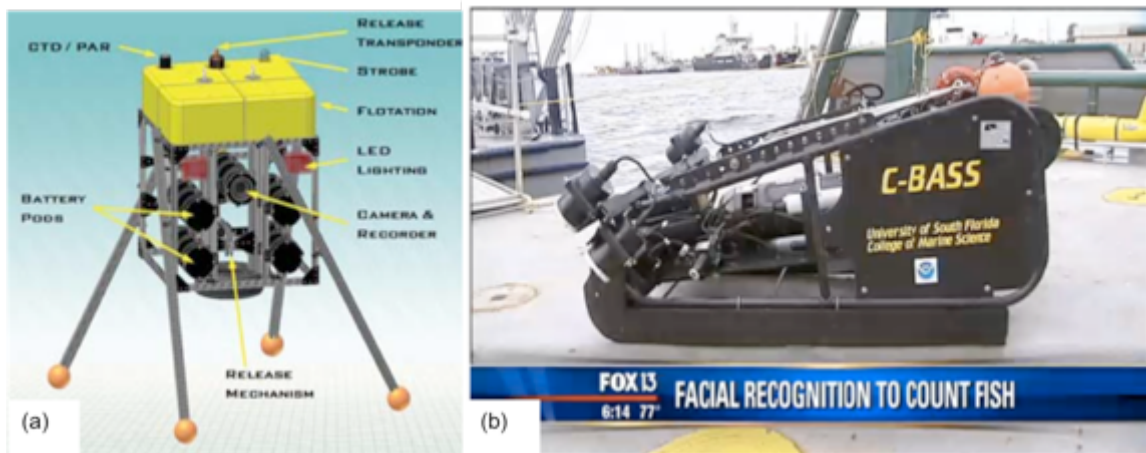


Figure 1-17 a) The *Medusa* underwater lander (www.sea-technology.com); b) the University of South Florida's *C-Bass* underwater camera sled (<https://eyesfinder.com/man-fish-sea>).

1.3 ASSESSMENT METHODS

Assessment of the U.S. national oceanographic research enterprise—its science priorities and infrastructure needs—has been addressed primarily through multi- and single agency studies since establishment of the first National Academy of Sciences Committee on Oceanography in 1927 (Bigelow, 1931). These studies have used top-down, portfolio-scope assessment methods, and face the challenges of scientific choice and value proposition analysis that have been identified and described in the literature (summarized below). This may in part be a result of Navy and scientific acceptance of the axiom that requirements drive the development of tools, and exacerbated by an impatience with the compromises of cost-effectiveness considerations in the face of a ‘this is needed, therefore cost is irrelevant’ mentality (Manager A).

An alternate approach, seen in lifecycle management practices (for individual equipment and classes of equipment) and the field of Science and Technology Studies (for broader technology issues) (Hackett, Amsterdamska, Lynch, & Wajcman, 2008), is a bottom-up examination of the factors that influence the success or failure of a particular technology. This approach has not been common in the marine research community, and is the basis for the quadrant model introduced here.

1.3.1 SCIENTIFIC CHOICE

The roots of U.S. discussion of national research prioritization can be found in Alvin Weinberg’s classic “Criteria for Scientific Choice” (Weinberg, 1962). Here, Weinberg identifies two criteria for making scientific choices, external and internal.

External criteria address the question, “why should the science be done” and should consider social, technological and scientific merit. Internal criteria, which answer the question, “how well is the science done,” include considerations of readiness of the field for exploitation and competence of the scientists. With respect to actually making choices based on these criteria, however, Weinberg recognized that many factors work against resolution: the resistance of human nature to name a ‘loser’; the comparative ‘free play’ of the federal budget process; a decrease of will to prioritize when funding is plentiful; and an overall attitude that any support of science is more useful than our larger wasteful expenditures (he notes smoking, advertising, and gambling), so prioritization is ‘silly’ (Weinberg, 1962).

Later studies added to Weinberg’s prioritization criteria (Committee on Science, Engineering and Public Policy, 1933; National Academy of Sciences, 1988; Press, 1988a; U.S. Congress, Office of Technology Assessment, 1991) but the assumptions for successful execution of these criteria remained under debate. Foremost among these assumptions are: (1) the ability of academic panels to judge and “stand behind conclusions” across disciplines (Teich, 1994; Weinberg, 1962); and (2) the ability of policymakers in Congress and the Executive Branch to “respond to recommendations from these groups in a rational and consistent manner” (Teich, 1994, p.103). Frank Press (1988), then president of the National Academy of Sciences, identified other arguments against research prioritization: “no one in the scientific community is wise enough to set priorities among fields;” and “to propose a list of priorities will only serve to divide our community and to insure a reduced budget” (Press, 1988b, p. 641).

For the past two decades, research prioritization has also been considered within the activities mandated by the Government Performance and Results Act (GPRA) of 1993, aimed at improving the overall management of the federal government through required annual strategic and performance plans and reports, and the development of specific goals and metrics (Office of Management and Budget, 1993). Although not a prioritization scheme *per se*, GPRA provides requirements for agencies to conduct assessments that guide budget decision-making in a similar way. The National Academy of Science's Committee on Science, Engineering and Public Policy (COSEPUP) addressed this challenge with a study to identify the most effective ways to evaluate the results of research, aid the federal agencies in implementation of GPRA, and develop mechanisms to evaluate the effects of GPRA on research practices. Their recommendations for assessing basic research included the Weinberg (1962) concepts of internal (quality) and external (relevance) merit, and added the idea of leadership merit, i.e. the degree to which the work establishes the United States as a world leader in research (Committee on Science, Engineering and Public Policy, 1999). To date, the level of detail of agency GPRA efforts has been insufficient to inform a study at the granularity of manned and unmanned undersea research equipment. Overall, the success of the GPRA effort is still unproven (Breul, 2007) and under discussion at the Congressional level (Brass, 2012).

A related avenue of assessment is that of public value, as described in the scholarship of Moore (Moore, 1997, 2013). The National Research Council's Committee on Human Spaceflight recently reviewed Moore's work as part of their charge to describe

“the expected value and value proposition of NASA’s human spaceflight activities in the context of national goals” (Space Studies Board, 2014, p. xi). Defining a value proposition as a “statement of the benefits or experiences being delivered by an organization to recipients, together with the price or description of the resources expended for them,” the Committee found that Moore’s Public Value Account (PVA) and Public Value Scorecard (PVS) (2013) techniques lacked the ability to capture the complexities of tradeoffs among priorities. Ultimately, they concluded that “...the challenges (of developing and applying value-proposition analysis at the agency level) may help to explain the absence of any value-proposition analysis of other federal science and technology programs...For the reasons described above, a rigorous analysis of the value propositions for NASA at the national level is beyond the capacity of this report—possibly of any report” (Space Studies Board, 2014, pp. 71, 76).

1.3.2 U.S. OCEANOGRAPHIC RESEARCH PRIORITIZATION

Despite these challenges, the ongoing work of science prioritization provides valuable guidance. The U.S. Administration’s Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB) are responsible for coordinating and providing Federal Research and Development (R&D) budget and priority information to the President (OSTP, 2016). An annual Memorandum for the Heads of Executive Departments and Agencies relays these priorities to federal agency leaders, and provides a measurement of the importance of general ocean research topics as compared to other national research needs (Donovan & Holdren, 2015).

National-level ocean priority studies have been conducted since the first National Research Council Committee on Oceanography was formed in 1927 (Bigelow, 1931) (See Appendix 1). Oceanography is one of the most federally-dispersed research fields in terms of agency responsibility; programs within the Navy, NOAA, the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), Department of the Interior (DOI) and others are all mandated, authorized, and funded by Congress to conduct research into various fields of marine science and oceanography (Watkins, 2004).

This distributed nature has resulted in a rich history of federal and academic coordination initiatives highlighted by the 1959 establishment of an Interagency Committee on Oceanography (ICO) (CQ Almanac, 1966), the National Advisory Committee on Oceans and Atmosphere (NACOA) (Hollings & Magnuson, 1971) and today's National Ocean Council (Executive Order 13547, 2010). The academic committee established in 1970 to address the challenges of coordinating the ocean infrastructure required for this work, the University National Oceanographic Laboratory System (UNOLS), continues to actively provide this function today (Ocean Studies Board, 2000a).

Each federal agency also produces periodic research strategies that provide indications of the relative importance of ocean research areas to different factions of the U.S. marine science community (Bureau of Ocean Energy Management, 2016; NOAA, 2013b; Office of Naval Research, 2015; Space Studies Board, 2007), and also often discuss research infrastructure challenges and priorities. Strategic documents developed

within research disciplines or programs, for example, NOAA’s Coral, Deep Sea Coral, Fisheries, and Ocean Acidification research plans (Puglise & Kelty, 2007; NOAA, 2010a; Interagency Working Group on Ocean Acidification, 2014; Merrick, 2013) typically provide more specific research goals to use for evaluation of the relationship between infrastructure and the research data needed.

1.3.3 OCEAN INFRASTRUCTURE ASSESSMENTS

The Bigelow (1931) National Academy of Sciences Committee on Oceanography report included consideration of ships and laboratories as supportive oceanographic research infrastructure; since then, ocean infrastructure has been assessed both as a suite of capability, and in system-specific efforts (e.g., ships, ocean observing systems). Significant coordination and attention has been applied to maintaining a national research vessel fleet, which has incorporated life cycle management techniques into its planning (Interagency Working Group on Facilities, 2007; Ocean Studies Board, 2009; UNOLS, 2015a, 2016).

United States national-level assessment of the value of undersea technology assets for oceanography began shortly after the first successful operational dive of the deep submersible *Trieste* (Committee on Oceanography, 1959, p. 196; Committee on Undersea Warfare, 1957). “Chapter 7: Engineering Needs for Ocean Exploration” of the first comprehensive U.S. assessment of oceanographic research and infrastructure (Committee on Oceanography, 1959) included a “Proposed Program for Deep Manned Vehicles” (National Research Council, 1959, p. 7-2). Whereas undersea marine research infrastructure has been a component of many overall oceanographic studies since then, it

has also been the focus of studies conducted by University National Oceanographic Laboratory System (UNOLS) and its DEep Submergence Science Committee (DESSC); the National Academy of Sciences' Ocean Studies Board (OSB); and other federal organizations (Appendix 1).

In the national oceanographic enterprise, marine research conducted with undersea vehicles has been referred to as 'submersible science' and 'deep submergence science,' but no established definition for these terms has been adopted. The mandate for an early UNOLS Submersible Science Study (1982) was to examine the "requirements for a national technical facility which gives access to the ocean from submerged 'manned' vehicles [with] sufficient breadth for consideration of alternative and complementary 'unmanned' submersibles" (UNOLS, 1982, p.2). Eight years later, one of the principal objectives of the next UNOLS submersible science study included: "Assess the trends, patterns, and directions for academically-based ocean science research programs that can be best served by submersible systems, both manned and unmanned... to cover the full range of depth requirements needed by science" (UNOLS, 1990, p.1). The most recent National Academy study dedicated specifically to national submergence science infrastructure, conducted in 2004, was tasked to "assess...capabilities of occupied and unoccupied vehicles... [and] make recommendations regarding the mix of vehicles needed..." Its mandate focused on evaluation of "future directions and facility requirements for deep submergence science" and defines the deep sea scientifically as beginning at the lower limit of the epipelagic zone (150–200 m), and operationally as

1,500–2,000 m, “based primarily on the depth capabilities of *Alvin* and *Jason II*” (Ocean Studies Board, 2004, p. 12).

The charge to the most recent DESSC workshop reflects an approach that has been generally consistent in each of these studies: “the objectives will be to 1) define the critical scientific research themes to be emphasized in the next decade, 2) to specify the scientific questions to be addressed and to define strategies needed to approach answers to these questions, and 3) to define what technological approaches are needed to carry out these objectives” (DESSC, 2016b, "Background" section).

1.3.4 OPERATIONS RESEARCH-INFORMED METHODS

The discipline of operations research (OR), which “deals with the application of advanced analytical methods to help make better decisions” (INFORMS, 2016), offers a broad range of mathematical, statistical, and managerial techniques that address value judgments. Within the U.S. marine research enterprise, two examples were found at the agency level of application of methods from the OR fields of Multiple Criteria Decision Making (MCDM), i.e., “the study of methods and procedures by which concerns about multiple conflicting criteria can be formally incorporated into the management planning process” (International Society on MCDM, 2016); and Portfolio Management, which is “the art and science of making decisions about investment mix and policy, matching investments to objectives, asset allocation for individuals and institutions, and balancing risk against performance” (Investopedia, 2003). These are, respectively, the National Research Council’s “Sea Change: 2015-2025 Decadal Survey of Ocean Sciences” (Ocean

Studies Board, 2015) and NOAA’s Observing System Integrated Analysis (NOSIA-II) (Office of Technology, Planning and Integration for Observation, n.d.).

1.3.4.1 Multiple Criteria Decision Making

The most recent U.S. Ocean Studies Board (2015) assessment of ocean research infrastructure, which addressed NSF’s Division of Ocean Sciences (OCE) activities, used an MDCM technique, the Analytical Hierarchical Process, to identify ocean research priorities (Briscoe, 2013; E. H. Forman & Gass, 2001), and developed an alignment matrix that ranked infrastructure systems with research priorities (Table 1.1).

		Sea level change	Coastal and estuarine oceans	Ocean and climate variability	Biodiversity and marine ecosystem	Marine food webs	Ocean basins	Geohazards	Subseafloor environment
Fleet and Other Ships	Global Ocean	C	I	C	C/I	C/I	C	C	C
	Regional/Coastal	I	C	C/I	C	C			
	3-D Seismic Ship						C/I	C	I
	Ice-Capable	C/I	I	C	C/I	C/I	I		
RODP	JOMDES Revolution	I		I			C	C	C
OOI	Coastal	I	I	I					
	Global			I					
	Cabled						I	I	I
Vehicles	AUVs				I	I			I
	ROVs						I	I	C
	AUVs		I		I	I	I		
	Glinters	I	I	I	I				
Other	OBSs						I	C	
	Field Stations / Marine Labs	I	C	I	C	C/I			
Other Critical or Important Infrastructure Assets		Argo, tide gauges, satellites, ice-ocean models, coring facilities and core repositories, mission-specific drilling platforms (MSPs)	River gauges, hydrologic models, satellites, coring facilities and core repositories	Argo, modeling, surface weather analyses, satellites, coring facilities and core repositories, acoustic tomography, MSPs	Fisheries surveys and vessels, sequencing facilities, manned/unmanned vehicles, satellites	Fisheries surveys and vessels, taxonomy, isotope facilities, manned/unmanned vehicles, satellites	Global seismograph arrays, magnetotellurics, manned/unmanned vehicles, Chilly, MSPs	Interferometric synthetic aperture radar, surface geodesy, satellites, magnetotellurics, coring, manned/unmanned vehicles, Chilly, MSPs	Sequencing facilities, manned/unmanned vehicles, Chilly, MSPs

Table 1.1 Alignment of NSF-funded major ocean research infrastructure to decadal science priorities. Priorities are along the top axis, with infrastructure type along the vertical axis. ‘C’ indicates a critical asset, and ‘I’ indicates an important asset. See text for further explanation (2015, Ocean Studies Board, p.42).

Limited to selection of “10 or fewer” questions or priorities, the committee identified eight marine research questions that were listed not by priority, but presented from ocean surface to sea floor (Ocean Studies Board, 2015). The committee then used four “categories of alignment”— critical, important, supportive, or not relevant—to conduct cross-matrix assessments of the eight research questions and the specific OCE infrastructure investments. The process involved two steps: the committee first formed research priority subgroups and evaluated each infrastructure type’s contribution to each goal; and then formed infrastructure subgroups, and appraised the importance of each infrastructure system to each research priority (Ocean Studies Board, 2015, p. 42).

1.3.4.2 Portfolio management

At NOAA, a portfolio management assessment of environmental data collection infrastructure as related to mission needs is being conducted on an Earth-observing scale. The NOAA Observing Systems Integrated Analysis, or NOSIA-II, “is a capability used to document the relationship between available observing systems and their impact on NOAA’s diverse services and scientific objectives” (NOAA NOSC, 2015, p. 7).

Although the effort is primarily product-focused, it will also address the value of research activities, including research supported by *in situ* marine research infrastructure.

NOSIA-II uses a value-tree approach (Figure 1-18) to link strategic goals to products to data sources to observing systems (NOAA NOSC, 2015, 2016). Subject matter experts rank the value (expressed as numerical scores) of components of each tier to the components of the next tier in the hierarchy.

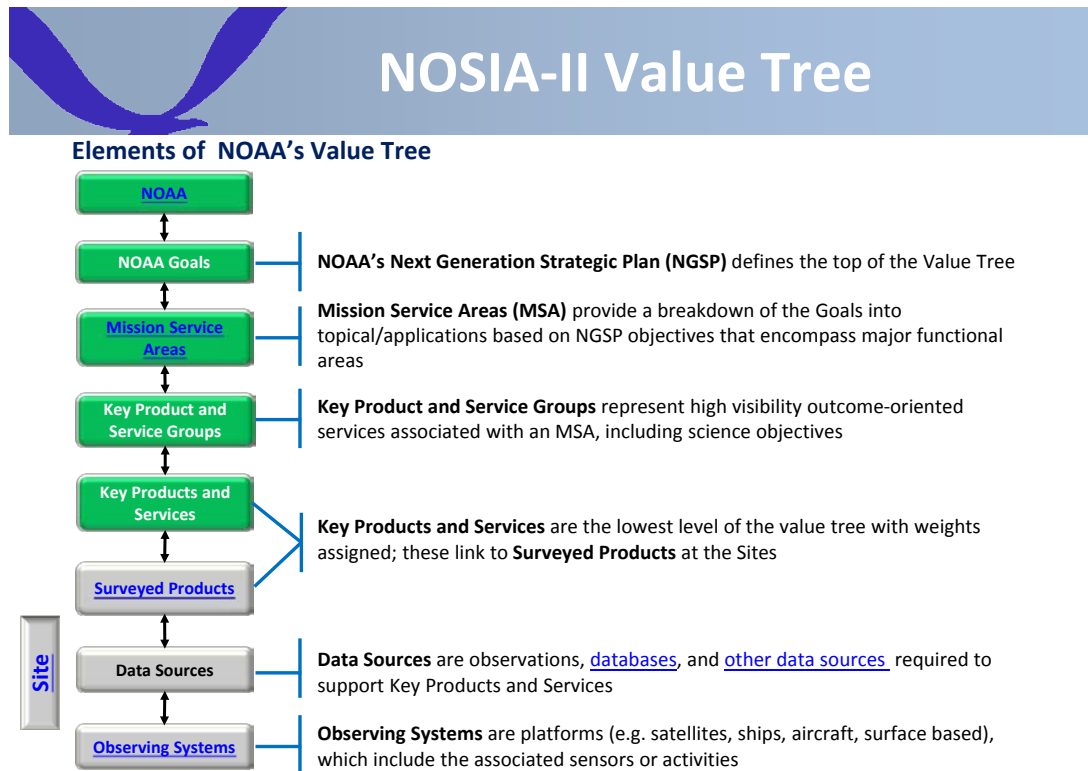


Figure 1-18 NOAA NOSIA-II Value Tree (<http://nosc.noaa.gov>).

These scores are entered into the Portfolio Analysis Machine (PALMAtm) computer program, which provides a “visualization of the hierarchy of objectives” as well as a portfolio of investment options (Moynihan, Reining, Salamone, & Schmidt, 2009). The effort has not yet led to results at the level of resolution of the UMRI examined here, but it does provide a potential method for future work (Cantrell, 2015).

1.3.5 LIFE CYCLE MANAGEMENT APPROACH

The above methods assess infrastructure systems in terms of their value to the suite of activities, or requirements, for which they are used. An alternative approach,

found in technology development and life cycle management practices, is to examine factors that impact the success of a particular system or group of systems. This avenue is explored here using the concepts of obsolescence, replaceability, and sustainment.

1.3.5.1 Obsolescence

A classic work on technology maturity by William L. Nolte (2008) of the Air Force Research Laboratory illustrated the Technology Life Cycle as a “Whale Chart,” (Figure 1-19), named after how the charted shape of usefulness of technology changes with time. The early stages of this diagram are relatively well studied, and include technology development assessment tools such as technology readiness levels (TRL) developed by NASA (Mai, 2015), and Technology Readiness Assessments (TRA) conducted by the Department of Defense (Assistant Secretary of Defense for Research and Engineering, 2011). The suite of undersea research infrastructure, however, includes many technologies that are in the later stages, or head of the Whale; a region that is less studied (Business Dictionary, n.d.-b; Campbell, 2009; Kasser, 2015; Nolte, 2008). Nolte (2008) acknowledges that: “there is a serious need to do research work that would extend technology maturity measurement beyond the tail. We all would benefit from the availability of tools that could help us not only react to product or technology obsolescence, but also predict and anticipate problems in the body and at the head of the whale” (Nolte, 2008, p. 120).

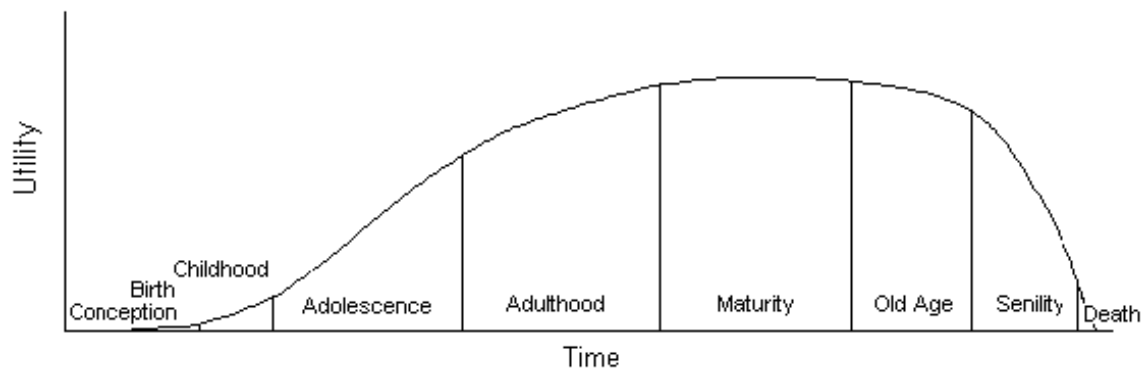


Figure 1-19 Stages of technology maturity—the Whale Chart (Nolte, 2008).

Technology historian Scott M. Campbell (Campbell, 2012) also encourages further study of the later stages of technology maturity:

Depending on the point of view, an obsolete technology can be perfectly usable and acceptable for decades. Technological diffusion is never instantaneous, but an upward sloping curve of acceptance over time. Unfortunately, historians of technology have notoriously ‘skewed towards studies of the origins of technological change and not to its results,’ and those behind the curve are often forgotten. Yet, when old replaces new, the now-obsolete technology provides the framework by which new and would-be users evaluate and interpret its replacement. The stories and perspectives of those who are otherwise ‘lagging behind’ can unlock many mysteries for historians. (p. 120)

The definition of ‘obsolete’ according to the Oxford English Dictionary includes: “No longer used or practiced; outmoded, out of date; worn away, effaced, or eroded;” and

“a thing which is out of date or has fallen into disuse” (Oxford English Dictionary, 2016). A Google query of ‘obsolete’ reveals that the basic definition is the discontinued use of something, with descriptors as to why the product is obsolete: a new product has superseded the old; the function it performed is no longer needed (e.g., the use of buggy whips to control horses pulling carriages); supporting components are no longer available; it has gone out of fashion; or it has worn out and can’t be fixed. ‘Obsolescence management’ tends to refer to component replaceability issues that are common in the avionics, rail transit systems, electronics, information technology, and similar industries (Amin, 2015; de Witte & Tauss, 2016).

One avenue of obsolescence management, however, includes a full-spectrum assessment of factors that influence a state of inactivity—that of management of buildings (Building Research Board, 1993). An assessment initiative within this field, a quadrant model developed by researchers at Delft University, Netherlands (Thomsen & van der Flier, 2011), presents a promising approach for UMRI assessment that will be developed further in this study.

1.3.5.2 Replaceability

The maturation of the robotics industry has brought a similar but slightly different angle to the technological supersession aspect of obsolescence, called ‘replaceability,’ that considers whether a new technology is *able* to, or *should* replace an old capability. Michael Decker (2000, 2006) (Decker, 2000, 2006) of the medical robotics profession has proposed an assessment framework of technical (means-end); economic (cost-benefit); legal (liability); and ethical (‘should’) replaceability. A similar categorization is

seen in building obsolescence studies (Building Research Board, 1993). Economics analysts have developed metrics to capture the technical replaceability of robots so that jobs and economic workforce impacts may be quantified. Along the ethical replaceability lines, a 2008 communications study entitled “Beyond Dirty, Dangerous and Dull: What Everyday People Think Robots Should Do,” found that “...Public opinion favors robots for jobs that require memorization, keen perceptual skills, and service-orientation. People are preferred for occupations that require artistry, evaluation, judgment and diplomacy” (Takayama & Ju, 2008, p.25).

When investigating the replaceability of HOVs, the question “Why Man?” leads to a broader discussion that encompasses the purpose of the activity, as well as the progressive development of ever improving technologies. These purposes range from subjective ‘inspirational’ goals to the practical side ‘dull, dirty and dangerous’ tasks that have long been targeted for robotic replacement—especially by military and industry—where an unmanned system can assemble an automobile, mine for coal, or diffuse a bomb with greater safety and efficiency than a human (General Electric, n.d.; Takayama & Ju, 2008). For ocean, space, and earth science activities, this range of considerations can be conceptually illustrated in Figure 1-20.

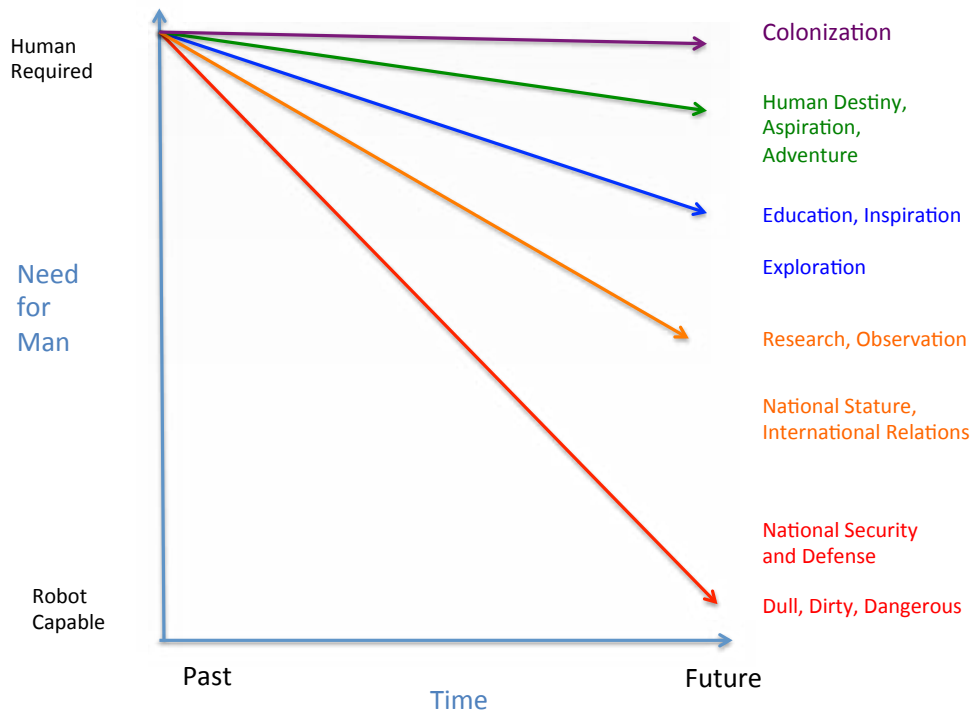


Figure 1-20 Conceptualization of robotic progression by task.

Ultimately, however, neither obsolescence nor replaceability is a consistently linear consideration: "... what makes something better is often highly contextual. Depending on the point of view, an obsolete technology can be perfectly usable and acceptable for decades. Technological diffusion is never instantaneous, but an upward sloping curve of acceptance over time" (Campbell, 2009, p.120). An online Google search illustrates this point with various popular lists of 'technologies that refuse to die' (Piltch, 2013) and even those that 'technology will never make obsolete' (e.g., duct tape, cast iron pans, Swiss army knives) (Catalog, 2014).

1.3.5.3 Sustainment

This continuum of obsolescence discussed above suggests consideration of a differently nuanced approach, one that can capture the factors that lead to the ability of system to endure in a useful capacity, i.e., to sustain or “keep in existence; maintain, continue, or prolong” (Free Dictionary, n.d.) operations. The term ‘sustainment’ is selected here instead of the term ‘sustainability’ in order to distinguish it from the environmental, economic, and social sustainability (Thwink.org, n.d.) sense of the term.

According to Merriam Webster (2016), sustainable is an adjective that means: “1) able to be used without being completely used up or destroyed; 2) involving methods that do not completely use up or destroy natural resources, and 3) able to last or continue for a long time.” The Department of Defense, which considers sustainability analysis as part of its Defense Acquisition Systems Engineering guidelines, notes that: “‘Sustainability’ differs from ‘sustainment’ in that it relates to the use of resources, and the associated impacts and costs over the system’s life cycle. In contrast, sustainment is more concerned with the end user’s ability to operate and maintain a system once it is in inventory and deployed” (U.S. Department of Defense, 2016, section 4.3.19.2). This ‘sustainment’ meaning is most applicable to undersea research technology assessment that is addressed here. (Note: the concept of ‘supportability’ was also investigated for use here, but has a limiting connotation as a design characteristic. Defined as the “degree to which the design characteristics of a standby or support system meet the operational requirements of an organization,” it is used in military sustainment field to mean “the ability to restore

a failed system back to its operational state as quickly and effortlessly as possible” (Mathaisel, Manary, & Comm, 2009, p. 177)).

The model that is developed for this study was discovered within the field of obsolescence assessment research, but the question for this study is not ‘Is a particular undersea research system obsolete?’ but rather, ‘What are the factors that lead/have led to the obsolescence or sustainment of a system?’

1.3.6 BUILDING OBSOLESCENCE AND THE DELFT MODEL

In the literature on obsolescence assessment, a potentially useful analogous framework for addressing undersea vehicle obsolescence emerges from research on the obsolescence of buildings. The sponsors of a 1993 National Academy of Sciences study on “The Fourth Dimension in Building: Strategies for Minimizing Obsolescence” observe that building obsolescence is “more difficult to comprehend” than the “range of consumer products that we discard...simply because newer, more advanced, and (presumably) better replacements are available” (Building Research Board, 1993, p. vii). Rather than a purely physical condition-based definition, the committee asserts that “obsolescence results when there is a change in the requirements or expectations regarding the use of a particular object or idea” (Building Research Board, 1993, p. 11). A group of researchers at Delft University in the Netherlands questions the necessity for demolition of buildings deemed to be obsolete by citing the emotional nature of the demolition of the Beatle Ringo Starr’s birthplace in Liverpool, and note that demolition may not be necessary even “for obsolete worn-down property as long as the owners and users continue to desire it...” (Thomsen & van der Flier, 2011, p. 353).

The four categories of obsolescence of buildings identified in the 1993 Academy Study conceptually translate well for undersea research vehicle assessment, and reflect the ‘replaceability’ approach described above. They are:

1. **Functional factors**, that is, those related to the uses a building or spaces within the building are expected to serve (e.g., when the building's occupants change);
2. **Economic factors**, referring primarily to the cost of continuing to use an existing building, subsystem, or component compared with the expense of substituting some alternative (e.g., when a building cannot compete effectively with its newer neighbors for tenants and rents);
3. **Technological factors**, referring to the efficiency and service offered by the existing installed technology compared to new and improved alternatives (e.g., when electrical power distribution and grounding systems are no longer able to accommodate the demands of current office automation); and
4. **Social, legal, political, or cultural factors**, that is the broad influence of social goals, political agendas, or changing lifestyles (e.g., when a building fails to meet the requirements set in new legislation for accessibility by people with physical disabilities). (Building Research Board, 1993, pp. 20–21)

Since that study, researchers have translated these concepts into coordinate matrices, whereby considerations similar to those above are binned into quadrants depending on the influence of originating factors (Leaman, Stevenson, & Bordass, 2010). Researchers from Delft Institute for Technology expand on Leaman, et al.’s (2010) thesis

with a quadrant model (referred to here as the ‘Delft Model’, Figure 1-21) that examines the causes of building obsolescence along two conceptual axes: that of internal (endogenous) and external (exogenous) cause, and that of physical and behavioral character (Thomsen & van der Flier, 2011).

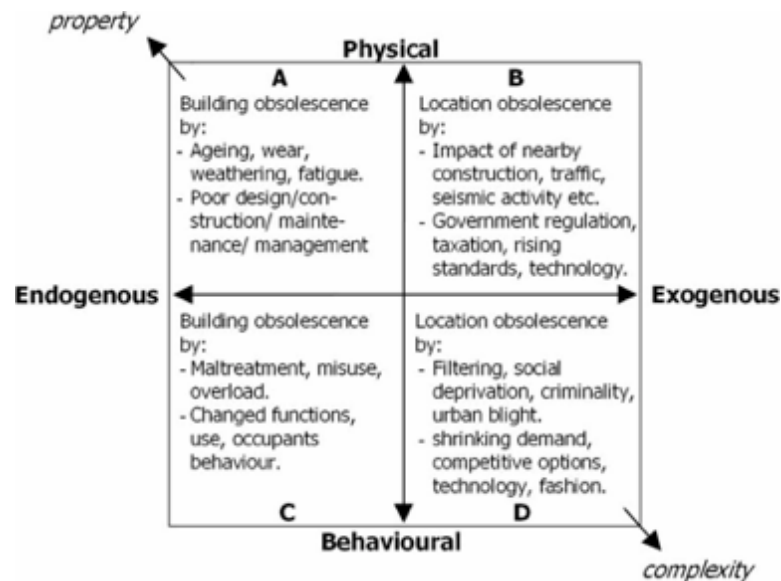


Figure 1-21 The ‘Delft Model’ (Thomsen and Van der Flier, 2011).

The objectives of the model are twofold, first to serve as a theoretical framework to trace, analyse, understand and model processes of ageing and decline of performance of buildings; and second, to serve as a diagnostic framework to investigate the probability and/or future risk of performance decline of buildings by aging and/or obsolescence and potential remedial actions (Thomsen, Nieboer, et al., 2015). Their work to date critically examines use of the model through case studies, suggests instruments to use to conduct assessments within each of the quadrants, and presents a ‘radar graphic’ that serves to

account for influences that fall between quadrant extremes (Thomsen, Nieboer, et al., 2015; Thomsen & van der Flier, 2011; Thomsen, Van der Flier, & Nieboer, 2015). This model and these techniques provided the inspiration for, and were used to initially test, a quadrant framework to investigate the factors that influence UMRI obsolescence and sustainment.

CHAPTER TWO : DEVELOPMENT OF A QUADRANT MODEL FOR UNDERSEA RESEARCH INFRASTRUCTURE

2.1 RESEARCH DESIGN

A study on the value of undersea marine research infrastructure (UMRI) is a complex undertaking that includes both objective (i.e. physical ability to collect data) and subjective (i.e. human value judgments and preferences) influences, and as such is particularly suited to a mixed methods research design model. Maxwell's (2013, p.5) Interactive Model of Research Design provided the primary guidance for the design of this study, which embraced the qualitative research concept of 'bricolage,' or an approach that "spontaneously adapts to the situation, creatively employing the available tools and materials to come up with unique solutions to problems" (Maxwell, 2013, p. 42).

2.1.1 RESEARCH PHILOSOPHY

The initial conceptual research framework for this study (see Maxwell, 2013, p. 10) focused on tangible, comparative data collection and technology attributes, which suggested the use of quantitative approaches, including variance-theory that addresses "difference and correlation," and an instrumentalist focus on "observable or measurable data" (Maxwell, 2013, p. 80). As the investigation progressed, using the sources of "(1) your experiential knowledge, (2) existing theory and research, (3) your pilot and

exploratory research, and (4) thought experiments” (Maxwell, 2013, p. 44), however, other less tangible factors—and more importantly, the interactions of how those factors related and influenced each other—emerged as more important to the larger perspective of national undersea marine research infrastructure. As the study shifted toward this examination of the relationships that influence oceanographic research equipment support, the more qualitative process-theory, which investigates “*how* things happen” (Maxwell, 2013, p. 82), and a realist focus, which allows for data to be used “as *evidence*...to be used critically to develop and test ideas about the existence and nature of the phenomena” (Maxwell, 2013, p. 80), promised to reveal more insights than previously considered quantitative methods (emphases in original text).

These concepts were incorporated into a revised study design, which focused on the testing of a quadrant model, described below, to fully explore the range of influential factors and impacts on UMRI system health.

Shifting to an overall qualitative approach was particularly valuable in its contribution to the intellectual study goals (understanding processes and development of theories and explanations), as well as practical goals of “generating results and theories that are understandable and experientially credible...(and) conducting research that is intended to improve existing practices, programs, or policies” (Maxwell 2013, pp.30–31). Quantitative methods remain applicable for further study on the contribution of tangible performance factors to the overall infrastructure dynamic, especially with respect to technical considerations. Even within this field, however, it will be important to discern between the impacts of actual performance and perceived performance.

2.1.2 RESEARCH QUESTIONS

Research questions differ from research hypotheses in that the former are designed to “state what you want to learn” whereas the latter are “statement(s) of your tentative answers to these questions” (Maxwell, 2013, p. 77). The guiding statements for this study evolved, as recommended by Maxwell (2013), through a number of iterations of both, to become the research questions:

(1) Does an assessment model exist, or can one be developed, that incorporates the full range of causative factors into the evaluation of undersea marine research infrastructure?

(2) How can this model be best illustrated and applied?

(3) What does a test of the model reveal about U.S. human-occupied research submersible sustainment?

2.1.3 RESEARCH DESIGN SUMMARY

The core of the final research design is the UMRI assessment model presented here. The model was developed by first applying and testing a quadrant model that addresses residential building obsolescence (Thomsen & van der Flier, 2011; Thomsen, Van der Flier, et al., 2015), and then by using the results of the initial test to adjust the model to more effectively capture the dimensions that emerged in the field of UMRI assessment. The testing of the quadrant model itself consisted of two levels of investigation, and the development of a technique for illustration of model results. The first step consisted of identification of common factors that impact human-occupied

submersible use within each quadrant (Chapter 3). These factors were then used to conduct case studies of five U.S. crewed undersea system operations (four submersibles and an underwater saturation habitat). An illustration technique, or quadrant map, was developed as a way to visually display the results of these case studies.

2.1.4 RESEARCH METHODS

Methods used for this study included targeted interviews, opportunistic communication, and examination of existing data (i.e. report categories, dive log information) to detect patterns and tendencies. The investigation suggested additional quantitative approaches, including surveys and field comparison experiments, which could provide additional insight and triangulation; these are identified for use in recommendations for further application of the model. A thorough literature review was instrumental in establishing a baseline for these activities. The resources that were consulted included: operational data and logs; previous oceanographic research assessment reports; submersible and marine technology books, magazines and websites that included data and published anecdotes; peer-reviewed papers that described research done with submersible research systems, as well as comparisons and characteristics of those systems; and personal experience as a program officer at NOAA's Undersea Research Program (NURP) and Office of Ocean Exploration and Research (OER) from 2005 to present. (Note: The Delft researchers identified assessment 'instruments' specific to each of their obsolescence quadrants (Thomsen, Nieboer, et al., 2015; Thomsen & van der Flier, 2011; Thomsen, van der Flier, et al., 2015). This technique would be helpful for

future targeted assessment case studies, but for this study, most of the methods and resources used served numerous aspects of the analysis.)

Throughout the course of the study, twenty-nine targeted interviews were conducted, with more than three dozen less structured information-gathering conversations held at venues of opportunity and via email with other subject matter experts. Participants were selected using the ‘purposeful’ method, with the goal of choosing “individuals or cases that are critical for testing (your) theories” (Maxwell, 2013, p. 97). This included obtaining input that was representative of types of stakeholders (i.e. managers, scientists, and engineers) and submersible systems (i.e. each of the case study HOV operations as well as research ROV use). Selection of interview location was both deliberate and opportunistic, with 11 conducted at the interviewee’s institution, five at a neutral location, and 14 over the phone. An important component of the research was the development of ‘productive relationships’ (Maxwell, 2013, p. 97) which consisted of engagement with senior oceanography professionals who provided historical perspectives, challenged assumptions, and offered alternative viewpoints and resources.

The result was a mix of undersea research infrastructure policymakers (20), scientists (26), and engineers/pilots (20) with familiarity with the *Alvin* (23), *Delta* (12), *JSL* (7) *Pisces* (12) and ‘other’ (6) HOV operations, as well as with research ROV (17) activities. Many interviewees were familiar with more than one submersible system. The number of interviewees familiar with each system resulted from efforts to obtain a similar level of familiarity with each operation, and capture viewpoints of users with different

experience levels, research goals, and previously stated preferences. The high number of *Alvin*-related interviewees occurred naturally as a result of its longevity.

The final number of interviewees was consistent with qualitative research methodology recommendations for achieving ‘saturation’ (Bonde, 2013; Mason, 2010) and proved sufficient for defining the quadrant model, particularly with respect to the development of HOV impact factors. ‘Saturation’ for this study was also considered in light of its description by Strauss and Corbin (1998):

A category is considered saturated ...when no new properties, dimensions, conditions, actions/interactions, or consequences are seen in the data. However, this statement is a matter of degree. In reality, if one looked long and hard enough, one always would find additional properties or dimensions. There always is that potential for the ‘new’ to emerge. Saturation is more a matter of reaching the point in the research where collecting additional data seems counterproductive; the ‘new’ that is uncovered does not add that much more to the explanation at this time. Or, as is sometimes the situation, the researcher runs out of time, money, or both. (p.136)

The number of participants contacted for each of the case studies was adequate for the purpose of this initial test of the model; they were selected purposefully to represent the most frequent users. This number should be expanded for any future, more in-depth analyses of each case.

The interview questions varied depending on the background of the interviewee (manger/policy maker, scientist, or pilot/engineer), aspect of the study (overall theory,

impact factor development, or case study) that was being targeted, and the need for clarifying information. Templates of essential questions were developed for policymakers, scientists, and engineers, and are included in Appendix (2).

Much of the emphasis during the case study questioning was on how prior attitudes may have changed with the maturation of remote technologies, and on what replacement activity had occurred in the place of the work that had been accomplished by the retired HOVs. The National Academy of Science's Committee on Human Spaceflight (2014) used this latter approach in light of the challenges of traditional public value propositions:

An alternative way to examine the value proposition of NASA human spaceflight is to consider the effects on various stakeholder groups if the program is terminated (which)...highlights where the lens of 'what would be lost' adds a perspective that was not captured in the discussion of rationales... (Space Studies Board, 2014, p. 76)

2.1.5 ANALYSIS TECHNIQUES

Analysis of the data was conducted using both "categorizing (such as coding or thematic analysis)" and more narrative "connecting" strategies (Maxwell, 2013, p.105). Results were recorded in matrices that first used categories defined by 'emic'—or "taken from participants' own words and concepts" (Maxwell 2013, p.108)—viewpoints of what attributes of HOVs were most impactful or valuable. The data were then reevaluated using 'etic'—or that which "represent(s) the researcher's concept" (Maxwell, 2013, p. 108)—categories established by the quadrant model (Technical, Operational, Functional,

Societal Impact). This latter matrix was especially consulted during establishment of the impact factors. Both emic and etic categorization techniques were also used to develop impact categories within the Functional quadrant of the model.

All interviews were personally transcribed and reviewed; casual interactions were documented using dated notes and memoranda. During this process, as well as during reviews of the data, a narrative approach that consisted of observing and questioning the historical and causal statements and/or assumptions offered by participants was used extensively. This practice proved invaluable in identifying the importance of interactions of factors and in validating the overall quadrant approach.

2.3 CREATING AN UNDERSEA MARINE RESEARCH INFRASTRUCTURE QUADRANT MODEL

2.3.1 QUADRANT ANALYSIS

Quadrant analysis can be an effective technique for illustrating complex relationships in a way that facilitates better understanding and action. Examples of successful quadrant use include the popular urgency/importance Eisenhower Decision Matrix (Eisenhower, 1954)—made popular in Steven Covey’s (1989) *7 Habits of Highly Effective People*—; *Pasteur’s Quadrant*, which broke through the linear approach to basic and applied research (Stokes, 1997); and for weighing outcomes of uncertainties for market analysis (Mahaffie, 2009). By categorizing successful U.S. lawmaking efforts by type and form of mobilization into *Four Pathways of Power*, Conlon, Posner & Beam (2014) provide guidelines for future lawmakers to consider that are appropriate to the

type of action they are pursuing. The building research model that inspired the methodology used in this study links obsolescence characteristics to four recommended management strategies: “Make invisible, make usable, make habitual, make acceptable” (Leaman et al., 2010, p. 572).

Venkatesh Rao, an independent researcher and author of *Tempo: Timing, tactics and strategy in narrative-driven decision making*, recommends the use of quadrants “when there is high ambiguity, overlap and fuzziness in the basic categories, and apparent high-dimensionality (lots of variables with complex coupling) but somehow, when they mix together, a few dominant patterns leap out” (Rao, 2009). Figure 2-1 (a) illustrates alternatives for describing issues with different characteristics of complexity. “Visual constructs live in a special sweet spot inhabited by issues that are too complex for rigorous analysis, and too structured or impoverished to support full-blown narrative treatments in the form of novels or stories. Within this universe, quadrant diagrams are in the Goldilocks position” (Rao, 2009). Given this schema, the issue of undersea marine research infrastructure assessment is appropriate for quadrant analysis.

Once an issue is identified as suitable for a quadrant, “Your primary job is to identify four interesting and complex clusters of phenomenology, without the aid of statistical or first-principles analysis, and think up two interesting lines that will separate them. These are the dominant patterns, and the organizing spectra/watersheds...If your lines end up being spectra, or related to each other in nice ways...that’s a bonus” (Rao, 2009).

Figure 2-1 (b) further describes techniques to use when creating a quadrant by considering the context and tangibility of the issue.

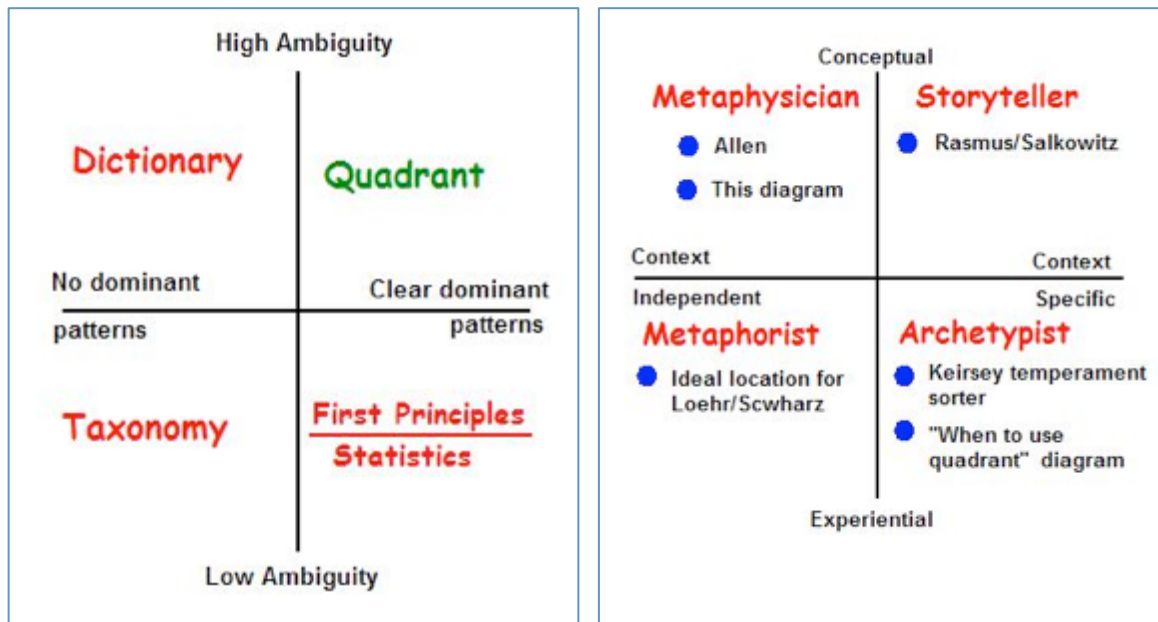


Figure 2-1 (a) Diagram of when to use a quadrant; (b) Diagram of how to create a quadrant (Rao, 2009).

This second quadrant is intended to address a wide range of philosophical pursuits; a specific, tangible issue like UMRI assessment fits in the ‘Archetypist’ quadrant. Rao continues: “The value of your diagram will be validated by your ability to think up evocative names for the quadrants. If people see your diagram and instantly feel a sense of relief and recognition, it means you are articulating and clarifying something they’ve already subconsciously noticed...If you are in the bottom right, be prepared to provide examples of real people, events and places. You want to talk about ‘classic’ (or

archetypal) members of the quadrant” (Rao, 2009). The four quadrant descriptions developed for this study: Technical, Operational, Functional, and Societal, are intended to be consistent with this guidance.

Ultimately, the value of a quadrant construct is the ability to determine actions that are likely to be successful in particular situations. By conceptualizing perceptible characteristics of a complex issue in distinct bins (the quadrants), stakeholders can more readily apply techniques and actions that worked in the past for similar situations, or that may show promise through deductive reasoning. Whereas an assessment model for undersea marine infrastructure is unlikely to result in recommendations as straightforward as the Eisenhower Decision Matrix’s “Do, Decide, Delegate, Delete” (Clear, 2014), it is intended to provide a similar capability for decision makers.

2.3.2 ADAPTATION OF THE DELFT MODEL

The building assessment model developed by researchers at the Delft Institute of Technology uses two distinguishing dimensions (see Figure 1-21, the ‘Delft Model’):

- (1) the character of the cause-effect relation: physical (related to the built artefact) or behavioural (related to the behaviour and actions of the main stakeholders, i.e. owners, residents and other users); and
- (2) the origin of the cause-effect relation: endogenous (i.e. from the building itself), or exogenous (i.e. from the environment) (Thomsen & van der Flier, 2011, p. 211).

It was selected for testing because of the similarities between the complex nature of the assessments and inclusion of a behavioral component. The UMRI model was

initially developed and tested using these determinants, with the adjustment of ‘intrinsic’ and ‘extrinsic’ labels as the origin of a cause-effect relation. During the analysis process, ‘intrinsic’ forces were sometimes difficult to distinguish from ‘physical’ characteristics, and ‘extrinsic’ forces tended to resemble ‘behavioral’ features. In the final analysis, a high degree of dependency between quadrant factors was identified, suggesting that this selection of axes characteristics might not be appropriate for direct adaptation to undersea vehicles.

This problem was investigated by comparing the differences between the systems of interest (i.e., Why didn’t this work?) and by reassessing the results and initial observations to develop definitions that more accurately portrayed the reality of UMRI assessment challenges (i.e., What will work?)

A few essential differences between buildings and undersea research systems contributed to the unsuccessful transition of the building obsolescence model as defined by the Delft researchers. Physically, undersea research systems are moving, non-fixed entities, so the central locational concern of building management does not translate well. Undersea vehicles are also more complex with respect to function; marine research systems perform tasks and collect data for a variety of purposes, whereas the buildings used in the Delft model have been narrowed to a single, residential use. Finally, a primary concern for buildings is physical deterioration, whereas the central concern issue for research infrastructure is the effective, efficient use of the system.

Reevaluation of undersea systems assessment was conducted by reviewing both the results of the Delft-based test, and the initial factors that led to a search for an

assessment model. The predominant factors that appeared in HOV literature included (1) tangible performance comparisons between HOV and ROV systems, (2) research purposes, and (3) economic considerations. Initial case study results (and personal experience) indicated that (4) human nature also played a significant role. These factors, the so-called “four interesting and complex clusters of phenomenology” (Rao, 2009), had emerged in the initial Delft test, and as such were confirmed as the basic aspects of the quadrant model.

The initial test also revealed differences in viewpoints between scientists and managers, and between on-site performance and concerns regarding the sustainment of a system and/or research enterprise. Revised “organizing spectra” (Rao, 2009) were developed by considering this insight and conducting some extrapolation of the original axes definitions.

2.3.3 HORIZONTAL AXIS: SCOPE OF ACTIVITY

Many quadrant models use the consideration of internal versus external forces as an axial measure (Conlan, Posner, & Beam, 2014; Kahan, 2008; Thomsen & van der Flier, 2011). Several factors—consideration of the question, ‘Internal or external to what’; acknowledgement of the core purpose of UMRI (i.e. the collection of marine research data); and initial model results that indicated a difference in narrow and broad activity perceptions—led to the identification of ‘activity scope’ as the aspect of the organizing spectra that best captured this internal and external sense.

The physical *in situ* activity conducted during an undersea dive represents internal considerations, and is termed ‘Mission’ for the purposes of this model. This usage of

‘mission’ is distinguished from the multi-day expedition sense of the term. Factors that apply to the business of providing a research system, or a research service, are external to the day-to-day operations, and are termed ‘Enterprise.’

2.3.4 VERTICAL AXIS: PERSPECTIVE

The terms ‘physical’ and ‘behavioral’ were useful in conducting an initial assessment of UMRI, but revealed an interweaving of ‘behavioral’ factors in all quadrants. Recognizing the differences in perspective between operators, scientists, and managers that emerged during model testing led to identification of an organizing spectra that retains the physical-behavioral sense, but accurately reflects the UMRI dynamic while allowing behavioral factors to interact throughout the quadrants as appropriate. ‘System’ refers to factors that reflect on the individual UMRI equipment, and relates closely to the ‘physical’ categorization. ‘Client’ refers to factors that relate to the users of the system and their needs, and reflects, but limits, the ‘behavioral’ sense.

Note that both the horizontal and vertical axes represent distinct concepts, and do not present scales of value. This becomes important when interpreting the location of factors within the resulting quadrants, described in section 2.6.

2.4 UNDERSEA MARINE RESEARCH INFRASTRUCTURE QUADRANTS

Based on the above considerations, the Delft quadrant model was adjusted to best address the sustainment of undersea marine research infrastructure, and is illustrated and described below (Figure 2-2).

Undersea Research Systems Quadrant Assessment Model

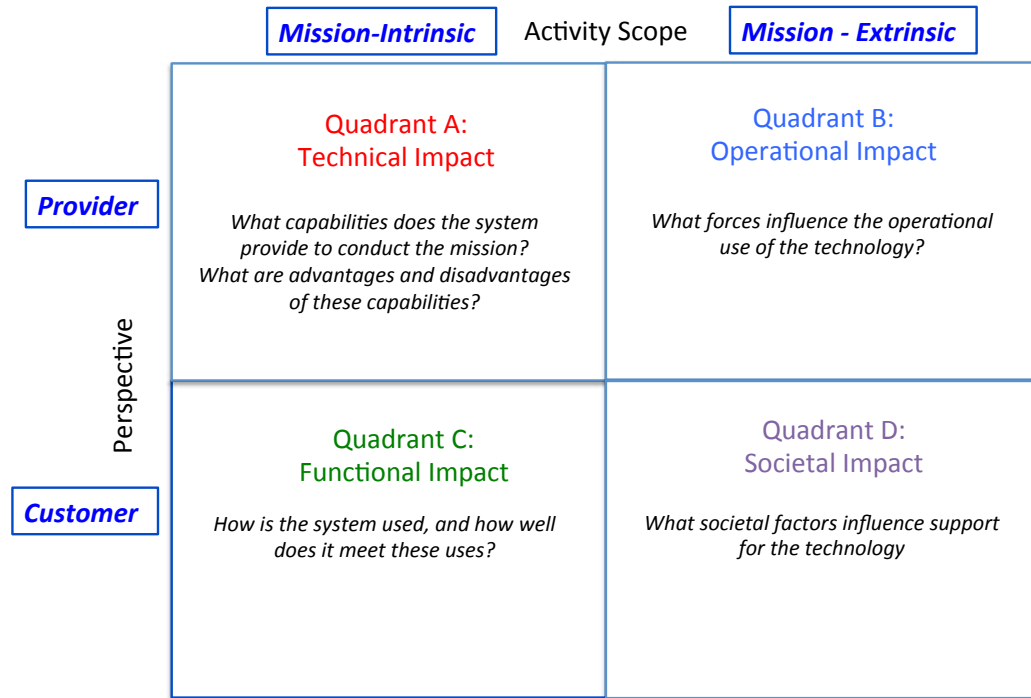


Figure 2-2 Undersea marine research infrastructure assessment quadrant description.

2.4.1 QUADRANT A: TECHNICAL IMPACT (SYSTEM-MISSION)

Technical impact of the physical factors of an UMRI system that are operative in the conduct of *in situ* marine data collection are considered in quadrant A. Evaluation of technical impact essentially addresses the questions: ‘What capabilities does the system provide to conduct the mission?’ And: ‘What are advantages and disadvantages of these

capabilities?’ A common follow up question in this line of investigation is: ‘Can something else perform the task better?’

2.4.2 *QUADRANT B: OPERATIONAL IMPACT (SYSTEM-ENTERPRISE)*

Impacts of factors related to the operation of a system that originate from beyond the specific mission activity are addressed in quadrant B. These are often business-enterprise level concerns, and include regulatory and safety (legal) guidelines, local availability of a particular piece of infrastructure, and financial considerations. They also include certain behavioral factors that directly affect physical operation (operating team expertise, safety performance and equipment reliability). Financial considerations are equipment- and operation-specific (reflecting capital costs, personnel requirements and launch methods), and differ from the external funding factors discussed under quadrant D. These factors all contribute to answering the question: ‘What forces influence the business-level sustainment of the technology?’

2.4.3 *QUADRANT C: FUNCTIONAL IMPACT (CLIENT-MISSION)*

Factors that are of interest to users of a system with respect to a specific mission activity are considered under quadrant C, and are referred to as ‘functional impacts.’ For the question of UMRI, the primary consideration of functional impact is with respect to its role in supporting marine research, i.e. *in situ* marine data collection. This line of investigation may also be used to explore the value of alternative functions (industry, tourism) that may support the availability of the equipment for research purposes, and answers the questions: ‘How is the system used, and how well does it meet these uses?’

2.4.4 QUADRANT D: SOCIETAL IMPACT (CLIENT-ENTERPRISE)

Factors of interest to sponsors of activity who are concerned with organizational or national level performance are termed ‘societal impact,’ and are assessed within quadrant D. These factors include societal value of research goals, organizational dynamics of particular groups, and individual charismatic influences. These considerations address aspects of the question: ‘What factors influence sponsorship for the research system?’

2.5 SCOPE OF APPLICATION

The variety of undersea research systems, and differences in technological maturity of these systems, makes a fully inclusive test of the model with the full range of systems unmanageably complex. Human-occupied research submersibles (termed Human Occupied Vehicles, or HOVs) involved in United States government-sponsored marine research were selected for this pilot study for a number of reasons:

- They represent the particularly challenging ‘submersible science’ mid-sized infrastructure subset of UMRI.
- The limited number of research HOV operations in the United States allows for a thorough examination.
- The ‘charismatic’ nature of manned activity tests unique behavioral aspects of the assessment.

- Research HOVs have experienced practically a full technological lifecycle in the course of a human lifetime, which offers the ability to conduct retrospective analyses on replacement activity.
- A replacement technology that addresses similar research data collection needs—Remotely Operated Vehicles (ROVs)—exists, and offers additional comparative perspective.

The field of marine research submersibles was narrowed to the four U.S. HOV operators that have been active since mid-1980. The suite of international research submersibles (Japanese *Shinkai 6500*, Russian *MIRs*, German *Jago*, Chinese *Jiaolong* and French *Nautilus*) faces similar technical, functional, and operational impact factors, but experiences a variety of different governmental and societal impacts. A study of each of these systems would provide insight into this societal aspect, but their inclusion would introduce a complication beyond the immediate goal of testing the model for U.S. research infrastructure policy. Another potential approach that was considered was to test the model with two subsets: deep (>1500 m) and shallow (≤ 1500 m) submersibles, which exhibit distinct technical and operational factors because of the engineering requirements at increased depths. This, however, seemed to introduce a preconception that could distort a first-order model test, so was rejected. The caveat of activity after the mid-1980s was selected because of the entrance of two of the four U.S. research HOVs (*Pisces V* and *Delta*), sufficiency of *Johnson Sea Link* records, and the emergence of research use of ROVs during this time frame. It was also during this time that the international submersibles mentioned above (except *Jiaolong*) were constructed.

2.6 ILLUSTRATION OF IMPACT

The Delft model introduced a potential method for illustrating the results of their approach with respect to building obsolescence. A radar diagram (Figure 2-3) was suggested to assist in presenting results and helping address issues “to be solved before the model can be used for diagnosis and certainly for treatment and prevention” (Thomsen, van der Flier, et al., 2015, p. 13). The issues ‘to be solved’ include the complexity of cause-effect relationships; dealing with this complexity in the model; and enabling measurement of obsolescence.

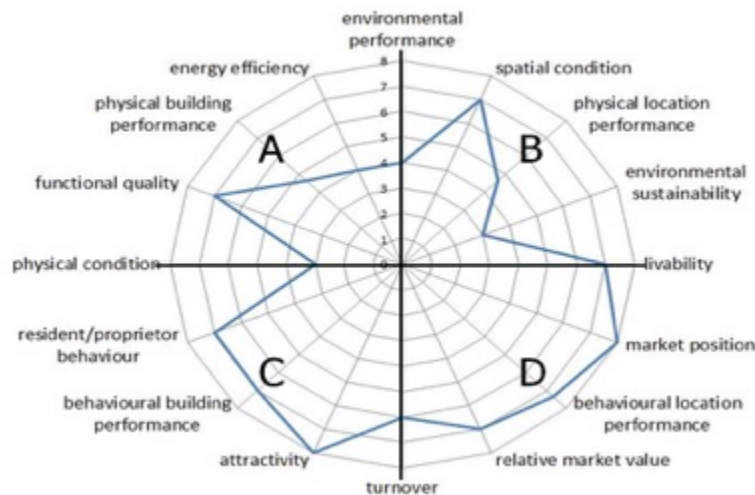


Figure 2-3 Delft radar graphic concept (Thomsen, van der Flier, et al., 2015).

In addition to creating an effective UMRI quadrant model, a goal of this study was to further the development of such a descriptive instrument. The suggested radar

diagram allows for illustration of the degree of impact of a factor with some indication of the relative strength of the drivers on each axis, but it limits the degree to which multi and cross-quadrant relationships between factors can be represented; i.e. the labeling of a factor as a spoke allows for comparison between only neighboring axes, with no ability to display diagonal (A-D and B-C) relationships. The diagram also does not allow for representation of whether an impact is positive or negative, which was a recurring characteristic of the data encountered in this study.

To address these limitations, a new model was created in which each factor is represented as a circle with three variables: size, which represents magnitude, or degree, of impact; color, representing the character (positive/negative) of impact; and location on the quadrant, which indicates existence of influence from another quadrant. A 3-step rating system was assigned to both size and color: size (degree): small = little impact; medium = notable impact; large = significant impact; and color (character): red = negative impact; yellow = both positive and negative impacts; green = positive impact.

Evaluations of ‘little’, ‘notable’, and ‘significant’ impact were made based on a combination of emphasis provided by interviewees, and the relative frequency of mention of the factor: little = <10%, notable = <50%, significant = >50%. ‘Negative’ refers to a force that acts against sustainment, whereas a ‘positive’ impact acts in favor of sustainment of the infrastructure. In two cases, a type of impact could be classified as both positive and negative: first, when a situation changed through time—such as a private sponsor who establishes an operation and later withdraws that support; and second, when a number of factors were combined into one labeled factor for simplicity

sake. The yellow shading, therefore, represents situations that require additional attention. Since the intention of this effort is to illustrate the strength of impacts for characterization and further investigation, this is consistent with the model design. When no notable impact was found, the template empty circle was retained.

During the analysis, a few factors exhibited a notable dependence on the dynamics of factors in other quadrants. The new design allows for indication of these cross-quadrant relationships by placement of the circle closer to other regions of influence. Because not all factors exhibited this characteristic, an inner boundary was created to highlight those that do. Factors that are located within the boundary are placed in a position close to the quadrant of influence. Other factors are distributed in the quadrant in a visually practical pattern with no particular indication of cross-quadrant impact.

This revised model remains limited in its ability to illustrate cause-effect processes, but provides the ability to describe more dimensions of assessment, and addresses measurement with the introduction of a quasi-quantitative scale as a first order approach. The template below illustrates this concept with constant size and color factors (Figure 2-4), and provides a key for further analysis; the factors themselves are discussed in more depth in Chapter 3.

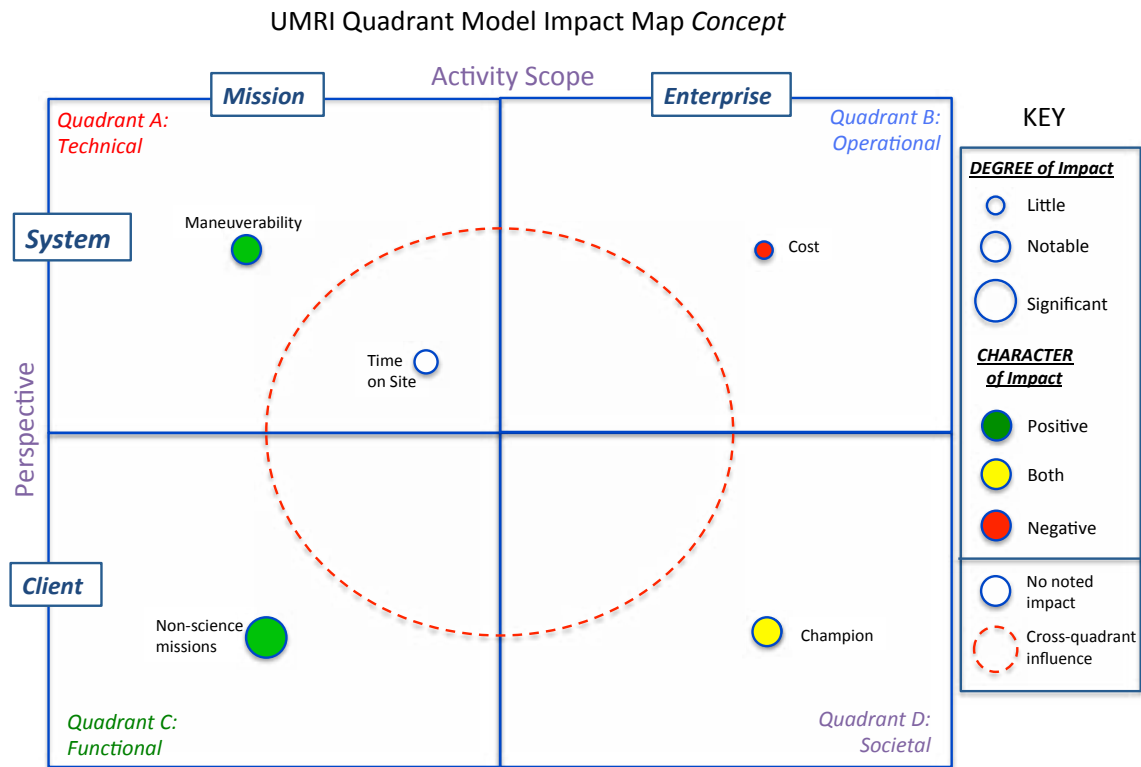


Figure 2-4 Quadrant model impact factor template example, with color and size key for analysis use.

2.7 VALIDITY

A number of techniques were used to address the validity, or “correctness or credibility of a description, conclusion, explanation, interpretation, or other sort of account” (Maxwell, 2013, p. 122) of this study. Concerns included the role of the researcher as a marine science program manager who had professional relationships with many of the participants, and the relative subjectivity of values assigned to case study factors.

Personal experience as a program manager for undersea submersible systems provided insight and access that might not have otherwise been available, but it also presented a challenge with respect to advocacy, and perception of advocacy, for or against particular systems and/or groups, thus introducing concerns regarding both researcher bias and participant reactivity. Potential personal bias was addressed through self-recognition, reflective exercises, and discussion with confidants. The purpose of the study and acknowledgement of the potential for partiality was reviewed and openly discussed with interviewees and participants.

The iterative nature of the development and the design of the model, in which data were used both to help determine specific impact factors, and to discover and document information about these factors for case studies, introduced a challenge with respect to relative subjectivity of the values assigned to the factors. This was addressed first by systematically comparing the values assigned to factors within and between case studies, and then by reviewing each case study result with the appropriate subject matter expert(s) to validate the conclusions. This combination of techniques was sufficient for illustrating the potential for use of the quadrant model and map, but for a more definitive determination of causal obsolescence or sustainment, additional methods should be employed. These may include proactive engagement with the user community through both a survey that directly records their judgments on the characteristics of each of the factors, and a means to solicit feedback on the effectiveness, strengths, and weaknesses of the method.

The history of discussion of the attributes and challenges of *in situ* marine research equipment, especially from the perspective of ‘manned vs. unmanned’, is replete with examples of articles, studies, and community engagement. The HOV research community consists of a discrete number of members, many of whom have spent decades using undersea research equipment; most of these users have at some point responded to questions regarding this debate in the past. In light of this, particular emphasis was placed on thoroughness of background research so that data collection would focus on new approaches and evolved perspectives. It is recognized that contrasting viewpoints will always exist for various marine research circumstances. Would a different researcher have reached the same conclusions regarding factor identification and value assignments? Not completely (probably never completely), but this attention to background information, ability to draw on research management experience, and practice of verifying results with participants were all exercised to reduce significant divergences.

CHAPTER THREE : CASE STUDY IMPACT FACTORS

The previous chapters introduced a quadrant model for assessment of the factors that contribute to obsolescence, or sustainment, of undersea marine research infrastructure (UMRI), reproduced here as Figure 3-1.

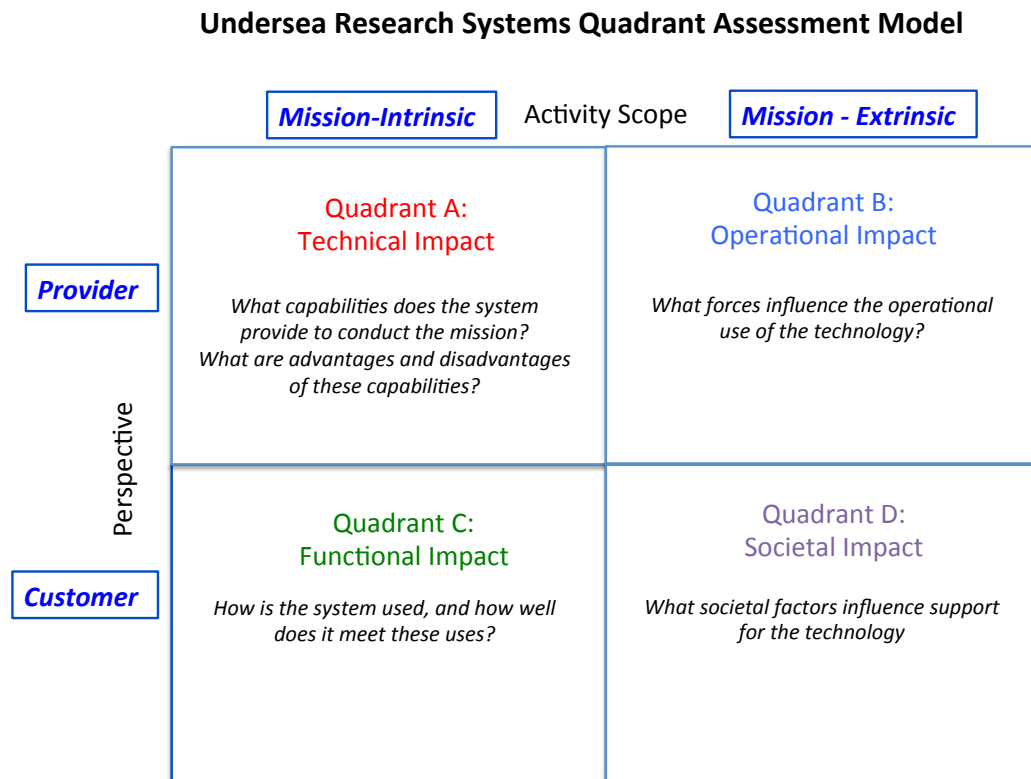


Figure 3-1 Undersea marine research infrastructure assessment quadrant description.

The model assesses Technical, Operational, Functional and Societal factors that occur from Provider/Mission, Provider/Enterprise, Client/Mission, and Client/Enterprise perspectives, respectively. This chapter further develops this model for application to a case study of U.S. research HOVs by identifying specific, common factors within each of the quadrants that contribute to the value of this infrastructure.

A significant characteristic of an assessment of research HOVs today is the existence of a niche-sibling, the remotely operated vehicle (ROV), and the prevalence of comparison between the two in operations and in literature. Therefore, much of this analysis reflects a comparison between these two alternatives. An additional dimension of HOV assessment is its extreme environment, human-occupied nature, which invites comparison with similar NASA studies (see Appendix 3). These comparisons will also be presented as appropriate throughout the analysis.

In addition to identification of factors common to HOVs that fall within each quadrant, this analysis notes the existence of cross-quadrant influence, or relationships between other factors. Quantification of impacts, whether relative or absolute, is not addressed during this step. This study results in a template for use in case studies as well as a number of observations and recommendations regarding model effectiveness.

3.1 QUADRANT A: TECHNICAL FACTORS

Technical impact of the physical factors of an UMRI system that are operative in the conduct of *in situ* marine data collection are considered in quadrant A. Evaluation of technical impact essentially addresses the questions: ‘What capabilities does the system

provide to conduct the mission?’ and ‘What are advantages and disadvantages of these capabilities? A common follow up question in this line of investigation is: ‘Can something else perform the task better?’

The literature regarding the advantages and disadvantages of marine submersibles is abundant; perhaps the earliest recorded assessment was the description of the “*Difficulties and Remedies*” and “*Great Conveniences*” of Cornelius Drebel’s submarine endeavor in the early 1600s by Oliver Cromwell’s brother-in-law John Wilkins (Beebe, 1934). One of the first recorded calls for use of HOVs for research in the U.S. was a resolution that emerged from a symposium on “*Aspects of Deep Sea Research*” that was hosted by the National Academy of Sciences’ Committee on Undersea Warfare in 1956:

We, as individuals interested in the scientific exploration of the deep sea, wish to go on record as favoring the immediate initiation of a national program, aimed at obtaining for the United States undersea vehicles capable of transporting men and their instruments to the great depths of the ocean. (Committee on Undersea Warfare, 1957, p. 176)

A 12-volume study of the U.S. oceanographic research enterprise that was conducted by the National Research Council (1959) at the end of the decade identified three specific arguments for HOVs, reflecting capabilities of the eye, brain, and body:

1. It permits man to view directly the environment and natural phenomena of the entire water column and the bottom.

2. It allows multiple and continuous measurements under the immediate control of the best available programming computer and control servo-mechanism—the scientist himself.
3. It permits selective sampling of the environment through vision, mobility and the use of specially adapted prosthetic accessories. (National Research Council, 1959, p. 3 of Chapter 7)

The components of this assessment have remained essentially the same through the years, even with the emergence of ROVs and comparisons of capabilities became more common (Bowen & Walden, 1992).

A manned submersible permits within the water column, or on the bottom, an interactive, cognitive and stereoscopic presence that can implement complex manipulations (sampling and equipment deployment) by powerful and dexterous robotic arms, and that provides the user with the capability to take large payloads to and from the bottom. (DeSSC, 1994, p. 15)

The most recent comprehensive federal assessment directed solely on U.S. deep submergence capability included comparative assessments within six “*Capabilities Needed to Reach Science Goals:*” Viewing and Documenting, Sampling, Platform Stability, Mapping and Surveying, Experiments and Time-Series Investigations, and Outreach (Ocean Studies Board, 2004, p. 67).

The literature that describes and compares the advantages and disadvantages of HOVs and ROVs reflects a myriad of different approaches as far as specific vehicle,

research discipline, data collection task, environmental situation, and commenter experience; as such it resists rigorous categorization and analysis.

For the purposes of this assessment, technical factors were initially parsed into four categories: ‘Tether,’ which deals with impacts resulting from the presence/absence of an umbilical; ‘Structure,’ which deals with the capabilities provided by size and engineering design; ‘Vision,’ which encompasses the faculties provided by the ability to use the human eye: rapid focus, color discernment, high definition, peripheral and stereoscopic vision; and ‘Being There,’ which includes spatial and contextual awareness afforded by other sensory input from the environment, and considerations in the field of virtual reality and human/robotic interface studies. Considerations regarding reliability and design also emerged from interviews and Ocean Studies Board (2011) portfolio-level recommendations. Three factors within the Tether category: maneuverability, time on site, and connectivity, emerged as significant during this investigation, and are therefore captured as separate factors for the quadrant map below.

3.1.1 MANEUVERABILITY

The ability to navigate complex topographic features, operate in certain environmental conditions, remain stationary, and traverse horizontal distances on the bottom, and determine precise position are all influenced by the existence of the tether. The operating method and degree of impact differs with depth. Small, shallow-water ROVs operate directly from the support vessel, whereas deep-water ROV operations typically employ an intermediate tether management system (TMS) or camera sled that decouples the motion of the ship from that of the ROV. Industry tether management

systems typically deploy a spool of cable via a ‘top-hat’ (a spool located above the ROV), or a ‘cage’ or ‘garage’, which also houses the vehicle during descent and ascent (Forum Energy Technologies, n.d.; Oceaneering International, 2015). Several deep research operations (NOAA Ocean Exploration, WHOI and the Ocean Exploration Trust) use an intermediate ‘camera sled’ which is connected to the ROV via a 40–50 m tether. These camera sleds are equipped with lights and cameras, providing a ‘bird’s-eye’ view of the working scene (Figure 3-2) (Nautilus Live, n.d.; NOAA Ocean Exploration, n.d.-c; Woods Hole Oceanographic Institution, 2016b).



Figure 3-2 NOAA Ship *Okeanos Explorer* with camera sled and ROV (Randy Canfield and NOAA).

These vehicles and the use of shipboard dynamic positioning (DP) navigation and thruster systems that help keep the surface vessel in a stationary position, have alleviated the restrictions on ROV maneuverability somewhat, but have not completely overcome the dependence of the ROV on its surface platform. In the words of one scientist familiar with both HOV and ROV operations: “Imagine walking a dog on a leash while you’re being towed by a helicopter” (Scientist M).

The degree of impact often depends on environment and mission; high currents and steep topography are typically the most challenging for a tethered vehicle. Strong currents create drag on the umbilical, impacting the ability of a vehicle to descend to the bottom, and to maintain control while on site. Several scientists also noted the advantages of a free-swimming vehicle in topography that included overhangs and tangling hazards, around structures such as oil platforms, and for research along steep atolls, where the ROV support ship is unable to station close enough to the dive site to provide access and avoid grounding (Scientist M).

Another maneuverability impact of the tether is the horizontal area that the undersea vehicle can cover underwater. This characteristic is of course strongly impacted by mission: the style of operation—whether transect or a more specific, on-site investigation—and the influence of currents. For shallower operations, the surface vessel supporting an ROV may purposefully motor or drift long distances with the ROV below. For deep work, the difference can be 4-5 times less area for an ROV than an HOV during the same submerged time frame (Scientist M); more movement can be logistically challenging. “[In a] perfect situation, we’ll call up to the command center and say please

move 10 feet—probably more like 10 m, but not a large distance. The ship will drag the [intermediate ROV system], it’s a hopscotch game” (Scientist D).

ROV systems that are designed for deep-water operations also experience overheating of the umbilical at shallow depths, limiting the minimum depth that the equipment can work to approximately 300 m (Engineers B, M). Another quality related to the tether and maneuverability is that of positioning accuracy. “It does seem like tracking on the subs is less accurate and less precise than tracking on the ROVs. I think having the tether and tracking on the surface improves your digital throughput...with an ROV, you get [navigation updates] every 2 seconds” (Scientist D).

Human skill level was also cited as a maneuverability factor, both for HOV pilots, with a number of pilots specifically named for their experience and dexterity, and for ROV pilots and crew, including the ship captains. “[During ROV operations], we could tell when [the ship crew] changed shifts—we’d be getting off track or going the wrong way. Even if someone would go to the bathroom, you could end up off reef pretty quickly” (Scientist D).

3.1.2 TIME ON SITE

A commonly cited advantage of ROVs over HOVs is the ability of ROVs to remain submerged for longer periods of time than HOVs. HOV time on station varies from 3 to about 10 hours depending on the depth and submersible capabilities. An ROV can theoretically remain on site indefinitely, but actual time on bottom is typically a tradeoff between mission, personnel cost, and shipboard logistical and environmental considerations. An example of this influence of Operational (quadrant B) and Functional

(quadrant C) factors is the difference between NDSF's *Jason* science dives, which average one to two days (Woods Hole Oceanographic Institution, 2016c), and NOAA's *Deep Discoverer's* exploration dives, which are typically performed within a workday, and supplemented with mapping activities in evenings (NOAA Ocean Exploration, n.d.-b).

An engineering solution from the human-occupied aspect is the use of a submarine that provides life support for a manned crew for long periods of time underwater, combined with the data collection capabilities of viewports and manipulators. The Navy's *NR-1* nuclear submarine provided this capability on a part-time basis in the 1990s, before its retirement in 1997, but the economic drivers for a replacement were beyond the need for its scientific capability (Vyborny & Davis, 2004).

3.1.3 CONNECTIVITY

Another frequently cited advantage that the tether of the ROV allows over HOVs is the ability to communicate in real-time with the surface, enabling more participants to be included in the real-time mission activity. Typical ROV operations are conducted from a shipboard self-contained laboratory that allows for a number of scientists to view on-site video and provide input on mission activities. 'Telepresence,' a combination of technologies that allow a person to participate in an event when not physically present, has enabled an innovative method of science that allows scientists in shore command center facilities across the country to participate in real-time ROV dives, providing scientific information on unknown species and at times directing the movements of the vehicle itself (Nautilus Live, 2015; NOAA Ocean Exploration, n.d.-d).

The impact of this capability is largely cited as positive, although some have begun to “wonder what the tradeoffs are [for more involvement] and how much it distracts you from doing the best and most science with limited time out at sea” (Scientist M). This value of being “completely focused and immersed—pun intended” (Scientist A) while relatively alone underwater in an HOV emerged during discussions on the factor of ‘Being There’, discussed later, and was a point that had not been highlighted in earlier published studies.

The Director of the NDSF has stated:

There’s no question that the strong suit for robotics is that you can engage a larger number of people in the process of exploration and discovery. But taking in all the undersea factors—currents, sounds, land forms, interactions between animals and their environment—humans are still far better at synthesizing what’s going on in the deep sea. We hear that all the time from researchers who have looked at the video monitors and data screens from Jason, but then also gone down in *Alvin*. It’s stunning how different their perception of the environment is. (Dixon, 2015)

The ability of a real time communication link to bring science to a larger audience was noted as crucial impact by several HOV scientists who had become familiar with telepresence missions:

One of the failures of [the submersible community] was that there was no one witnessing the dives. How cool would that be to watch real people in a

submersible doing real research in real time? I think that was the nail in the coffin [for manned submersibles]. (Scientist K)

NURP [NOAA Undersea Research Program]’s problem was that it gave money to researchers, and researchers went off and they published it, and it wasn’t really seen by the public. Now they’ve moved it to the opposite model. (Scientist T).

Today, engineers are testing optical and acoustic communication links that can replace the tether between an ROV and a nearby (within 100 m) control module located on the seafloor, providing real-time control of the system from the surface, but these systems are not yet in common use (Farr, 2013). The use of fiber optics for similar communication capability with HOVs has been initiated for several submersible operations, but has not yet become operational (Engineer B, Scientist M).

3.1.4 STRUCTURE

3.1.4.1 Stability

HOVs employ a variety of buoyancy and trim systems that enable them to descend, ascend, “(run) hither and yon...follow a sloping bottom, handle additional weight in the form of...samples, and surface with sufficient freeboard for safe transfer of personnel and equipment” (Busby, 1976, p. 279). These systems must be power-efficient, and include main and variable ballast tanks, compressed air and pumps, syntactic foam, and lead or steel ballast. They can be further classified as ‘Reversible’, or “capable of providing at least one positive and negative cycle during a dive” and ‘Irreversible’, or

able to “provide only a one-time, one-way function” (Busby, 1976, p. 285). The worksite stability and agility of HOVs will vary somewhat depending on these systems. As a rule, ROVs are positively buoyant and must operate their thrusters continuously to remain submerged. Some designs do employ variable ballast systems that enable the ROV to maintain neutral buoyancy underwater, or provide additional payload capability (Busby, 1979).

The use of a variable ballast system increases platform stability, and enables HOVs to hover without use of thrusters, which “minimizes sediment or flow field disturbance; enables fine manipulation of fragile equipment, samples, or experiments even in regions of rough topography; and allows quantification of objects on the bottom ...and in the water column...” (Ocean Studies Board, 2004, p. 71). The *Johnson Sea Link* submersibles, for example, were renowned for their ability to conduct mid-water sampling and research. Several scientists attributed this stability, and the HOV pilots’ skill in taking advantage of this feature, to a superior ability to collect small, elusive, and/or fragile marine samples (Scientists K, L, P, S).

3.1.4.2 Payload and manipulators

In past literature, HOVs were noted for superior robotic arms, or manipulators, and ability to transport large amounts of samples to the surface (UNOLS, 1990). In large part these capabilities have converged, as deep ROVs are able to support the same manipulators as HOVs, and ‘elevators’ have been developed to bring ROV samples to the surface (Ocean Studies Board, 2004, p. 69, 2015).

3.1.4.3 Noise

Electric and hydraulic systems that control thrust, trim (via air ballast or movable weights), and manipulators on both HOVs and ROVs emit noise into the ocean environment (MTS ROV Committee, 2016a). The amount of noise will depend on the system design, and on how frequently the system(s) must be used given the buoyancy of the vehicle and environmental situation. One scientist noted that “the (ROV) hydraulics actually scream” (Scientist P), whereas HOVs, which are better able to remain neutrally buoyant without use of thrusters, are typically quieter. The impact of this noise varies depending on the task, and is an especially important and active field of research for fisheries science (Laidig, Krigsman, & Yoklavich, 2013; O’Connell & Carlile, 1994; Rountree, Juanes, & Blue, 2002; M. M. Yoklavich, Reynolds, & Rosen, 2015).

3.1.4.4 Ruggedness

The value of physical indestructability, or toughness, of HOVs was cited by users of the small *Delta* submersible, which was built for geological studies, and “ruggedized to...have access to more complicated terrain” (Scientist O). This factor is similar to but not equivalent to that of reliability (Section 3.2.6).

3.1.5 VISION

All men by nature desire to know. An indication of this is the delight we take in our senses; for even apart from their usefulness they are loved for themselves; and above all others the sense of sight. For not only with a view to action, but even when we are not going to do anything, we prefer seeing (one might say) to

everything else. The reason is that this ‘seeing,’ most of all the senses, makes us know and brings to light many differences between things. (Aristotle, 350AD)

The human eye is a complex instrument; it provides high definition, fast focusing, color discernment, depth of field, three-dimensional awareness, and peripheral vision. Although comparisons between the human eye and cameras are not straightforward because of the complications of eye anatomy, central and peripheral vision, and the involvement of the brain in what we actually ‘see’ (Cambridge in Colour, n.d.; Cicala, 2012; Weitz, 2016), video and camera technology in use today can closely replicate many of the capabilities of the human eye (Ward, 2015).

A few research circumstances do still exist in which the human eye detects anomalies that are difficult if not impossible to see via video, such as heat-shimmer of water over a vent system (Engineer I) but additional capabilities of cameras, such as low light and multispectral technologies, are providing research advantages. The zoom capability of cameras has led some HOV scientists to rely more on the view on an internal video screen than the view out a submersible window (Scientists N, U), and brings undersea life ‘up close’ to unlimited viewers via telepresence (NOAA Ocean Exploration, n.d.-a). One scientist using NOAA’s *Deep Discoverer* ROV noted, “One thing that was excellent about the ROV was...the ability to zoom the camera in on targets in the distance and get a better sense of what it looked like that was better than our own eye” (Scientist T).

Infrared and sonar technologies are providing increased visioning capabilities in low visibility situations (Brahim, Gueriot, Daniel, & Solaiman, 2011; Chidami, Guénard, & Amyot, 2007; Dragland, 2016) and detection of bioluminescence (Jabr, 2010).

Until extremely recently there was nothing out there that was as good as the human eye for actually seeing bioluminescence. We actually have now camera systems that are able to record a little bit more than what the human eye can see.
(Scientist P)

3.1.5.1 Stereo

“The strongest argument for HOVs is that there is no replacement for in situ human three-dimensional visualization and situation awareness” (Ocean Studies Board, 2004, p.100).

Stereoscopic, or 3D, video movies and headsets for entertainment, gaming, and military use have come a long way since Sir Charles Wheatstone’s 1833 reflecting mirror stereoscope (The Turing Institute, 1996). Like regular video, stereo capability can be used for both post-recording analysis and real-time observation. The use of stereo and panoramic video technology is also not new to the underwater world (Klevebrant & Svensson, 1983). In the past decade, use of stereo for marine research post-recording analysis has become an operational capability for fisheries science (Boutros, Shortis, & Harvey, 2015; Letessier et al., 2013; Mallet & Pelletier, 2014; Murphy & Jenkins, 2010; Williams, Rooper, & Towler, 2010) and coral research.

Currently with ROVs or with subs, the video we have is our data, and the scale is the laser in the video. I can measure one colony at a time...with 3D cameras I can

measure a half dozen colonies, whatever is in the frame, because I can triangulate.

I get better areal and size estimates with stereo cameras. (Scientist D).

3D capability has been used extensively for marine archaeology (Henderson, Pizarro, Johnson-Roberson, & Mahon, 2013; Hiltz, 2014; Lange, 2015; Woods Hole Oceanographic Institution, 2015c). This 3D work includes post-expedition modeling, which, with 3D printers, can produce a physical replica of an object that can remain undisturbed on the ocean floor (Fox, 2014).

Stereo vision for real-time control of remote vehicles has been in development for decades (Corke, 1996; Hightower, Smith, & Wiker, 1986; Ishibashi, 2009). Scientists who have used earlier iterations have reported mixed results, in one case saying that “...believe it or not, (3D) became very distracting to us. We were sitting there in the control room, and a fish would come flying out of the screen at you, and you would duck. [We] ended up taking it off...” (Scientist E). Visual system engineers who have tested 3D systems with a number of ROV pilots report that, “There’s somewhat of an age bracket where the older long-time pilots don’t really want it, younger are more interested in it” (Engineer G) and have observed that “most of the seasoned ROV operators have learned how to do 3D to 2D conversion in their head, where 3D helps less experienced people more than the very experienced people” (Engineer I).

Although stereo capability has been integrated in some research areas, the cost and availability of 3D systems still restrict their use in many marine research venues (Engineers B, H).

3.1.5.2 Panorama

The free-swimming diver comes closest to exercising directly his senses in the ocean (primarily seeing, touching, and hearing). The man in the manned submersible, however, is sensing his environment remotely, except for one sense: that of sight... Therefore, the primary reason for placing man at the scene is to make use of his active, interpretive ability to see... Where man's presence at the work site is essential, he should be given panoramic visibility to enable him to use his sight freely. Manned submersibles with large viewports or transparent pressure hulls are preferable. (Talkington, 1976, p. 1,9)

Engineering and the physics of the high pressure deep-sea environment have limited the use of transparent pressure hulls to relatively shallow depths—deep submersibles use thick acrylic cones as viewports (Winner, 2014). Although the argument for panoramic vision ostensibly then applies primarily to shallow submersibles that offer the increased visibility of glass or acrylic spheres, users of *Alvin* and *Pisces* report that the ‘corner of the eye’ and actual range of visibility through the 4–7” viewports are still an asset of HOV use (Scientists G, M).

If one asks for the single attribute which links the use of manned submersibles with good science, the most often heard answer is the confidence one has in knowing the orientation and spatial relationships of the object that is being measured or sampled. (UNOLS, 1982, p.5)

One submersible engineer described the advantage of this wide range of vision by using the analogy of walking to the front of a classroom to retrieve a piece of chalk from a

chalkboard: as you navigate between the desks, your brain characterizes the room so that even before turning to leave, you know what the possible exit routes are (Nuytten, 2012). More specific advantages of panoramic awareness are discoveries that have been made because of that peripheral vision (Scientists D, L, O, Q), and an overall ecosystem awareness:

For example, sitting on a seamount in a submarine (where it is) shallow enough to have ambient light; you can see a whole ecosystem at work, can put together the pieces because you're there witnessing it yourself. Machines don't do that very well. They can do what you tell them, [they] can find limited patterns. (Engineer B)

Most agreed, though, that the benefit is difficult to quantify:

I remember particularly in the Gulf of Alaska, diving with *Alvin*—you look at the video you see, here's a coral, a couple meters later, you'd see here's another coral, it was a low density habitat. But when you look out the side view, you could see that it went on forever, so it gave me a lot better understanding of the habitat...but I can't put that in a science paper, except maybe in the discussion. I could say, and, by the way this habitat seemed to continue in all directions. But unless I could measure it, I wouldn't be able to report it in a scientific paper. (Scientist D)

Panoramic still and video cameras are now widely available and increasingly being used in the marine environment (GoPro, n.d.; Kodak, 2016; Leonard, 2016; OceanGate, 2014). The Woods Hole Advanced Imaging and Visualization Laboratory has developed a real-time visualization system that mimics human vision with 3D on a

forward screen, and HD views on two side screens, providing a 150-degree field of view. Engineers noted that the combined system “surprisingly was very, very warmly received” and “a win-win with experienced (ROV pilots) in that it was something they hadn’t had before” (Engineer H). As with stereo capability, cost and availability were cited as factors that challenge more extended use of this capability (Engineers B, H).

3.1.6 BEING THERE

The chief advantage and glory of manned submersibles is clearly the human intelligence onboard. Allyn Vine, who championed the idea of submersibles in the 1950s, viewed this human presence—constantly sensing, probing, adjusting, guiding—as irreplaceable...The best possible instrument aboard the Beagle? Charles Darwin, of course.” (Ballard & Hively, 2000, p. 227)

The capabilities provided by ‘being there’ are classified within the technical rather than functional quadrant because, although they are a result of human presence, the impact is due to the physical aspect of that presence more so than a behavioral decision. These factors are perhaps the most elusive to quantify in the discussion of human versus robotic capabilities, but perhaps the most discussed. Specific advantages of ‘being there’ that are cited include: contextual awareness, which encompasses not only the use of peripheral vision as described above, but also the more subtle sound and motion cues that are experienced on site; the ability to react and adjust; and the improved efficiency that comes with the mental focus of full ‘immersion,’ if you will, in the task. A NASA operational exploration research team has coined the term ‘Real-Time Intellectual Resolution’, “i.e., the ability to perceive and react to the environment in a meaningful

manner” (Lim, 2015) to describe the advantage of the manned aspect of coordinated manned and unmanned exploration systems, ascribing superior decision-making, responsiveness, and discovery abilities to this ability (Trembanis et al., 2012).

Submersible designer and entrepreneur Phil Nuytten asserts:

Why do we have men in the space station, why not just machines? In the end it’s all about getting man with his wonderful computer up on the top of his shoulders and his hands, and his hand-eye skills, and his coordination, his imagination and all of his senses to that place so he can do what man does, or she for that matter. (Nuytten, 2005)

The qualities of human presence are cited as being particularly advantageous for activities beyond routine and predictable ‘dull, dirty, and dangerous’ tasks (General Electric, n.d.; Takayama & Ju, 2008) such as exploration, where contextual awareness allows for the development of hypotheses and identification of anomalies; and scientific field work that, much like surface geology, requires an understanding of the geographic context to understand processes.

The space community lends insight and experience to the manned exploration discussion, as John Glenn wrote in response to an ocean exploration inquiry:

In short, man’s ability to rapidly perceive, analyze, and relate an experience provides the most beneficial results from such an exploration. ‘Serendipity’ is the word for it—the encountering of good things unforeseen at the outset...I believe it is safe to assume that with man’s on-the-spot curiosity, adaptability and

reliability, this manned space exploration will eventually result in the greatest possible information and rewards. (Terry, 1966, p. 223)

A thought-experiment analogy emphasizes the capability aspect of the discussion: “How does a robot replace a team of scientists searching for new species in a tropical forest?” (Manager A) With respect to scientific discovery, NASA’s most recent Human Space Committee report concluded that:

The particular skill of humans in noticing anomalous or emergent features and events and rapidly scanning an environment for sought features is what continues to give humans an edge over robots in the context of exploratory science. (Space Studies Board, 2014, p. 62)

The importance of *in situ* fieldwork for ocean sciences has long been recognized, here by one of the first two men to descend to the deepest point in the ocean, Dr. Don Walsh:

Without rehashing the standard arguments about ‘why man?’ the idea of placing the trained mind and eyes at the site of investigation is certainly not novel. In general, the scientist depends on *in situ* examination of the object of his studies. It is not enough to have some third party take samples from their natural environment and bring them back to the scientist’s laboratory. He must study the context from which the samples came and their relationship to their natural environment. (Geyer, 1977)

Or, in the words of a marine geologist: “This [*in situ* work] is why skilled crime scene investigators walk around crime scenes and don't just take photos” (Scientist Q). The case

studies in Geyer's "*Submersibles and Their Use in Oceanography and Ocean Engineering*" (1977) provide thorough discussion and examples of this in situ research value of manned presence (Geyer, 1977, Forward, p.X).

One advantage of human presence that emerged more often in interviews than in older literature is the ability to be focused while in a submersible. Given that the increased number of ROV and telepresence missions in the past 10 years has provided more of a contrasting experience, this relatively recent recognition is perhaps not surprising.

Scientists working in *Alvin* consistently describe themselves as focused and conscious of every sensation throughout their dives. To engage the human consciousness at this level requires nothing short of complete physical presence...a fully engaged researcher making observations and sampling on the seafloor using an HOV is more effective and accomplishes much more than the equivalent hours spend observing and sampling using current ROVs. (Fryer et al., 2002, p. 533)

Another scientist suggested that this focus results in more comprehensive reports:

If you put a scientist in front of a flat screen and said 'look and tell me what you see and write it up when you come back', and do the same thing in a submersible, I'll guarantee you that... scientist will be more detailed in his description of the seafloor and what's happening after being down there first hand, in situ looking at it than he would looking at it [from] behind a screen. (Scientist E)

From a visual system engineer: “In the submarine...your senses are all attuned to what’s going on there. That’s as important as being able to replicate the view out of the porthole of the submarine, we know we can do that” (Engineer H).

These observations can be compared to the mentally focused state of ‘flow,’ described by psychologist Mihaly Csikszentmihalyi (1990, p.4) as “the state in which people are so involved in an activity that nothing else seems to matter.” Although developed to explain happiness and contentment, the concept of flow is also attributed to enhanced performance (Nakamura & Csikszentmihalyi, 2014). Research into the measurement and effects of flow offers an opportunity to gain further insight into the impact of ‘being there’ (Nakamura & Csikszentmihalyi, 2014; Schweinle & Bjornestad, 2009).

The disadvantages of ‘being there,’ including physical discomfort (Figure 3-3) and reduced efficiency, are also well discussed.

At a certain point you transition from wanting the experience, wanting to be there, to just being a boring old scientist and you just want the data and the samples—you don’t care. It’s important to have that singular experience...but I think once somebody’s done it and they’ve dealt with some of the issues like ‘where do I go to the bathroom’ and ‘where do I stretch out my legs,’ then after they see some of the drawbacks of being packed in a small space for a while, they get interested in other things. (Scientist D)

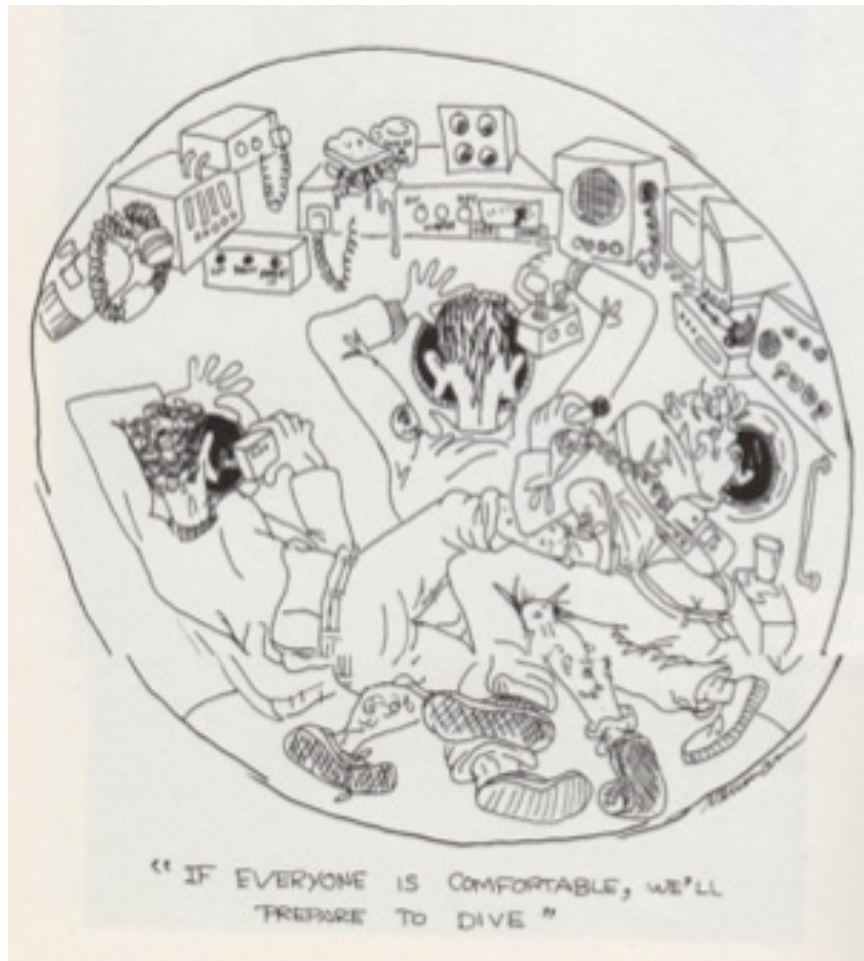


Figure 3-3 Cartoon depicting life onboard *Alvin* (by Conrad Neumann, from Kaharl 1990 p.212).

Dr. Robert Ballard states that physical limitations and efficiency considerations contributed to his efforts to move away from HOVs and towards remotely operated vehicles, and connected capabilities:

The human race has evolved itself into a corner, like the koala bear that can only eat eucalyptus or the panda that can only eat bamboo shoots. The point is that we can only live on a fraction of the planet, and we'd better get used to that. I began

to think that telepresence was the way to go because I was tired of being in an elevator; what percentage of my dive time was spent getting to and from the job? [Telepresence] came more from efficiency, and because we don't get much money - how do we maximize our bottom time?" (R. Ballard, personal communication, November 20, 2015).

3.1.6.1 Virtual reality

As with visual systems, remote conceptual capabilities are converging as robotic technologies improve. As predicted more than two decades ago:

Manned or Unmanned? Eventually, it won't matter...Manned subs still give us better stereo and peripheral vision, more operational flexibility, and the immediacy of being there; ROVs have greater endurance and lower operating costs but can suffer from tunnel-vision, clumsy maneuvering, and a sense of detachment. However...further advances in robotic control systems, stereoscopic and high definition video, low-light and acoustic imaging will bring a time when robot technology is so 'transparent' that a human observer on a ship or in an office cannot tell by any objective sense that he is not in the ocean, directly controlling his actions (i.e. 'telepresence'). ... With the further development of technology in imaging, control and artificial intelligence, not only will the contrasts between manned and robotic approaches to in situ oceanography diminish, but our formerly 'blind' samplers can be equipped with enough real-time and real-place information to erase the in situ distinction altogether. (Madin, 1990, p. 21)

The Committee on Human Spaceflight recently concluded that:

The relative benefits of robotic versus human efforts in space science are constantly shifting as a result of changes in technology, cost, and risk. The current capabilities of robotic planetary explorers...are such that although they can go farther, go sooner, and be much less expensive than human missions to the same locations, they cannot match the flexibility of humans to function in complex environments, to improvise, and to respond quickly to new discoveries. Such constraints may change some day. (Space Studies Board, 2014, p. 2)

The emerging technology just over the horizon that best addresses ‘being there’ is that of virtual reality (or full 360 degree), 3D immersion in a digital environment. The capability has made stumbling advances in the past, and is admittedly still ‘in its infancy,’ but recent industry attention—within gaming, travel and real estate industry—indicates that its commercial availability is accelerating (Bajarin, 2016).

3.1.6.2 Human-robot interactions

The rapid advances in autonomous technology have also led to evolving perspectives on the role of man-in-the-loop. Marine robotics engineer David Mindell (2015) identifies three ‘mythologies of twentieth century robotics and automation’: the myth of linear progress, the myth of replacement, and the myth of full autonomy. Through an examination of case studies of robotics and autonomy in his book *Sea, Air, War, and Space*, Mindell concludes that “it is not ‘manned versus ‘unmanned’ that matters, but rather, where are the people? Which people? What are they doing? And when?” (2015, p.15).

This realization is not new; in 1983 John Craven, former chief scientist of the Navy's Special Projects Office (Craven, 2002; Hoffman, 2005; Schudel, 2015), noted in a conference keynote speech that:

There should be no debate that all our underwater systems are man-machine systems extending or amplifying human performance in the sea in its most cost-effective configuration for a specified mission... such a concept neither requires nor eliminates the need for humans to be located in or under the sea, but ...with advanced technology, we may indeed find the human in the sea far more frequently than one might first imagine. (Craven, 1983, p. 2)

This perspective has largely evolved into the formal research field of human-robot interaction (HRI), which has been the topic of an international conference since 2006, and a dedicated journal since 2012 (Human-Robot Interaction Conference, 2006; Journal of Human-Robot Interaction, n.d.). NASA in particular has sponsored significant research in the field (Google Scholar, 2016).

3.1.7 FACTORS AND COMMENTS

The factors that emerged from this discussion for use in case studies are presented in Table 3.1 below, with a notation of influence from other quadrant factors. There is an inherent dependence of the value of a capability on the particular type of research activity (quadrant C) being conducted; this dynamic will be reflected during case study evaluations.

Table 3.1 Quadrant A Technical Impact Factors, related quadrants, and comments

Factor	Cross- Quadrant Impact	Comments
Maneuverability		Environment and mission can influence value of tethered and untethered operations
Time on Site	B, C	ROV bottom time strongly influenced by mission (i.e. research or exploration) and/or operating costs
Connectivity		Real-time shipboard and telepresence participation
Structure		Stability, payload and manipulators, noise, ruggedness
Vision		Human eye comparison, stereo, panorama
Being There		‘Real-time intellectual resolution’, pattern recognition, immersion, virtual reality and human-robot interaction

3.2 QUADRANT B: OPERATIONAL FACTORS

Operational impacts of factors directly related to system sustainment that originate from beyond the specific mission activity are addressed in quadrant B. These are often business-enterprise level concerns, and include cost and business model considerations, regulatory and safety (legal) guidelines, local availability of a particular piece of infrastructure, and behavioral factors that directly affect physical operation, i.e., operating team expertise, safety performance and equipment reliability. Financial considerations are equipment and operation-specific (reflecting capital costs, personnel requirements and launch methods), and differ from the external funding factors discussed under quadrant D. These factors all contribute to answering the question: ‘What forces influence the business-level sustainment of the system?’

3.2.1 FINANCIAL FACTORS

Cost is widely recognized as a primary driver for marine infrastructure selection (Ocean Studies Board, 2011, 2015; M. M. Yoklavich et al., 2015). The most recent analysis of NSF ocean research infrastructure includes a conceptual diagram of cost versus relevance to research goals of those assets (Figure 3-4).

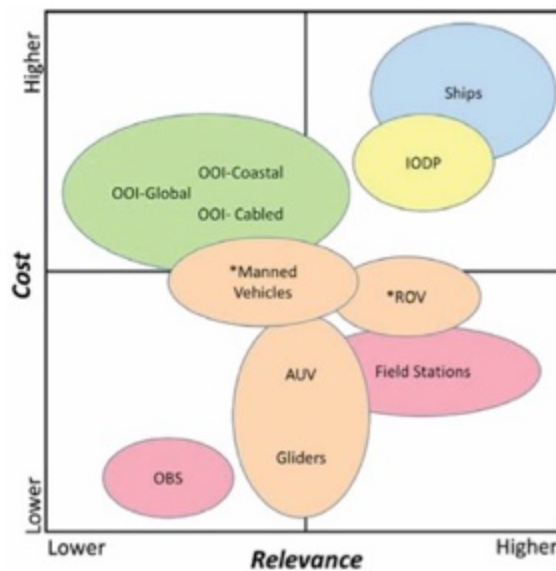


Figure 3-4 Relative cost versus relevance conceptual diagram of NSF OCE research assets. (* Cost of support vessel was not included) (Ocean Studies Board, 2015).

Financial and economic factors for use of undersea systems include capital and operating costs, as well as consideration of the business model; i.e., ownership versus leasing, and public versus private or industry versus academic host. Capital costs vary by depth rating and equipment complexity, whereas operating costs are typically driven by surface support and personnel time.

3.2.1.1 Capital costs

The cost of constructing a deep HOV today can range from the \$10 million contribution reportedly spent by James Cameron on his 11,000 m-rated *Deepsea Challenger* (Broad, 2013) to the \$74 million cost of the 7000 m-rated Chinese *Jiaolong* (Xinhua, 2012). Upgrades to *Alvin* in 2012–2014, including a new personnel sphere and other 6500 m-rated hardware, cost \$40.9 million (Ocean Studies Board, 2015). The private submersible company Triton has advertised a \$25 million price tag for a 36,000 foot-capable vehicle under development (Davis, 2014). Deep research ROVs, by contrast, cost on the order of \$6 million for 3000 m capability, and \$2–5 million for 1000 m- to 3000 m-rated vehicles (D. Michel, personal communication, August 24, 2016; B. Midson, personal communication, April 5, 2016).

The capital cost of a shallow submersibles (< 1000 m) is typically between \$1 to \$5 million (Spence, 2013); the emergence of the private yacht submersible market has increased the availability of these vehicles. Similar depth-rated ROVs usually range between \$250,000 to \$500,000 (Engineer R). Small, very shallow (<100m) systems are available for less than \$6000 (Video Ray, 2016).

For the purposes of this assessment, capital cost for submersibles is usually a ‘sunk cost’, i.e., the submersible has already been purchased, and so capital cost factors will become impactful when considering upgrades and alternatives.

3.2.1.2 Operating costs

Operating expenses depend primarily on the support vessel and number of personnel required for safe operations. Costs for deep research HOVs and ROVs are typically similar: both require large vessels, robust handling systems, and similar numbers of personnel. The NDSF's operation of *Alvin* and *Jason* provides a comparison mechanism; over the past decade, the day rates and annual operating costs (through some variance due to overhaul and repair requirements, shipping fees, and additional temporary personnel) have on balance been within about 5% (Midson, 2016; National Deep Submergence Facility, 2016); the 2014 day rate for *Alvin* (\$16,000) was less than that for *Jason* (\$23,000) (Ocean Studies Board, 2015).

Shallow-system operational costs vary depending on launch mechanism, vehicle size and distance from shore. HOVs typically require larger and more expensive launch mechanisms than ROVs; the smallest shallow ROVs can be operated by hand from a small boat. Operating cost differences between public and private operations will also vary because of insurance requirements: government-sponsored activities are self-insured, whereas private enterprises must invest in liability protection.

3.2.1.2.1 Launch alternatives

Submersible designers and operators have employed a variety of alternative launch mechanisms that reduce or eliminate the dependence on a large, expensive support vessel. For near-shore operations, submersibles can be launched from a towed platform (Kerby, 1991; OceanGate, 2016), or self-propel to nearby dive-sites (Stanley, 2016;

Substation Curacao, 2016). The *Delta's* lightweight design enabled it to be lifted by smaller cranes, and therefore smaller vessels. Its launch and recovery procedure involved using the crane to lift the unoccupied sub into a secure position alongside the support vessel, where passengers embarked and disembarked. (Section 3.2.2.3 discusses considerations with respect to requirements for human-rated lifting systems). The use of a catamaran-style design for the support ship, in which the submersible is cradled within the ship's structure, was used for the early *Moray* 'manned torpedo' (Forman, 1999, p.262), and is seen today in the submersible yachting industry (U-Boat Worx, n.d.).

3.2.1.2.2 Telepresence

The advancement of telepresence has offered the opportunity for increased shipboard personnel efficiency through remote scientific and even maintenance participation; although this has not yet revolutionized shipboard costs, it is the subject of continued attention (Scientist C).

3.2.1.3 Unit cost per observation

Another aspect of cost, which was recommended by the Ocean Studies Board (2011), is consideration of cost in relation to data collected, i.e.: "What is the unit cost of observation (cost per unique observation) provided by this infrastructure, and how does the cost compare to that of other forms of measurement for the same information?" (p. 55). This approach combines factors from Functional Quadrant (C); whereas determination of unit cost of observation is a complex undertaking that is beyond the

scope of this study, identification of it as a factor is instructive as a component of the model.

3.2.2 BUSINESS MODEL

The business model factor considers a range of circumstances including the ownership of the system (i.e., public or private), the nature and capabilities of the operating organization (i.e., industry or academic), and the funding mechanism (i.e. lease, contract, or grant). Organizations that operate government-owned equipment enjoy a relative security of consistent support, but may be subject to limitations regarding use. Ownership provides control over the operational agenda, but also requires significant administrative and shore support, including the need to maintain a qualified personnel cadre. During times of constrained funding, different institutions are more and less able to retain these subject matter experts within the organization so that they are not lost to the operation if and once funding is restored. Business model-related considerations that enabled the Texas A&M university-sponsored *Diaphus* submersible program viable submersible operation during the 1970s included:

- (1) The submersible is totally paid for.
- (2) The pilots do not depend on the submersible program for their basic salaries, insofar as they devote only part-time to submersible operations.
- (3) The system is relatively simple and easily maintained.
- (4) Operating expenses are low.
- (5) No profit motive exists (Geyer, 1977, p. 105)

The NDSF response to the Sea Change report (2015) noted that the ability to draw from a multi-skilled team of technicians contributes to the success of the NDSF: “The facility model (characterized as ‘subsidized use’ in the [Sea Change] report), is one of the key mechanisms to enhance personnel. The larger group produces collaboration, skills enhancements, and a dynamic environment that attracts personnel” (Soule, 2015, p. 9).

The leasing model supported Delta Oceanographics (who operated the *Delta* submersible) and its research partners for several decades. The use of industry ROVs leased for research has had mixed reviews: a project that has sponsored valuable marine research with ROVs near offshore oil rigs (SERPENT, 2016) has been a success, but NOAA programs have reported challenges in navigating differences between scientific and industry equipment and operating cultures (Managers G, N). In response to an Ocean Studies Board (2015) suggestion to include consideration of funding wider range of private and international ROV and AUV systems for research, the Chief Scientist of NDSF noted:

The cost of commercial ROVs and AUVs are generally higher than day rates for [the ROV] *Jason* & [the AUV] *Sentry*; commercial ROVs and AUVs are not designed to respond to the needs of science users as purpose-built ROVs like *Jason* & *Sentry* in terms of incorporating new sensors, operating in unusual environments, and providing (quality controlled) data; and commercial pilots and operators are not as skilled in the types and diversity of tasks required by the science community. (Soule, 2015, p. 12)

The market for submersible research is also a primary business consideration for a privately supported initiative: “Why didn’t anyone copy [*Delta*]? The thing is a supply and demand issue—[there is] only so much demand. We can’t use a dozen of them” (Scientist O); and: “With these different vehicles, the issue becomes you have to keep everybody busy enough so where they’re still there when you need them” (Scientist A).

Business model considerations are inherently linked to enterprise-level support factors discussed in quadrant D.

3.2.3 SAFETY PERFORMANCE

Safety is one of the most important and frequent concerns noted in evaluation of HOVs. The aspect of safety encompasses a number of elements, including design elements and construction of a particular vehicle; the organization’s safety processes and procedures; the expertise of the system operators; the safety performance record; the certification and classification regulations and inspections (system-enterprise concerns); and the perception of risk by clients (a client-enterprise factor).

Appraisal of the ‘safeness’ of the physical design and construction of a vehicle may be subject to individual views (i.e., inherent safety of single-person submersibles) but official assessment of this construction is through the certification/classification process, described below. The behavioral use of a vehicle is an important impact on assessment of safety. Busby (1976) describes 37 submersible incidents that occurred in the early days of submersible activity, categorized under causes of: buoys (surface buoys that used to be used to track submersibles), entanglement, separation from support craft, loss of electrical power, environmental hazards (natural and manmade), launch/retrieval

incidents, and operational incidents. His work and that of the Chairman of the Marine Technology Society's Undersea Vehicle Safety Standards Committee, who analyzed 20 submersible incidents for his committee's study, resulted in the conclusion that "good seamanship and maritime sense paralleled that of sound submersible design" (Busby, 1976, p. 695; Pritzlaff, 1972).

Safety records are compared officially through the use of a standard incident rate established by the U.S. Bureau of Labor, which is based on 100 employees working 40 hours per week, 50 weeks per year (200,000 hours) (OSHA, n.d.). The U.S. Research Vessel Operators Committee (RVOC) safety subcommittee (of the academic oceanographic coordinating body, the University National Oceanographic Laboratory System (UNOLS)), tracks UNOLS shipboard safety incidents on quarterly and annual bases, recording between 15 and 25 at sea incidents per year since 2004. Statistical incident rates for individual HOV operations can be calculated from records that are required to maintain certification.

The primary safety concern for HOVs, however, is the risk of fatality. The research submersible community has experienced one fatal incident, in 1973, when the *Johnson Sea Link I* submersible was trapped by underwater debris. The dive had been planned as a short excursion, and two occupants of the separately pressurized diving chamber of the submersible perished before the sub could be recovered, 32 hours after becoming trapped (Forman, 1999).

An additional behavioral consideration with respect to safety is a tendency for accidents to occur to operators at the ends of the experience spectrum. "The fatalities and

serious incidents occur to the newbies and the oldsters” (Manager A). The concept of ‘normalization of deviance’, or “the gradual process through which unacceptable practice or standards become acceptable” (Boe, 2013), which was developed by Diane Vaughan during her analysis of the 1986 Challenger explosion (Vaughan, 1997; Whitehead, 2009), offers scholarship to further address this issue.

3.2.4 CERTIFICATION

Certification and classification are methods by which the safety of vessels is evaluated and maintained. A short review of classification and certification of marine vessels provides background of considerations faced by users and sponsors of submersible support vessels, translated then to issues regarding the submersibles themselves.

3.2.2.1 Oceanographic research ships

Marine vessel classification is “a system for the independent technical assessment” of ships that is intended to “verify the structural strength and integrity of essential parts of the ship’s hull and its appendages...” (International Association of Classification Societies, 2011, p. 4). A vessel is issued a certificate when it meets the rules of a classification society as verified by relevant surveys; compliance is typically referred to as being ‘in’ or ‘out’ of class (early classifications used letters and numbers to indicate the condition of hulls and equipment, giving rise to the expression ‘A1’ for ‘highest class’). The International Association of Classification Societies consists of twelve classification societies (International Association of Classification Societies,

2011). U.S. vessels are typically, but not required to be, classified by the U.S. member of IACS, the American Bureau of Shipping (ABS).

Within the U.S., marine research vessels are subject to U.S. Coast Guard (USCG) regulation and inspection requirements as oceanographic research vessels (ORV or R/V) (Designation of Oceanographic Research Vessels, 2012). This research vessel designation, originally established by the Research Vessel Act (RVA) of 1965, provides relief from passenger and cargo vessel standards that are inappropriate for research activities (D. Nixon, 1987; D. W. Nixon, 2000; Sacks, 1995). The U.S. stakeholder group responsible for initiating and supporting the RVA, the Research Vessel Operators Council (RVOC), organized in 1962 for that purpose and which remained active after passage of the Act. In 1970, the RVOC was incorporated into the newly established University National Oceanographic Laboratory System (UNOLS) organization (Dinsmore, 1996).

The RVOC created the first Research Vessel Safety Standards (RVSS), published in 1976 (Dinsmore, 1996), in response to loss of a small, 48-foot R/V, the *Gulf Stream*, with all 5 hands off the U.S. northeast coast in 1975 (Bogorff & Jacobs, 2006). Compliance with these standards is required for an institution to maintain membership in the UNOLS organization. The tenth edition of the RVSS was released in 2015 (UNOLS, 2015b), and includes guidance for HOV operations.

3.2.2.2 Submersibles

Submersibles are also subject to classification requirements; the American Bureau of Shipping (ABS) has issued specific guidelines for classification of human-occupied

submersibles, and other hyperbaric facilities, since 1968. The American Society of Mechanical Engineers' (ASME) *Pressure Vessel for Human Occupancy* (PVHO) standard, initially developed in 1974, provides design and fabrication guidelines that are used by many classification societies (American Society of Mechanical Engineers, 2007; Nuytten, 2013; Workman & Maison, 1998).

U.S. federal oversight of submersible operation, however, has been less straightforward than that for research ships. In 1968, the U.S. Coast Guard established the Underwater Safety Project (USP) to address the then-growing demand for underwater vehicles, and an anticipated need for U.S. Coast Guard jurisdiction over this industry, but it was terminated when expectations for broader use of submersibles waned (Marine Board Commission on Engineering and Technical Systems, 1990; U.S. Coast Guard, 1993). The Marine Technology Society, a non-profit professional organization, published three sets of non-binding submersible safety guidelines during this time (MTS Undersea Vehicle Committee, 1968, 1974, 1979). When the Atlantis Submarine company proposed operations from St. Thomas, U.S. Virgin Islands, in the mid-1980s, the U.S. Coast Guard reengaged, providing certification for the submersible *Atlantis III* in 1987, and in 1993 publishing "Guidance for Certification of Passenger Carrying Submersibles" (U.S. Coast Guard, 1993) which provides guidance for submersibles or submarines carrying more than six passengers. Small submersibles carrying fewer than six passengers, however, must meet "Uninspected Vessel" requirements (Uninspected Vessels, 2015; U.S. Coast Guard, 2016), but do not receive validation, through certification, by the U.S. Coast Guard. Recreational submersibles are subject to the "Boating Safety" requirements for

pleasure boats (Boating Safety, 2015), although the USCG acknowledges that: “the guidelines of this circular generally do not apply” (U.S. Coast Guard, 1993, p.4).

Lately, this absence of an official certification has been detrimental enough to an emerging private submersible industry that the chairman of the Marine Technology Society’s Manned Underwater Vehicle committee convened a subcommittee under the American Society of Mechanical Engineers Pressure Vessels for Human Occupancy (ASME PVHO) to revisit these private and industry submersible operational certification issues (Kohnen, 2016b).

Research submersible certification issues within UNOLS have been historically focused on *Alvin*. As a Navy-owned system, DSV *Alvin* had always been certified under U.S. Navy deep submergence system certification requirements (Naval Sea Systems Command, 1998; U.S. Coast Guard, 1993; Woods Hole Oceanographic Institution, 2015b) and as such did not require RVSS-like guidance. In mid-2000, however, consideration of certification of an upgraded *Alvin* by the American Bureau of Shipping (ABS), and a proposed use of the *Delta* submersible from a UNOLS vessel, called for a need to clarify submersible launching support (man-rated crane) requirements (Managers C, E, G). The *Alvin* ultimately remained under Naval Sea Systems Command certification authority, but the committee that was established to address this need published a UNOLS Human Occupied Vehicle Safety Standard and an RVSS chapter dedicated to HOVs in 2009 (UNOLS, 2009b, 2009a). Like the RVSS, the UNOLS HOV standards are provided as voluntary guidelines for member institutions, and are used in evaluating federal funding support.

3.2.2.3 Launch and recovery

“It is generally agreed that the most dangerous part of operating a deep submersible occurs at the air/sea interface” (MTS Undersea Vehicle Committee, 1974, p. G-5). Most modern research submersibles are launched from their support vessels while operators are inside, requiring the lifting mechanism to meet Occupational Safety and Health Administration (OSHA) 'Hoisting Personnel' standards (Cranes and Derricks in Construction, 1979). The *Delta* and *Nekton*-class submersibles were designed with an entry turret that provides a high freeboard, allowing operators to enter and exit the submersible while it is secured alongside the support vessel. The UNOLS HOV guidance (2009) states: “If the handling system will ever be utilized while the HOV is occupied in the lift/launch/recovery/deck-transfer modes, it must be rated for such service by ABS, NAVSEA, or another appropriate classification society” (OSHA, 1979). The consideration of the possibility for use of a non-certified crane in emergency situations, as well as, in the case of *Delta*, the hoisting of the submersible above the water's surface while loading and unloading, limits federal sponsorship of such submersible operations (Managers C, P, Q).

3.2.5 OPERATING TEAM

An impact on success that is not well documented in literature, but that emerged strongly during this study, is the value of the expertise of the team of personnel who operate a submersible system. Although this factor may be considered a behavioral impact, it is included here because the influence of team expertise directly influences the

physical performance of a system. Comments similar to this from a *Johnson Sea Link* scientist—“I don’t think enough has been said about the team and the personnel that surrounded those submersibles which is what really made them hugely, hugely productive” (Scientist P)—were received from users of all systems studied here.

3.2.6 RELIABILITY AND DESIGN

Reliability, or “the ability of an item to perform a required function under stated conditions for a stated period of time” (IEEE, 1995, p.33) for submersible operations depends on the physical construction of the equipment, but is also strongly impacted by external factors such as personnel experience, expertise and training, and program support, and is closely related to the ‘operational team’ factor of quadrant D.

A related factor is equipment deterioration, which is a more straightforward technical factor. For HOVs, Pressure Vessel for Human Occupancy (PVHO) requirements for sphere and viewport life and pressure cycle must be considered (American Society of Mechanical Engineers, 2007; Stachiw, 2004).

Considerations regarding technological maturity, which influences reliability, and design flexibility were raised by the Ocean Studies Board (2011) with respect to “affordability, efficiency and longevity” of research infrastructure: “Is the infrastructure technologically mature, or are there limiting technological (or other) challenges?” and “Does the infrastructure have design flexibility to take advantage of future trends in technology (e.g., through upgrades, component swap-out)?” (p. 55).

3.2.7 AVAILABILITY

One of the recommendations of the Ocean Studies Board (2011) Critical Infrastructure Study was consideration of the question: “Is the infrastructure broadly accessible to the ocean research community? Does it promote or leverage community talents or capabilities?” (p. 55).

Availability of infrastructure is more typically the result of regional and historical choices by oceanographic institution leaders and scientists than top-down portfolio decisions. These regional investments often lead to the conduct of increased research operations with a specific piece of equipment in areas close to the host institution. Texas A&M’s *Diaphus* in the 1970s (Geyer, 1977, p. 98); and the Monterey Bay Aquarium Research Institute’s ROVs (MBARI, 1997, n.d.-b) are examples of this tendency. The Centers of NOAA’s Undersea Research Program (NURP) each sponsored different research capabilities, so that scientists within each region were more likely to become familiar with and use the technology offered by the regional Center. *Alvin* operators and users experience what has been termed a ‘yo-yo’ syndrome, as NSF projects send it and its support vessel back and forth to Atlantic and Pacific dive sites (Ocean Studies Board, 2004).

A deep sea coral manager noted correlations between prevalence of certain data collection methods and geographic location—ROV data collected off the U.S. West Coast by MBARI ROVs, submersible data collected in the Pacific region by HURL’s *Pisces* submersibles, and towed sled and dredge data collected around New Zealand and

Norway (Manager D)—this observation is confirmed for U.S. activity through examination of NOAA’s Deep Sea Coral Data Portal (NOAA, 2016).

Although availability is initially influenced by cross-quadrant behavioral factors such as preferences of the sponsors (quadrant D), it is essentially an extrinsic, physical factor when evaluated as a factor of system choice.

3.2.8 FACTORS AND COMMENTS

The factors that emerged from this discussion for use in case studies are presented in Table 3-2, with a notation of influence from other quadrant factors.

Table 3.2 Quadrant B Operational Impact Factors, related quadrants and comments

Factor	Cross-Quadrant Impact	Comments
Cost		Capital and operating costs
Business Model	D	Strongly dependent on sponsorship
Safety Performance		An ingredient of risk perception (D)
Certification		An ingredient of risk perception (D)
Operating Team		Impacts safety performance, reliability
Reliability		Some technical basis (A), strong operating team dependence
Availability	D	Location is often determined by preference of program sponsor

3.3 QUADRANT C: FUNCTIONAL FACTORS

Factors that are of interest to users of a system with respect to a specific mission activity are considered under quadrant C, and are referred to as ‘Functional impacts.’ For

the question of UMRI, the primary consideration of functional impact is with respect to its role in supporting marine research, i.e. *in situ* marine data collection. This line of investigation may also be used to explore the value of alternative functions (e.g., industry, education, tourism) that may support the availability of the equipment for research purposes, and answers the questions: ‘How is the system used, and how well does it meet these uses?’

3.3.1 RESEARCH FACTORS

Determining the components for the research-based functional factors entailed assessment of the interactions between the complex system of factors pictured in Figure 1-1. For purposes of this assessment, this conceptual diagram was simplified to consider a relatively linear representation of the infrastructure, research activities, data, and research questions of a particular science discipline (Figure 3-5).

Determining the relationships between each of these four categories remains a complex undertaking. NOAA’s Observing System Information Assessment (NOSIA) provides a qualitative system to capture this effort, but the program has not yet addressed the level of detail of identifying the linkages between research questions and particular data requirements for the *in-situ* marine research that is being examined here. The most recent National Academy of Science ocean research and infrastructure study, “Sea Change: 2015-2025 Decadal Survey of Ocean Sciences” employs a rigorous qualitative technique to assess infrastructure in comparison to research topic, but does not parse the question to the level of data or activities (Ocean Studies Board, 2015). Given that the Functional quadrant C represents the *use* of the infrastructure, the most representative and

obtainable component of this diagram to use as a factor was the ‘Research Activities’ element.

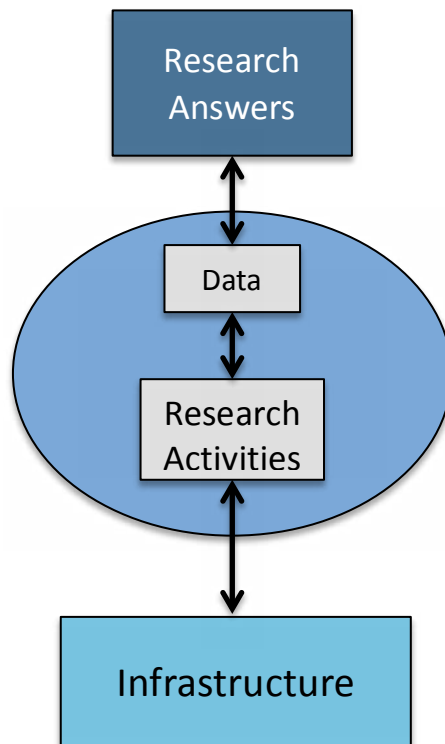


Figure 3-5 Conceptual representation of a simplified research-to-infrastructure logic chain.

Research activity categories were developed by first examining the research disciplines in which submersible systems have contributed to develop a deeper understanding of the range of study, and to seek a categorization that might lead to common activities. This analysis involved both a top-down assessment of past community submersible science studies, and a bottom-up examination of submersible system-specific logs and records.

3.3.1.1 Comparison of submersible science goals

Submersible science needs have been addressed within a variety of national ocean science reports, including overall ocean priority, ocean observatory, exploration, and discipline-specific studies (DeSSC, 2016d). For this aspect of the model development, studies that have specifically addressed submersible vehicle infrastructure needs since 1982 were selected. These include eight studies and workshops (DeSSC, 1994, 1999, 2016c; Hanson, 1986; Marine Board, 1996; Ocean Studies Board, 2004; UNOLS, 1982, 1990); and two recent National Academy Ocean Studies Board studies that included submersible vehicles in comprehensive (Ocean Studies Board, 2011) and unique (Ocean Studies Board, 2015) ways. The primary research goals identified in each report were captured and the goals were placed into categories.

The common categories that emerged from these reports are: geology, biology, chemistry, physical and air-ocean system, polar and coastal, and other. Within the ‘geology’ category, the goal of mid-ocean ridge/tectonic processes appeared in all ten reports. ‘Biological’ studies appeared in all reports, most frequently titled as benthic and water column/open ocean goals, with a growing emphasis on ecosystem and biodiversity aspects. Six reports included specific ‘chemical’ goals, most frequently related to geochemistry or biogeochemistry studies of hydrothermal systems. ‘Physical’ oceanographic research begins to appear more prominently in the most recent three reports with the rise of climate change science goals. ‘Polar and coastal’ regional goals appear in five of the studies; the ‘other’ category captures a few applied goals such as resource extraction and national security.

3.3.1.2 Analysis of submersible activity logs

Submersible activity logs (Delta Oceanographics, 2015; HBOI, 2009; HURL, 2014; Woods Hole Oceanographic Institution, 2016) submersible-specific summary records (Hawai'i Undersea Research Laboratory, 2012; Kaharl, 1990; J. K. Reed, Shepard, Koenig, Scanlon, & Gilmore, 2005; M. M. Yoklavich & O'Connell, 2008), and interviews of scientists and pilots were used to develop a submersible-based categorization of activity. Submersible activity logs characterize dive activities in different ways. The WHOI logs use relatively consistent terminology that describes the discipline of the scientific study, e.g., biology, geology, and geochemistry. The *Delta* logs use short summary terms, e.g. “transect, recon, scallop” to describe the activity. HBOI and HURL logs contain more descriptive mission and project entries. Each log also notes location, depth, and chief scientist names—information that can be used to help determine the nature of the research activity. Although the data are normalized by use of percentages, records after 1985 were used in order to capture a common time frame for all four submersible groups. This quantitative approach is used for illustrative, not statistical, purposes; the exact numbers may vary by a few percentage points given the multi-disciplinary nature of many missions and interpretive nature of the task. The categories that emerged that best capture the nature of the submersible activity for future study are presented in Table 3.3.

The percentages of the primary topic activities for each of the four U.S. submersible operations were calculated using operational log data, and by confirming activity with HOV users, and is illustrated in Figure 3-6.

Table 3.3 Submersible activity categories

Topic	Subtopic	Description
<i>Biology</i>		Dives that collect visual and physical data to support hypothesis-driven research on marine biological systems
<i>Biology</i>	<i>Biomedical</i>	Dives that are conducted for the purpose of collecting samples of organisms for biomedical assay
<i>Biology</i>	<i>Deep Sea Coral</i>	Dives conducted to explore, sample and research deep sea coral and deep sea coral ecosystems
<i>Geology</i>		Dives that collect visual and physical data to support hypothesis-driven research about the marine geological environment
<i>Deep Hydrothermal Vents</i>		Dives that research and explore biogeochemical characteristics of seafloor hydrothermal activity and ecosystems at greater than 1000m depth
<i>Shallow Seeps</i>		Dives that research and explore biogeochemical characteristics of methane hydrate and seafloor hydrothermal activity and ecosystems at less than 1000 m depth
<i>Mid-water studies</i>		Dives that collect information from the water column, typically regarding biological and chemical characteristics
<i>Mid-water studies</i>	<i>Platform</i>	Dives conducted in mid-water on and around an underwater structure (i.e. oil platform)
<i>Transects</i>		Dives that traverse a defined pattern to conduct a quantitative survey of the geology, habitat, fauna and/or flora of an ecosystem or region
<i>Archaeology</i>		Dives conducted to explore and research remains of human activity in the sea
<i>Other</i>		Dives include test, training and certification; outreach (filming and demonstration), maintenance of undersea structures, and commercial salvage or surveys

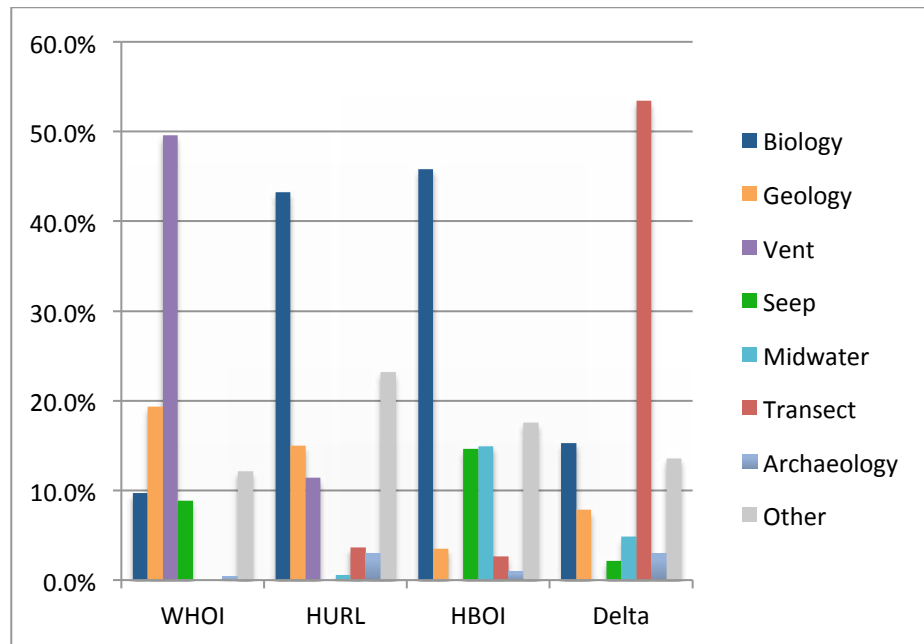


Figure 3-6 Percentages of dive activity by discipline for four U.S. submersible operations (derived from organizational logs for dives since 1985).

3.3.1.3 Activity categories

The classifications from the above effort emerged as a combination of research discipline (e.g., biology, geology), site-specific (e.g., vent, seep), and method-based (e.g., transect) factors, a variation that inhibits a consistent assessment of ‘how well does the equipment meet these uses.’ The categories were therefore simplified to provide a basis from which to test the Functional quadrant of the model. The activity categories that were selected to be representative of the variety of research functions are: macro-ecosystem understanding; micro-ecosystem understanding; transect; mid-water; and other missions (Table 3.4).

Table 3.4 Functional categories and descriptions

Category	Description
<i>Macro Ecosystem Understanding</i>	Overall characterization of an underwater ecosystem, exploration; emphasis on visual data sampling
<i>Micro Ecosystem Understanding</i>	Detailed characterization and study of small-scale undersea ecosystem components; physical specimen sampling
<i>Transect</i>	Controlled, measured ecosystem assessment
<i>Midwater</i>	Investigation of the pelagic environment
<i>Other</i>	Other activities such as outreach, industry, testing and training

The activity of ‘sampling’ was considered as a separate factor for this analysis, but instead was integrated into the general descriptions of macro- and micro-ecosystem understanding categories. Samples include both physical specimens and visual observations (Hourigan et al., 2015); the requirement for or sufficiency of one or the other depends on the goal of the research project. Determination of the species of an organism, for example, often requires a physical sample versus a photograph or video (Scientists A, D). The increasing capability of technology also affects the sufficiency of the sampling method: high definition video, stereo images, advanced manipulator arm capabilities, and new sampling techniques such as multi-spectral and genetic analysis all change the sufficiency of the sampling method. When further developing the research factors of the model, the description of sampling methods will provide a key element.

3.3.2 OTHER MISSIONS

Neither manned nor unmanned submersible technology is used solely for marine research: military, industrial and tourism interest and investment have played a large role in developing and maintaining the availability of submersible tools. The ability of a

research operation to leverage non-research activity or opportunity—for technological or financial advantage—can impact its obsolescence and sustainment.

Education has been identified as a value that also results from undersea research activity, whether directly or indirectly. This has become even more prevalent with the emergence of telepresence technology, which brings real-time undersea exploration and research activity to a wide range of viewers. The impact that educational value brings to a submersible operation varies both by technical communication capabilities and by the societal emphasis and effort that a sponsoring organization applies to this activity. It will be considered here within the category of other missions.

3.3.3 ENVIRONMENTAL CONDITIONS

Environmental conditions such as currents, sea state, and bottom topography can affect the on-site performance of undersea systems on a mission-centric basis. This factor can occur on a small scale (i.e., a particular dive day), or can affect an entire discipline of study (e.g., deep sea corals under Gulf Stream currents, ground fisheries in areas of rough habitat). Physical characteristics of a system, such as existence of a tether, or overall propulsion power, will influence the degree of environmental impact.

3.3.4 PERSONAL PREFERENCE AND CONTINUITY

Personal preference expressed by users, whether to continue with a known system, or engage the use of various types of systems, also influences infrastructure selection. Although not cited as a major impact, several researchers expressed that they found a comfort level with a particular system once they became familiar with its

capabilities, and would actively choose to continue using it. Others noted that they preferred to employ a variety of systems, or were more amenable to using the system that was most available. One scientist likened a researcher's willingness and resolve to use alternate tools to losing an arm: "you start feeding yourself with your left arm...we're not out of business—we wouldn't be good scientists if we were out of business by losing a tool—but it's more difficult, not as efficient" (Scientist E).

For some marine research, especially fisheries science and monitoring, the uniformity of using the same data collection method is an important aspect of the work (Kilduff, Carmichael, & Latour, 2009). In these cases, the adoption of alternate technologies often requires deliberate consideration, and thorough comparative analysis, prior to use. Although initiating from the behavioral use of a system, this is also an extrinsic consideration (quadrant B) influenced by legislative and scientific method considerations.

3.3.5 FACTORS AND COMMENTS

The factors that emerged from this discussion for use in case studies are presented below (Table 3.5). Whereas the societal priority of the activity is a consistent impact for each factor, that aspect is captured in quadrant D; otherwise, the only other cross-quadrant impact was that of legal requirements and scientific practices (quadrant B, an extrinsic concern that relates to a particular system) on selection for purposes of data continuity.

Table 3.5 Quadrant C: Operational Impact Factors, related quadrants and comments

Factor	Related Quadrant(s)	Comments
Macro Ecosystem		Overall characterization of an underwater ecosystem, exploration
Micro Ecosystem		Detailed characterization and study of small-scale undersea ecosystem components
Transect		Controlled, measured ecosystem assessment
Mid-water		Investigation of the pelagic environment
Other		Other activities such as outreach, industry, testing and training
Data Continuity	B	Influenced by legal and scientific practices
Personal Preference		Preferences can arise for reasons beyond the science mission
Environment	A	Equipment capabilities may be more or less suited for certain environmental conditions

3.4 QUADRANT D: SOCIETAL FACTORS

Factors of interest to sponsors of undersea marine research activity who are concerned with organizational or national-level performance are termed ‘Societal impact,’ and are assessed within quadrant D. These factors include societal value of research goals, organizational dynamics of particular groups, and individual charismatic influences. For HOVs, inspirational considerations of human nature’s desire for adventure are included here. These considerations address aspects of the question: ‘What factors influence sponsorship for the research system?’

3.4.1 SCIENCE PRIORITIES

The quadrant model allows separation of the consideration of the quality of a system's data collection activity from the importance of the research that that activity supports. This factor allows for deliberation of the contribution that research priorities, stated or otherwise, makes on infrastructure sustainment. These priorities can be found at a variety of organizational scales, from national research priority memoranda and reports (Donovan & Holdren, 2015; Joint Subcommittee on Ocean Science and Technology, 2007), to agency-specific science goals (NOAA, 2013b; Office of Naval Research, 2015), to discipline-specific research strategies such as ocean acidification or deep-sea coral plans (Interagency Working Group on Ocean Acidification, 2014; NOAA, 2010a).

The degree to which these research priorities actually impact system health is not straightforward. In an effort to simplify the question, one research sponsor offered that:

A system may be essential for collecting a certain type of data, but if that data does not contribute to science that is of interest to research sponsors, the data collection, and therefore the system, should not be supported. (Manager A)

Another sponsor however, noted that:

The reports are all done around this [science]...but it's not much of a driving factor, unless it happens to be the science of the day, like climate change. The longer-term science, the understanding piece, doesn't get attention. It's not marketable. (Manager G)

Eventually, this factor can be developed to include consideration of other perspectives that were introduced in the recent Ocean Studies Board report, "*Critical*

Infrastructure for Ocean Research and Societal Needs” (2011): “How dependent is an area of research on the specific infrastructure? Does the infrastructure serve multiple science questions or applications that yield multiple benefits, especially across more than one domain or discipline?” and “What is the potential for serving applications or missions in multiple agencies?” (p. 55)

3.4.2 GOVERNMENT SPONSORS

The Navy, National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), and other federal, state and local organizations have all provided funding for U.S. undersea research operations and undersea research vehicle development. Organizational dynamics, internal procedures and interagency cooperative mechanisms—such as the University National Oceanographic Laboratory System (UNOLS) and DEep Submergence Science Committee (DESSC)—have exerted significant impact on this investment.

The issues related to public support for ‘big science,’ or “large-scale scientific research consisting of projects funded usually by a national government or group of governments” (Merriam-Webster Dictionary, n.d.) and ‘little science,’ or “scientific research that does not require much in the way of resources or personnel” (Oxford English Dictionary, n.d.-a) have been well discussed (de Solla Price, 1963; Space Studies Board, 1994; Stein & Good, 1986). The field of oceanographic research experiences similar dynamics. The International Geophysical Year (IGY), International Decade of Ocean Exploration (IDOE), and Ocean Drilling (now Discovery) Program (ODP) all provided ‘big science’ impetus for oceanography, whereas the “fundamental research

mission” of the NSF is “the support of individual investigators (i.e. small science)” (Clark, 2000; Reeve, 2000; Toye, 2000). NSF ocean program managers have recognized that “Dealing with cooperative field programs and shared-use instrumentation was a particular problem in the life sciences” (Toye, 2000, p.99); a problem exacerbated by the multidisciplinary challenges inherent in the field of oceanography.

Additionally, the collection of marine research data requires marine research systems that fall within a ‘mid-size infrastructure’ (defined roughly as including infrastructure that cost less than \$25 million to build) oversight gap, as identified by NSF’s National Science Board (2003): “While there are special NSF programs for addressing ‘small’ and ‘large’ infrastructure needs, none exist for infrastructure projects costing between millions and tens of millions of dollars” (p.3). A follow on report addressed this midsize infrastructure, termed ARIF, or Advanced Research Instrumentation and Facilities, of which marine submersibles were included as an example (Committee on Advanced Research Instrumentation, 2006). The study found that equipment falling under this category was not handled by the NSF infrastructure programs (Major Research Instrumentation program nor Major Research Equipment and Facilities Construction account) nor were there any general ARIF programs at the other federal funding agencies. Agencies have dealt with these challenges to oceanographic research facilities in different ways.

3.4.2.1 National Science Foundation

The National Science Foundation’s Division of Ocean Sciences (OCE) evolved from various programs. The first ‘Oceanography Program’ was established separately

from the ‘Geology,’ ‘Geophysics,’ and ‘Geochemistry’ programs within an ‘Earth Sciences Section’ in 1962. By 1967 ‘Oceanography’ became its own section, with sub-components of ‘Physical Oceanography,’ ‘Submarine Geology,’ ‘Geophysics,’ and ‘Oceanographic Facilities’ programs. ‘Biological Oceanography’ emerged from the NSF ‘Biological and Medical Science’ organization, and was transferred to the ‘Oceanography Section’ in 1970, while marine chemistry was established within the ‘Oceanography Section’ in 1974 (Reeve, 2000).

Early in its history, the NSF separated funding for oceanographic research and facilities, which differed from the Navy’s (Office of Naval Research) practice of funding projects inclusively (Clark, 2000). Research vessel and oceanographic technology support at NSF have evolved organizationally so that today, oceanographic research infrastructure is managed within the Integrated Programs Section (IPS) of the Division of Ocean Sciences (OCE) as ‘Oceanographic Facilities Equipment and Support,’ which includes: ship operations (Ship Ops); ship acquisition and upgrade (SAU); shipboard scientific support equipment (SSSE); oceanographic technical services (OTS); oceanographic instrumentation (OI); and other facility activities (OFA), which includes deep submergence and UNOLS activity support (National Science Foundation, 2016a).

The deep submergence infrastructure support under OFA is provided via a grant to the Woods Hole Oceanographic Institution (WHOI) for the National Deep Submergence Facility (NDSF). The NDSF has evolved from a deep submergence laboratory (that initially supported the Navy-purchased *Alvin* submersible) into a facility that operates the *Alvin*, a deep ROV, *Jason*, and an autonomous underwater vehicle,

Sentry. In light of National Academy of Sciences recommendations regarding ARIF, OCE established a mid-size infrastructure fund in 2003 (Yoder, 2002). The fund was ultimately used to support improvements to the *Alvin* submersible as recommended by the Ocean Studies Board report, “Future Needs for Deep Submergence Science” (Ocean Studies Board, 2004).

3.4.2.1.1 Impacts: process

The separation of infrastructure and research funding has been beneficial for the NSF-supported infrastructure included within NDSF, but results in a disadvantage for scientists whose proposals include use of non-NSF supported equipment. NSF science proposals that request use of the NDSF vehicles need only request scientific support; the expense of the infrastructure is not included for reviewer evaluation. Scientists wishing to use non-NDSF equipment, however, are required to include the additional cost of this equipment in their proposals. This has been noted as an advantage for users of NDSF equipment, but a significant disadvantage for investigators who may wish to use commercially available equipment or systems provided by a non-NSF supported academic institution (Ocean Studies Board, 2015; UNOLS, 1990). An Ocean Studies Board (2004) recommendation that “a small pool of additional funds...be targeted specifically to support the use of non-NDSF vehicles...” (Ocean Studies Board, 2004, p. 4) was not implemented because of this proposal-based award process at NSF (Managers B, C, F, J).

3.4.2.1.2 Impacts: leadership.

A unique aspect of NSF leadership, the practice of employing program directors and managers who are ‘rotators,’ is worthy of note. Rotators, or scientists who remain attached to their academic institution while serving one to four year assignments at NSF (Mueller-Parker, 2007; National Science Foundation, 2016b), provide a different core of expertise, and allegiance, than agencies staffed primarily with government employees (Managers C, F, G). Within a multi-disciplinary study area such as oceanography, this also introduces a consideration of the familiarity with a particular aspect of the science; scientists with backgrounds in marine geology and geophysics led the Oceanography/Ocean Sciences division between 1973 and 2000 (Ocean Studies Board, 2000b). Detailed analysis into the contribution of each of these factors is beyond the scope of this study, but they are noted here as ingredients of overall agency impact.

3.4.2.2 NOAA’s Undersea Research Program

The National Oceanographic and Atmospheric Administration (NOAA)’s National Undersea Research Program (NURP) supported *in situ* marine research between 1980 and 2013. The program consisted of a small headquarters staff and a network of four to seven competitively established, regionally distributed academic centers whose mission was to:

Provide scientists with the tools and expertise they need to investigate the undersea environment, including submersibles, remotely operated vehicles, autonomous underwater vehicles, mixed gas diving gear, underwater laboratories

and observatories, and other cutting edge technologies...while assisting scientists in acquiring data and observations that provide the information necessary to address a variety of NOAA's priority goals. (NOAA, 2010b)

The Centers were encouraged to employ their choice of undersea technology, and competitively select their own marine research projects within guidelines provided by the NURP office. Funding was provided via grants and cooperative agreements.

NURP was established as the result of an initiative by NOAA's Manned Undersea Research and Technology (MUST) office to develop and operate a new piece of ocean mid-size infrastructure: a research submarine with a laboratory and saturation diving capability called *Oceanlab*. When the expense of the project was deemed excessive, NOAA requested that the Ocean Studies Board conduct a study to: "(1) identify scientific needs and ocean research topics requiring undersea research activities, and (2) define the types of facilities and techniques needed to support scientific requirements" (NOAA, 1980, p. 2). Noting that *Oceanlab*'s "lack of strong support by any major segment of the ocean scientist community seemed to stem from the narrow range of important problems in which this technique (saturation diving) plays an essential role", OSB and NOAA broadened the study so that "*Oceanlab* would represent a program to improve the capabilities of the U.S. scientists to carry out ocean research requiring complex observational or manipulative activities throughout the ocean" (Ocean Sciences Board, 1980, p. 10).

Based on this study and other assessment activities, NOAA (1980) concluded that:

- (1) Facilities capable of performing undersea research projects should be supported by NOAA;
- (2) Support for undersea facilities should be determined by the scientific research needs and priorities that these facilities can satisfy;
- (3) Responsibility for operational management of these facilities should be in universities or oceanographic institutions rather than in NOAA;
- (4) Funding support for scientific research proposals would be integrated with funding support for the facilities necessary to perform the research; and
- (5) An ongoing interactive process with experts in ocean engineering would be established to insure new facilities employing the best available technology will be considered to satisfy research requirements. (pp. 3–4)

An initial competitive process to establish regional Centers, conducted in 1980, resulted in awards for three new university programs at the University of Hawaii; University of Southern California (USC); and a consortium headed by the University of North Carolina, Wilmington (UNCW). Support was continued for an undersea research laboratory (a stationary, ambient pressure habitat that uses the principle of saturation diving to allow divers to live and work on the seafloor), *Hydrolab*, located off St. Croix and operated by Farleigh Dickinson University (FDU) (Finkle, 1985). USC and FDU both left the program shortly thereafter. A combination of program competition, and community and Congressional influence, added the University of Connecticut, Avery Point, in 1983 (Finkle, 1985); the University of Alaska, Fairbanks in 1990 (Youngbluth, 1993); Rutgers University in 1992 (Rutgers University, 2008); and a consortium headed

by the University of Mississippi, the National Institute of Undersea Science and Technology, in 2002 (NOAA NURP, 2009a). The *Hydrolab* was succeeded by the *Aquarius* undersea saturation laboratory, which operated off St. Croix (between 1985–1989), and then moved to Key Largo, Florida, where it was operated by UNCW from 1993 until 2012 (Kohanowich & Potts, 2010; Potts, 2016). Ownership of the *Aquarius* was transferred to Florida International University (FIU) in 2014 (Potts, 2016).

NURP funding directly supported the infrastructure required to operate a research program with the *Pisces* submersibles of the Hawaii Undersea Research Lab, and provided funding for competitively awarded research operations conducted with the *Delta* and Harbor Branch *Johnson Sea Link* submersibles through regional center proposals. From its establishment, until it experienced funding restrictions in mid-2000, NURP also contributed to the NDSF under the terms of a tri-agency memorandum of understanding (MOU) to support use of the NDSF’s vehicles, primarily *Alvin*, for NOAA research (Manager G). Use of the vehicles of the NOAA vessel fleet was acquired through a competitive, proposal-based process (Managers E, G). NURP officially merged with NOAA’s newly formed Office of Ocean Exploration in 2007 (NOAA NURP, 2009b), and was discontinued as a funded program in 2014 (NOAA, 2012, 2013a; NOAA Office of Oceanic and Atmospheric Research, 2014).

Other NOAA offices also funded marine *in-situ* research activities on a mission basis. NOAA’s Office of Ocean Exploration, established in 2001, funded a number of HOV exploration missions using HBOI’s *Johnson Sea Link* submersibles through a competitive proposal process, between 2001 and 2009 (NOAA Ocean Exploration,

2016). NOAA's Ocean Exploration and National Marine Sanctuary Programs (NMSP) supported and participated in a shallow one-man submersible initiative, the "Sustainable Seas Expedition," between 1999 and 2003 (National Geographic, 2000; NOAA, 1999; NOAA Ocean Exploration, 2002). The National Marine Fisheries Service (NMFS) used the *Delta* submersible for groundfish surveys for more than 20 years, often with NURP support (M. M. Yoklavich & O'Connell, 2008).

3.4.2.2.1 Impacts: business model

The 1980 NOAA decision that "funding support for scientific research proposals would be integrated with funding support for the facilities necessary to perform the research" contrasts with the NSF determination to separate marine research infrastructure support from scientific awards. The resulting funding models at each NURP Center varied (i.e., HURL funds supported *Pisces* infrastructure, but not research; the West Coast and Pacific Region Center funded projects that combined research with innovative use of a variety of undersea systems; and UNCW supported both research projects and *Aquarius* undersea laboratory infrastructure). The impact of these different models varied with each Center.

3.4.2.2.2 Impacts: budget process

The selection and funding of NURP Centers was subject to a high degree of Congressional direction throughout its tenure, with appropriation language specifying percentages and amounts of the budget to be directed to particular programs and regions

(Manager G). The NOAA administrative budget submission did not include NURP between 1983 and 1997 (Managers G, E). This led to a dynamic in which:

Individuals made a big difference. And it was strong individuals in a couple of those centers who kept things going for a long time because of their personal commitment and working the system in their universities and on the hill.

(Manager G)

As with the description of NSF factors above, these considerations will be incorporated into the impact assignment during case study assessments.

3.4.2.3 Other public sponsors

The U.S. Navy has been a principal sponsor for U.S. oceanographic research investment since before World War II, and was largely responsible for early development of HOVs, including the *Alvin* (Busby, 1976; W. Forman, 1999; Pinsel, 1982; Sapolsky, 1990). The Navy remains a significant investor in the UNOLS research fleet and in unmanned undersea vehicle technology (for research and other purposes), but has not sponsored marine research missions using the *Alvin* submersible since the mid-1990s (*Alvin* LOG). The Office of Naval Research (ONR) and Naval Sea Systems Command (NAVSEA) continue to provide certification support for the submersible under a memorandum of agreement and with funding from NSF (Manager T).

The National Aeronautics and Space Administration (NASA) sponsors a robust oceanography program that focuses primarily on remote sensing applications (NASA, n.d.). *In situ* marine data collection techniques are used for calibration and validation of satellite measurements, but NASA does not typically sponsor traditional marine research

conducted with submersibles. Submersible systems are used, however, for analog mission and human-robot interface applications. These include training and testing missions at the *Aquarius* underwater saturation laboratory, under the NASA Extreme Environment Mission Operations (NEEMO) program, and missions using a *Deep Worker* submersible and an autonomous underwater vehicle (AUVs) at *Aquarius* and in Canada's Pavilion Lake (Forrest et al., 2010; Loff, 2016; Trembanis et al., 2012).

Other programs within the Department of the Interior (the Bureau of Ocean Energy Management (BOEM), and U.S. Geological Survey (USGS)), the Environmental Protection Agency (EPA), and various state and local agencies also conduct *in situ* marine research, monitoring and observation activities using undersea vehicles and divers. With respect to HOVs, the *Delta* was the most affected by this source, with sponsorship by California, Alaska, and Washington state fisheries programs (M. M. Yoklavich & O'Connell, 2008). BOEM and USGS have partnered with NOAA Ocean Exploration on ROV exploratory missions, and State and local organizations have been active users of small ROVs (Video Ray et al., 2013).

3.4.2.4 Interagency mechanisms

Unlike exploration and research of outer space, which is under the federal purview of a single agency, NASA, oceanography in the U.S. falls within the realm of numerous federal agencies with a wide range of missions that include basic science, conservation, national security, and management of resource extraction. Oceanography itself is a multi-disciplinary research field composed of a spectrum of biological, geological, physical, and chemical science disciplines. The need for expensive, often

common research infrastructure to address this multi-disciplinary research field has led to the establishment of both public and academic cooperative organizations.

Within the federal realm, a research vessel Federal Oceanographic Fleet Coordinating Council (FOFCC), now the Interagency Working Group on Infrastructure and Facilities (IWG-FI), has operated since 1981, focusing primarily on oceanographic ships (Interagency Working Group on Facilities and Infrastructure, 2013; Office of Technology Assessment, 1981). Whereas this group has begun to include consideration of remote and autonomous systems, it has not significantly impacted management of undersea marine research infrastructure to date. The academic UNOLS cooperative structure, however, has provided decades of guidance for *in situ* submersible marine data collection systems.

3.4.3 UNIVERSITY NATIONAL OCEANOGRAPHIC LABORATORY SYSTEM

The academic ocean facility coordinating organization, UNOLS, has played a consistent and vital role in coordination of the nation's oceanographic assets since its establishment in 1970 (Ocean Studies Board, 2000a, p. 117). Composed of “institutions that use, or operate and use, seagoing facilities and maintain an academic program in marine science,” UNOLS facilitates inter-academic coordination, and provides recommendations to Federal supporting agencies regarding ocean infrastructure matters (UNOLS, 2013).

The UNOLS' DEep Submergence Science Committee (DESSC), which superseded the original *Alvin* Review Committee (ARC) in the early 1990's, operates under the mandate to oversee use of the suite of undersea vehicles at WHOI's National

Deep Submergence Facility (NDSF), as well as to provide an interagency forum for other submersible research coordination and discussion (DeSSC, 1993). A Shallow Submergence Committee was established within DESSC in 2001 to focus on alternate, non-NDSF technologies (DESSC 2001), but disbanded in 2005 because “Access to non-NDSF issues is being addressed. Safety concerns regarding use of non-Navy inspected HOVs will be addressed by (the HOV Safety Committee)” (DeSSC, 2005). Differences in recommendations and results between NDSF (deep) and non-NDSF (typically shallow) undersea infrastructure are apparent throughout the history of this organization (DeSSC, 1994, 1999; Ocean Studies Board, 2004; UNOLS, 1982, 1990).

3.4.4 PRIVATE SPONSORSHIP

Private funding for HOVs has consisted of a rich intertwining of industrial investment, individual entrepreneurs, and wealthy patrons. As large business investment in HOVs for military and oil field use waned in the 1980's, small private organizations (such as Delta Oceanographics, Perry Oceanographics, Nuytco and Hawkes Ocean Technologies) arose to provide HOV services as well as innovations and sales. Wealthy entrepreneurs and partnerships between submersible inventors and wealthy patrons have played an important role in U.S. submersible history: Beebe and Barton's *Bathysphere*; Edwin Link and Seward Johnson's *Johnson Sea Link* submersibles, John Perry's line of submersibles, Graham Hawkes and Steve Fosset's *Deep Flight* and James Cameron's *Deepsea Challenger* are all examples of this model (Beebe, 1934; Cameron, n.d.; Fecht, 2011; Link, 1973; Perry, 1996; van Hoek & Link, 1993). Today, Nuytco continues with a focus on one-man atmospheric suits, and has been joined by a growing private

submersible market targeted at the yachting community, with SEAmagine (established in 1999), Triton and UBoat Worx all manufacturing small submersibles (Kohnen, 2013, 2016b).

3.4.5 ACADEMIC

The ‘academic’ factor includes consideration of two aspects of academic influence: any particular advantage or disadvantage provided by a specific university sponsor/operator of a system(s), and any notable impact exerted by the academic community in an informal manner. This latter collective impact of scientific users of submersible science infrastructure on its sustainment is in some measure captured within the UNOLS considerations, but this factor provides an opportunity to note when other factions of the academic community may be particularly influential in the chronicle of a system. Hanson (1989) describes this *ad-hoc* activity:

The scientific (and technological) funding agencies are responsive to demands and requests made by their constituents...There are many ways in which to gather people together to influence a process. They can include: proposals (many individual or one large joint proposal), public discussions of the issue in question, reports by working groups established for this issue particularly or for advice in general on the area of concern, establishment of a newsletter, etc. The point is to develop a community of individuals who have more influence collectively than any of them would have individually. (p. 138)

3.4.6 CHAMPIONS

The contribution of a ‘champion,’ or a “Person who voluntarily takes extraordinary interest in the adoption, implementation, and success of a cause, policy, program, project, or product” (Business Dictionary, n.d.-a) has long been recognized as an ingredient for success in the fields of technology and product innovation and management (Carnell & Shank, 2016; Frey, 1991; Markham & Aiman-Smith, 2001; Schon, 1963; Thompson, Estabrooks, & Degner, 2006).

No ordinary involvement with a new idea provides the energy required to cope with the indifference and resistance that major technical change provokes. It is characteristic of champions of new developments that they identify with the idea as their own...to a degree that goes far beyond the requirements of their job.

(Schon, 1963, p. 84)

Champions have also been recognized as a necessary, but not sufficient, factor for success: “...we now know that a champion moves projects along, while projects with no champion struggle—but having a champion does not guarantee market success” (Markham & Aiman-Smith, 2001, p. 44).

Most of this literature examines the role of a champion in product innovation and change management, rather than for continued sustained use of a product, although Frey (1991) defined champions as “people who believe in new products and also understand the gritty tasks of actually building them” (p. 46). Within the oceanographic technology community, many systems are linked with individual commitment and perseverance: Argo profiling floats and Dr. Stan Wilson (Various, 2012); satellite ocean observations

and Carl Wunsch (Matthews, 2016; Wunsch, 2016); the Ocean Observatory Initiative and Dr. John Delaney (Delaney, 2010); telepresence and Dr. Bob Ballard (Ballard & Hively, 2000); and the Eye in the Sea bioluminescence sensor and Dr. Edie Widder (Jabr, 2010) are only a few of many examples. For the purposes of this study, the existence of a champion or champion-like figure is noted as a potential factor for social impact consideration.

3.4.7 RISK PERCEPTION

An important ingredient in the calculation of the impact of safety on undersea marine research infrastructure selection lies within the field of risk perception. Risk perception is particularly significant when assessing an activity that puts humans in harm's way, and in which the result of a mistake can be fatal.

The tendency of program managers to fund, and researchers to use, HOVs will in part rely on their perception of the 'riskiness' of the venture. Paul Slovic (1987) related in a classic article on risk perception that: "In short, 'riskiness' means more to people than 'expected number of fatalities'" (p. 285). Risk perception studies have shown that many factors, such as "voluntariness of exposure...familiarity, control, catastrophic potential, equity, and level of knowledge" also "seem to influence the relation between perceived risk, perceived benefit, and risk acceptance" (Slovic, 1987, p. 283). In his evaluation of hazards as to degrees of awareness and controllability of risk, "underwater construction"—the hazard most similar to HOV use—ranked closely with "sport parachutes" and "general aviation" (Slovic, Fischhoff, & Lichtenstein, 1985; Slovic et al., 1985).

A National Safety Council model of risk perception categorized factors that affect risk tolerance as macro-level (sanctions and enforcement); meso-level (peer and community pressure); and micro-level (perceived knowledge, optimism bias) (Campbell Institute, 2014). Whereas this study did not attempt to further assign these factors with respect to HOV use, interviews did reveal differences in safety approaches and attitudes between the funders and the users of submersible equipment. Although all interviewees stressed the importance of safety, the staff of organizations that were responsible for financing the operations expressed more reliance on documented procedures, while the users—both operators and scientists—tended to assess the risk of submersible operations in a broader sense, and related personal experiences with safety of operations.

“[I think] the risk management side of things with institutions and such is a bigger issue now probably than it was back then. Safety records are good but [there is a] societal perception of risk” (Scientist O).

“Navy inspected the ALVIN, they were rigorous about it...NSF was very nervous about getting into funding facilities [for which] they didn’t know the inspection process better” (Manager C).

“I think the Funding agencies are the ones saying no, we prefer to see ROVs used because it’s safer, nobody’s down there” (Scientist D).

“DELTA was such a simple machine, a safe machine. I liked the submersible because (I) felt comfortable, safe. I knew if something happened I could get up...” (Scientist E).

An additional factor observed in risk perception research, that “Risk concerns may provide a rationale for actions taken on other grounds or they may be a surrogate for other social or ideological concerns” (Slovic, 1987, p. 285), was not investigated for this study.

Risk perception is an extrinsic, behavioral factor, but that perception typically draws strongly on information from Operational (quadrant B) factors: safety incidents and certification status, and depends on the Technical (quadrant A) structure of a vehicle.

3.4.8 INSPIRATIONAL

First, we must be honest with ourselves about ourselves. Man has the desire to see, to know, to be there. He has an ego and he wishes to leave his personal mark, he wants others to acknowledge that achievement, then pushes on... That man is a searching, conquering, proud being must be taken into account. It is not being said here that this conviction is good or bad. But only that it exists and must be recognized. (Talkington, 1976, p. 9)

The ‘inspiration,’ or “process of being mentally stimulated to do or feel something, especially something creative” (Sangeeta, 2013) provided by the ability to personally visit the sea floor often leads to ‘aspiration,’ or “hope or ambition of achieving something” (Sangeeta, 2013), that goes beyond personal pleasure to include marine scientific and/or conservation activity. This phenomenon is widely acknowledged, but difficult to quantify. The appeal of adventure has been a powerful force for HOV development and exploration. Frank Busby (1976), who wrote the classic, comprehensive

submersible reference “Manned Submersibles” (Busby, 1976) described how this motivation reached beyond individuals to organizations:

There was yet another factor impossible to assess: the magnetic attraction of man to the deep ocean. The opportunity to be on the very frontiers of abyssal exploration is powerful tonic... When scientists and engineers, who spent years on rolling, pitching ships trying to piece together what lay beneath their decks, sense the opportunity to see this realm with their very eyes, decisions can be made which transcend profit-and-loss statements. Whether large or small, corporations are groups of individuals, the attraction of the deep ocean is no less to the engineers or vice presidents of General Motors or North American Rockwell than it is to a Piccard or Perry. (Busby, 1976, p. 51)

One of the ‘rationales for human spaceflight’ identified by the NASA Human Space Exploration study (2014) was:

Shared destiny and aspiration to explore. The urge to explore and to reach challenging goals is a common human characteristic. Space is today a major physical frontier for such exploration and aspiration. Some say that it is human destiny to continue to explore space. While not all share this view, for those who do it is an important reason to engage in human spaceflight. (Space Studies Board, 2014, p. 2)

In this study, ‘Satisfying a basic human drive to explore new frontiers’ was cited most often (22%) as the ‘most important’ reason for human spaceflight. It was considered ‘very important’ by 45% of the respondents, second to ‘Inspiring young people to pursue

careers in science, technology, engineering, and mathematics’ (47%), and was the second-most frequently mentioned justification for human spaceflight (30%), just behind ‘humans can accomplish more than robots’ (32%) (Space Studies Board, 2014, pp. 98–101).

During targeted interviews, responses to questions about inspiration were varied; almost all respondents admitted to being drawn by the ‘cool factor’—the promise of a journey to the ocean floor. During the latest DESSC-sponsored submersible science workshop in January 2016, DESCEND2, participants engaged in a spirited conversation about the advantages and disadvantages of telepresence, with a small, but strong contingent still in support of the excitement of the opportunity to personally visit the seafloor (Scientist U). However, many also acknowledged a greater impact of physical discomfort, a need for increased efficiency, and an appreciation for the draw of new virtual technology.

The maturation of virtual reality, avatars and social media have introduced a rapidly evolving, and increasing, ‘inspirational value’ of virtual experience (Kim, 2015). A student in a University of Hawaii Cyberpsychology class concluded a Second Life analysis project with the observation that: “The advancement of virtual technology is more than computer games or new methods of communication, but a revolutionary development in history that has very real and mostly positive implications for the social interactions of human beings” (McGrath, 2010). The intrinsic human drive to explore and experience may be coming to be matched by this pull of escapism. University of

California, Santa Barbara psychology professor Jim Blascovich and Stanford University Virtual Human Interaction Lab's Jeremy Bailensen (2011) write:

Driven by imaginations that have long sought to defy the sensory and physical constraints of physical reality, humans continuously search for new varieties and modes of existence, only this time we're doing it via the supposedly cold machinery of digital space. (Blascovich & Bailenson, 2011, p. 8)

Film director James Cameron might best encompass and represent this tension.

Blascovich and Bailenson (2011) introduce their book, *"Infinite Reality: Avatars, Eternal Life, New Worlds, and the Dawn of the Virtual Revolution"* with a description of Cameron's futuristic tale, "Avatar," in which a genetically engineered body is controlled by a remote human mind. On March 26, 2012, Cameron became only the third human to reach the deepest depths of the ocean, in person, in a small HOV (Cameron, n.d.). With respect to the inspirational rationales of manned exploration, he has stated: "No kid ever dreamed of growing up to be a robot" (Cameron, 2013; Walsh, 2014).

Assessment of the impact of inspirational factors for this study includes a sense of each submersible community's local experience of the role of the 'excitement' factor in their work, as well as consideration of recruiting and national pride impacts described below.

3.4.8.1 Recruitment

One avenue of study that attempts to value the inspirational factor is recruitment. Does the promise of personal exploration, adventure and excitement attract new scientists to these—and other—important research fields? The need for long-term studies to

robustly address this question has precluded definitive answers, but the NASA literature provides informed insight. NASA's "*Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration*" report (Space Studies Board, 2014) found that 'inspiring young people to pursue careers in science, technology, engineering, and mathematics' and 'satisfying a basic human drive to explore new frontiers' were both 'very important' reasons for human space exploration for nearly half of stakeholders (47% and 45%, respectively). When asked an open-ended question about reasons for human space exploration, however, only 6% of the responses mentioned 'careers in science, technology, engineering and mathematics.' The NASA panel concluded that, "although the effect on students can be used as a rationale for some spending on ... the human spaceflight program, few in the education realm would view this effect itself as a rationale for funding the human spaceflight program" (Space Studies Board, 2014, p.61). Their conclusion also recognizes that the space program is not unique in motivating students, and that a successful path to becoming a scientist depends on many factors other than initial inspiration.

Determination of the role of manned research opportunities in inspiring marine scientists faces similar challenges to those described by the Space Studies Board, including the need for long-term longitudinal studies. The Ocean Project (Meyer, Isakower, & Mott, 2014), a non-profit partnership of more than 2000 aquariums and natural history museums, has conducted national public opinion research on ocean conservation issues since 1998, and may provide a potential venue for such investigation

3.4.8.2 National pride

Another of the rationales that NASA (2014) identified to support manned space exploration was:

National stature and international relations. Being a leader in human space exploration enhances international stature and national pride. Because the work is complex and expensive, it can benefit from international cooperative efforts. Such cooperation has important geopolitical benefits. (Space Studies Board, 2014, p. 2)

The Ocean Studies Board (2011) also identified national stature as a guiding consideration for infrastructure value: “Does the infrastructure serve other issues of national strategic importance (e.g., leadership in ocean science and technology, resource development, national security, education?)” (p.55).

International cooperation was certainly an integral aspect to manned research submersible activity during the 1970’s International Decade of Ocean Exploration (IDOE) activities, particularly ‘Project FAMOUS’ (French-American Mid-Ocean Undersea Study), which included cooperative programming and dives by the *Alvin* and French submersibles *Cyana* and *Archimede* (Heirtzler & Andel, 1977; National Science Foundation, 1982). In 1990, ocean scientist and marine lawyer Dr. John P. Craven described ocean salvage, Law of the Sea, and Exclusive Economic Zone rationales for manned submersible capability and concluded:

Thus we see that the practical uses of a manned deep ocean capability are so vital to the security of the world and to the establishment of responsible jurisdictions in

the seabeds of the world that hortatory appeals to occupy the seabed ‘because it is there’ are not necessary. (John P. Craven, 1990, p.13)

Today, however, international HOV capabilities, such as China’s 7000 m capable *Jiaolong* submersible, are noted but not necessarily pursued on a U.S. national scale (Monastersky, 2012). For assessment purposes, this factor can reflect not only national but state or other local ‘pride of ownership’ forces that may impact the sustainment of equipment.

3.4.9 FACTORS AND COMMENTS

Whereas societal factors can be influenced by particular technical, operational, or functional features, they more typically exert impact *on* aspects of other quadrants. The science priorities are closely related to the functional activities, and form an inherent dynamic that interweaves with Functional (quadrant C) considerations. A summary of societal factors is presented in Table 3.6.

Table 3.6 Quadrant D Societal Impact Factors, related quadrants and comments

Factor	Related Quadrant(s)	Comments
Science Priority	C	Reflects research activities
Public		
UNOLS		
Private		
Academic		
Champions		
Risk Perception	A, B	Influenced by safety record information, structural matters
Inspirational		

3.5 SUBMERSIBLE MODEL FACTORS SUMMARY

3.5.1 CASE STUDY TEMPLATE

The undersea systems model template, Figure 3-7, displays the identification of the factors described above.

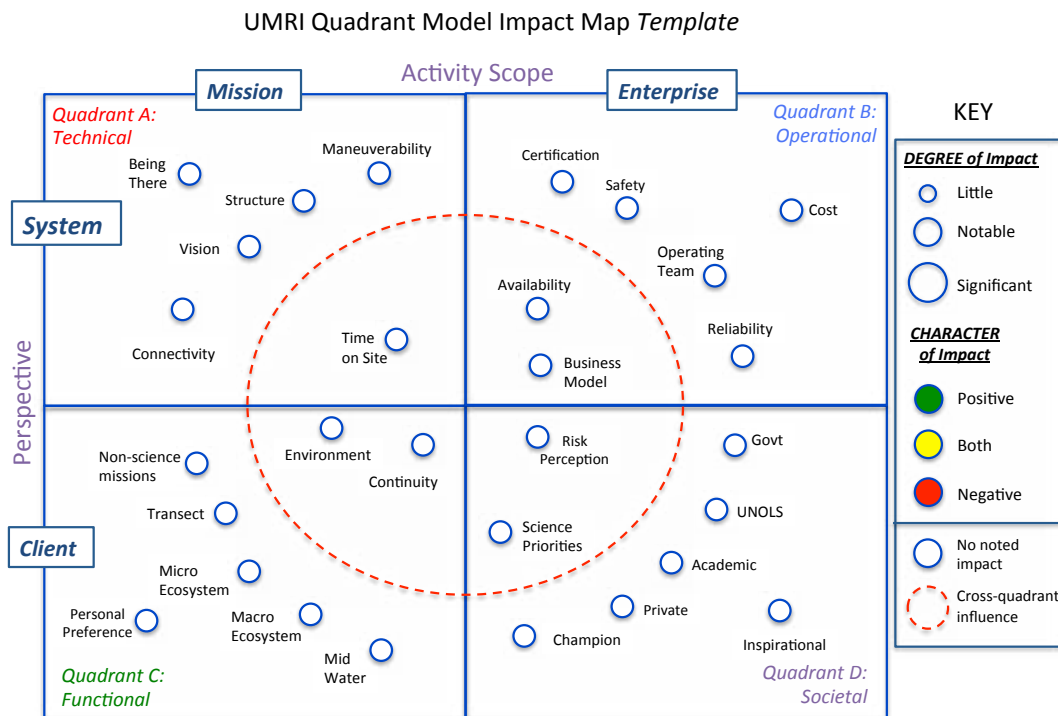


Figure 3-7 Template for undersea marine research infrastructure (UMRI) quadrant model impact factors for HOVs, with size and color key for use during analysis.

3.5.2 OTHER CONSIDERATIONS

Two aspects of research infrastructure consideration arose during this study that are worthwhile to be aware of and recall at the end of the process: a portfolio management approach, and recognition of the value of a suite of equipment, or ‘toolbox.’

3.5.2.1 Portfolio approach

Specific portfolio management approaches, such as those utilized by NSF’s Ocean Sciences Division (Ocean Studies Board, 2015) and the fisheries research community’s visual survey tool efforts (M. M. Yoklavich et al., 2015) offered valuable information for completion of various aspects of the quadrant model. Ultimately, use of the quadrant model is intended to inform future portfolio-level analyses. The Ocean Studies Board (2011)’s recommendations regarding considerations to address when determining “affordability, efficiency, and longevity” of ocean research infrastructure includes factors that can be addressed within the quadrant analysis, or supplied by a variety of analyses of systems within the infrastructure portfolio:

- Is there an appropriate infrastructure portfolio to manage uncertainty?
- Does the infrastructure portfolio avoid redundancy with investments by non-ocean industries or agencies?
- What is the balance between risk and potential benefits? Is risk managed appropriately (e.g., by spreading investment in technology development over several competing groups)?

- Does the infrastructure leverage other sources of support (e.g., from states, international partnerships, public-private partnerships, or the private sector)?
- Is there an appropriate infrastructure portfolio to manage a combination of sustained, episodic, and event-driven requirements? (p. 55)

3.5.2.2 The ‘Toolbox’

An observation that occurred frequently in the literature of the manned and unmanned submersible discussion, and appeared often during interviews, is that, rather than an ‘either-or’ decision, a combination of technologies is both necessary and complementary for marine research support (Bowen & Walden, 1992; Liberatore, Askew, Tusting, & Olson, 1997; Madin, 1990). This includes the use of separate vehicles for individual projects, as well as a ‘nested approach’ using multiple vehicles, such as the use of autonomous vehicles to conduct bathymetric site surveys that are used to plan ROV and HOV dives (Bowen & Walden, 1992). A scientist experienced in the use of a variety of systems noted the challenge of maintaining the ability to choose:

I always think about these sub issues as not an either or as a general class, it’s having all the tools available for the job you need to do. And you’ve just got this toolbox that has all these different things in it that you can draw from. (Scientist A).

Another researcher noted the emerging prevalence of ROV and telepresence-capable platforms and noted:

That [ROV activity] is great, I just hope that's everything we need, because we're killing our submarines at the same time...if everyone brings potato salad to a potluck, it's not a true potluck. (Scientist T)

CHAPTER FOUR : CASE STUDIES

Previous chapters developed a quadrant model for assessing the sustainment of undersea marine research infrastructure (UMRI), and established common impact factors using the case of U.S. manned research submersibles. This chapter tests the model with case studies of four major U.S. research submersible operations (*Alvin*, *Pisces IV/V*, *JSL I/II* and *Delta*) and a unique saturation-diving undersea research laboratory (*Aquarius*), examined during a time period from the mid-1980s to present. The analysis assigns quasi-quantitative values to the magnitude and degree (positive/negative) of significant impacts for each case based on analysis of existing literature and interview data; as such it represents an estimate of value for the purpose of illustrating the capabilities of the model.

The first case presented examines the most persistent of the four submersible operations, the Woods Hole Oceanographic Institution (WHOI) National Deep Submergence Facility (NDSF)'s *Alvin* program, which has been in operation since 1964, and identifies factors that have contributed to its sustainment. The University of Hawaii's Hawaii Undersea Research Laboratory (HURL) has operated the *Pisces V* and *IV* submersibles since 1987 and 2000, respectively; the submersibles remain in operation at a reduced pace. The Harbor Branch Oceanographic Institution (HBOI), now a part of Florida Atlantic University (FAU), operated the *Johnson Sea Link (JSL) I* and *II*

submersibles from 1971 and 1975, respectively (Dove, 2011), until 2009. Delta Oceanographics, a private company, operated the *Delta* submersible from 1985 until 2009. The *Aquarius* undersea saturation diving habitat, added as a unique test for the model, was sponsored by NOAA's Undersea Research Program (NURP) from 1986 until 2012, and is now owned and operated by Florida International University (FIU). Although it is a stationary versus mobile research asset, it is a manned undersea research facility that faces sustainment considerations that are similar to the factors identified for this HOV investigation.

The dive frequency of each of the submersible operations through the years is illustrated in Figure 4-1. The data are normalized by dive day (*Delta* would conduct 3–5 dives/day, *JSL I/II* often conducted 2 dives/day, and *Alvin* and *Pisces* operated 1 dive/day). For HBOI and HURL, the frequency represents the activity of both sister submersibles.

4.1 ALVIN: THE NATIONAL DEEP SUBMERGENCE FACILITY

The *Alvin* has been in continuous operation, notwithstanding periodic maintenance periods, by the National Deep Submergence Facility (NDSF) at Woods Hole Oceanographic Institution (WHOI), since its launch in 1964 (to be more exact, there are no pieces of hardware on the present *Alvin* that were part of the 1964 submersible, but the operation has provided continuous marine research services throughout this time (Engineer B)). Despite questions of its replacement with the maturing *Jason* ROV in the early 1990s (Travis, 1993), *Alvin* has continued to work alongside the ROV, and other

undersea technologies within the NDSF. A 2004 national study recommended the addition of a second ROV and a more capable HOV (Ocean Studies Board, 2004), and helped lead to improvements to the *Alvin*—a new sphere and other upgrades—that were completed in 2014. Although *Alvin* is currently still rated to 4500 m, the improvements are intended to enable an eventual 6500 m capability (Manager F, Engineer B).

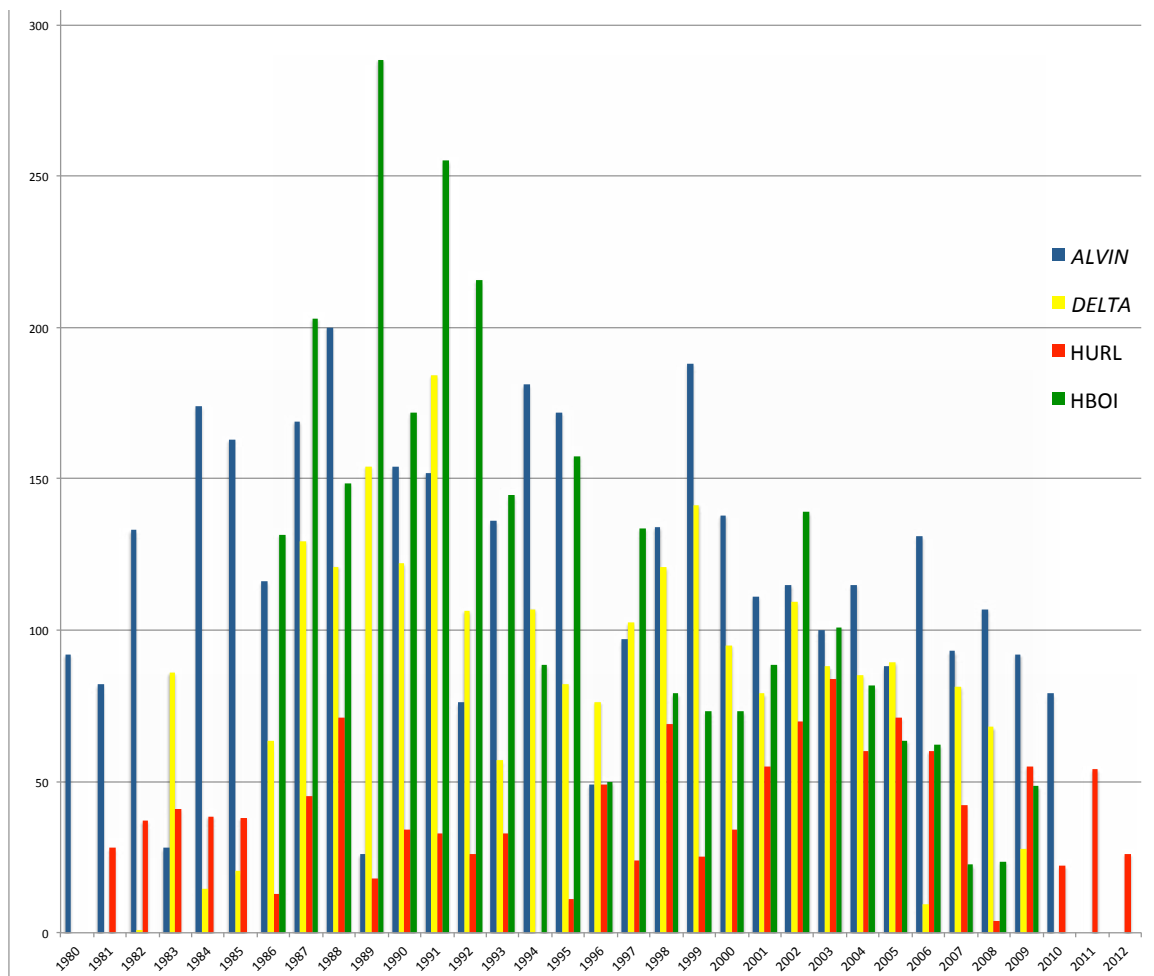


Figure 4-1 U.S. Submersible operation dive days 1980–2012 (derived from operational records). Numbers for HURL and HBOI include activity of both sister submersibles *Pisces IV/V* and *JSL I/II* respectively.

The history, scientific activity, and considerations of the value of the *Alvin* submersible are well documented (Ballard & Emery, 1970; Ballard & Hively, 2000; Busby, 1976; Forman, 1999; Geyer, 1977; Kaharl, 1990; Terry, 1966). Dive logs that include numerous variables such as location, mission, personnel and comments are available on line for all years of operation (Woods Hole Oceanographic Institution, 2016e). Annual and semi-annual community discussions of *Alvin* and NDSF assets are documented in DESSC meeting minutes (<https://www.unols.org/committee/deep-submergence-science-committee-dessc>). A 2004 Ocean Studies Board report gathered significant user input on the value of the submersible, and the submersible was recently included in an OSB examination of infrastructure value for the NSF Division of Ocean Sciences (DSOS). Sixteen engineers, scientists, and managers contributed information about *Alvin* and NDSF during targeted interviews.

4.1.1 QUADRANT A: TECHNICAL FACTORS

In response to the Ocean Studies Board Decadal Survey of Ocean Sciences (2015), the chief scientist of the NDSF commented that: “*Alvin* & ROVs ... have largely converged in terms of capabilities with the distinction being bottom time, mobility, and quality of observation” (Soule, 2015, p. 5).

‘Bottom time,’ or time on-site, is negative here for *Alvin*, as it refers to a 10 hour endurance for *Alvin* as compared to a typical 1–2 day mission length for the NDSF ROV *Jason* (Woods Hole Oceanographic Institution, 2016a, 2016c). ‘Mobility’ refers to the positive freedom of movement of the *Alvin* compared to the tethered *Jason*, and is still cited as a primary advantage of *Alvin* by senior NDSF personnel (Engineers C, J).

‘Quality of observation’ translates to both positive and negative factors. The new *Alvin* configuration provides overlapping views that give better peripheral and overall awareness, as well as the ability to detect elusive temperature ‘shimmers’ and small movements (Engineer I), but other scientists assert that the ability to zoom to make small scale observations, provided by new cameras, has been a more valuable capability (Scientists D, N).

The deep-depth capability of *Alvin* is reflected as a positive asset with respect to the impact of ‘environment.’ The aspect of ‘being there’ remains an elusively positive commodity for *Alvin*, lauded as “the cognitive ability of humans to put things in context, make connections between natural phenomena” (Engineer B). NDSF has recognized the limitations of connectivity of *Alvin* as compared with *Jason*, and is investing in fiber optic and through-water communication alternatives (Engineers A, B, H, J).

4.1.2 QUADRANT B: OPERATIONAL FACTORS

Despite an operational day rate that is similar to comparable technologies (2014 rates were \$16,000 for *Alvin*, \$23,000 for the ROV *Jason* and \$14,000 for the AUV SENTRY (Ocean Studies Board, 2015)), cost remains a factor for *Alvin* operations. The Ocean Studies Board (2015) identified “concern about the importance of and costs associated with ALVIN, including its need to use Atlantis as a dedicated tender at a time when more general-purpose Global class ships are needed,” as well as the need to critically consider the “planned Phase 2 upgrade to increase *Alvin*’s depth capability to 6,500 m, which needs to be framed in the context of both its alignment to the decadal science priorities and overall OCE infrastructure costs” (Ocean Studies Board, 2015, p.

54). The NSF responded that it “anticipates no changes in the NSF-NDSF relationship” and “currently has no specific plans to implement the Phase 2 *Alvin* upgrade and will likely work with the NDSF at the appropriate time to potentially increase *Alvin*’s capabilities during scheduled overhauls” (NSF Ocean Sciences, 2015, p. 5).

With respect to safety, the rigor of the U.S. Navy classification and inspection process, and dedication of the operational crew, has provided positive safety impact for the submersible (Managers B, C, G, J). The one serious incident that *Alvin* suffered (when it was lost at sea with only minor injuries to the crew while being recovered onboard its support ship LULU in 1968), is known now more for the scientific discovery that was made upon its recovery a year later. A baloney sandwich that had been left by one of the scientists in the vehicle was soggy but edible, leading to new deep sea *in-situ* experiments on bacterial decomposition “and a blossoming of deep-sea microbiology that has yielded unfathomed biochemical discoveries...” (Madin & Lipsett, 2014).

The impact of location availability on *Alvin* operations is driven more by research needs than by its home base location, leading to positive impact for those sites, but negative impact for other missions, as described by the Ocean Studies Board (2004):

Over the past two decades the ridge-crest time-series studies at particular locations (Juan de Fuca Ridge, the East Pacific Rise north of the equator, and the northern Mid-Atlantic Ridge) have dominated the use of *Alvin*... The strong pressure to revisit these sites on an annual or biannual basis has been the major factor limiting access of *Alvin* to other geographic locations in the oceans. This has been termed the ‘yo-yo’ effect as Atlantis and *Alvin* have been pulled back

and forth through the Panama Canal... the net result has been a geographic limitation on HOV use elsewhere in the oceans. (p. 63)

The business model is effective both because of the funding model used by its primary supporter, NSF (as described further in sections 3.4.2.1 and 4.1.4), and the facility model of operational support provided by its host institution, WHOI, as recognized by a recent Ocean Studies Board (2015) report:

An advantage of the NDSF facility structure is that it enables diverse groups of scientists to have access to, and OCE funding for, NDSF assets, using a formal request process. In much the same way that UNOLS ship time is not included as an expense in NSF proposals, scientists requesting use of NDSF vehicles do not have to include vehicle operations expenses in their proposal budgets. This is an incentive for use of the NDSF vehicles and, conversely, a disincentive for use of other, non-NDSF deep submergence assets that have to be included in NSF science program budgets. (p. 54)

The deep submergence vehicles are then also available to non-NSF agencies at an annually calculated day rate.

A second aspect of the business model that enhances success is an NDSF organizational policy that allows for and encourages staff to participate in work on a variety of deep submergence systems within NDSF and Woods Hole (Soule, 2015, Engineers B, C, J). The NDSF Chief Scientist states:

NDSF's value to the science community lies in both its advanced and adaptable vehicles, but equally importantly in the personnel and their collective engineering

and operational abilities and knowledge. The facility model (characterized as ‘subsidized use’ in the [“Sea Change”] report) is one of the key mechanisms to enhance personnel. The larger group produces collaboration, skills enhancements, and a dynamic environment that attracts personnel. (Soule, 2015, p. 9)

Also related to this policy is the resulting long-term expertise and commitment of the operational team.

4.1.3 QUADRANT C: FUNCTIONAL FACTORS

The *Alvin* has filled a niche for deep, small ecosystem study of hydrothermal vent and ridge systems since the discovery of the vents by scientists diving in *Alvin* at the Atlantic Mid-Ocean Ridge in 1977 (Woods Hole Oceanographic Institution, 2002). Although it has been used for salvage, archaeology, and other research tasks (Ballard & Emery, 1970; Ballard & Hively, 2000; Ballard & McConnell, 1995; Forman, 1999; Kaharl, 1990; WHOI, 2015a), since 1985 the submersible has spent almost half of its dive time exploring and researching these unique vent ecosystems, with more than 90% of these dives conducted in ocean depths greater than 2000 m of water (*Alvin* records analysis, Woods Hole Oceanographic Institution, 2016). This unique niche has exerted a positive impact on *Alvin* continuity, and is closely related to positive academic community (D) and scientific priority (D) forces.

4.1.4 QUADRANT D: SOCIETAL FACTORS

Many client-driven, enterprise level factors have worked together to provide sustainment for *Alvin* operations. Early Navy and WHOI cooperation established an

operational base, and NSF developed and fostered what has become a strong partnership with the NDSF. Within NSF, funding allocations for facilities are decided internally from a broader congressional appropriation (Managers C, F, J). Historically, division managers often came from geological and geophysical backgrounds (Reeve, 2000), and as such were largely supportive of the deep marine geological *Alvin* work. The Navy and NOAA have also supported *Alvin* activity; between 1974 and 2010, a memorandum of understanding (MOU) between NSF, Navy, and NOAA provided intent for annual financial commitment at an accepted ratio (60/20/20). Since the elimination of the NURP program in 2013 and the 2012–2014 renovation of *Alvin*, this funding model has shifted to a day rate, so that each agency funds on a mission basis (Ocean Studies Board, 2015).

UNOLS, DESSC, and the original *Alvin* Review Committee have all provided proactive, positive, and constructively critical support for *Alvin* operations throughout its tenure. Woods Hole Oceanographic Institution has also provided a supportive home and sponsor for *Alvin* (Managers C, F, J).

The scientific priority of deep-sea geological and hydrothermal vent studies provided significant impact with respect to scientific support for much of *Alvin*'s career, although lately this support has not been as apparent. The final report of the latest DEep Submergence Science DESCEND2 workshop Benthic Work Group (2016) reflects much broader research priorities, and does not include consideration of HOVs, instead endorsing 'Full-Ocean Depth ROV/AUV' as one of a number of 'Technical Enhancements' recommended for future deep ocean research (DeSSC, 2016a). The Ocean Studies Board (2015) assessment of NSF OCE infrastructure notes that:

Although the committee recognizes the value of HOVs to conduct real-time observations and sampling, manned vehicles are limited in their alignment to the decadal science priorities. HOVs are important for studying the sub-seafloor ocean environment, marine food webs, and biodiversity and marine ecosystems, but ALVIN is not critical to any priority (Table 1.1). This is due to the greatly increased capabilities and availability of ROVs, AUVs, and gliders... (p. 54)

The impact of champions on the success of *Alvin* is noteworthy. Although the submersible's development was the result of the work of several champions—Harold (Bud) Froelisch of General Mills, Trieste 'Officer in Charge' then-Lieutenant Don Walsh, and Chief of the Office of Naval Research Captain “Swede” Momsen, and WHOI's Dr. Allyn Vine, after whom who the submersible is named (Forman, 1999)—one of its most ardent early proponents, Dr. Robert Ballard, became a detractor, and an early champion of ROVs and telepresence for marine exploration and research (Ballard & Hively, 2000; Ballard & McConnell, 1995; Nautilus Live, 2015). Despite this relatively public shift, a long history of program managers, scientists, engineers and pilots have played important roles in maintaining *Alvin* capability.

Although national prestige in undersea infrastructure considerations is typically not as much of a factor as it is for manned space exploration (Space Studies Board, 2014) the *Alvin*, as the deepest diving U.S. submersible, is typically the submersible cited when comparisons of national capability are discussed (Ocean Studies Board, 2004). University and national prestige were included as positive factors to some degree during WHOI leadership considerations for support for the recent *Alvin* renovation (Managers J, R).

Continued certification support from the U.S. Navy is in part due to legacy practice, and in part due to the *Alvin*'s status as the nation's only deep diving submersible (Manager T).

Many anecdotes exist as to the advantage of the inspirational draw of the *Alvin* and its attraction for future marine scientists; even relatively senior scientists expressed this excitement at a recent Deep Submergence Science Meeting (Scientists U, X). A crewmember from the *Alvin* support ship *R/V Atlantis* provided particularly enthusiastic input for the 2004 "Future Needs" study (Ocean Studies Board, 2004):

Plants termed Entheogenic have the capacity to awaken our spirit. You will notice it shares a root with the word 'enthusiasm.' *Alvin* is an Entheogen. You see it on the face of everyone who climbs out of that sub; you see it in the eyes of the men and women standing on the fantail applauding the divers as they emerge. Why are these people clapping? Because they're happy. Why? BECAUSE *Alvin* MAKES PEOPLE HAPPY. *Alvin* EXCITES PEOPLE. (Capitalization original) (Kevin Threadgold, 2003)

4.1.5 ALVIN ANALYSIS AND IMPACT MAP

The *Alvin* has been successful primarily due to Societal (D) and Functional (C) factors. Federal and academic individual and organizational support, singularity of investment, and historically noteworthy science activity (hydrothermal vents, deep geology), have all contributed to this success. The *Alvin* may be subject to technological replacement, but to this point, it has continued to serve its role alongside the development, and maturation of the similarly capable *Jason* ROV.

The model could describe each factor that arose during research. An illustration of the degree and character of the impacts described above is presented in Figure 4-2.

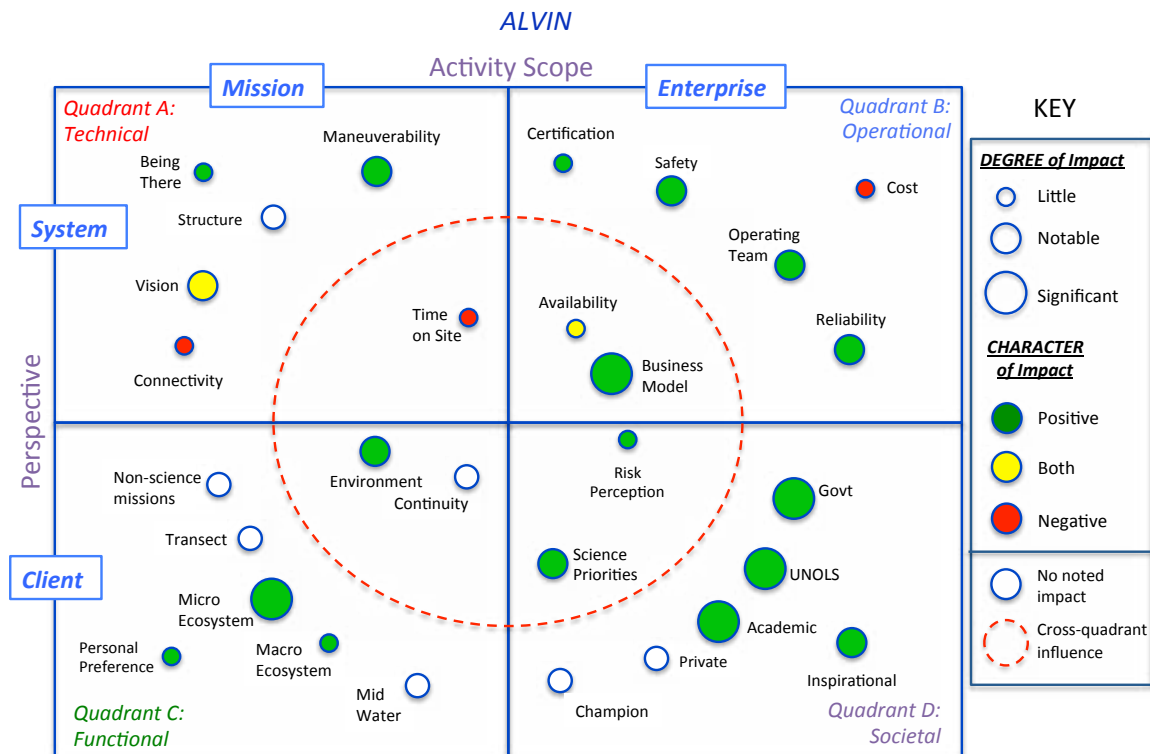


Figure 4-2 *Alvin* Impact Map.

4.2 PISCES IV AND V: THE HAWAII UNDERSEA RESEARCH LABORATORY

The Hawaii Undersea Research Laboratory (HURL) was as one of four original National Undersea Research Program (NURP) research centers competitively established by NOAA in 1980, and conducted marine research with HOVs throughout its tenure. The *Pisces IV* and *V* submersibles are numbered consecutively as per their original construction by the Canadian HYCO company in 1971 and 1973, respectively (Busby, 1976), although they were acquired by HURL in the opposite order: *Pisces V* in 1986, and *Pisces IV* in 2000.

The program that was originally proposed to NOAA included operation of an undersea saturation habitat, the *Aegir*, and the *Star II* (later renamed the *Makali'i*) submersible (Ocean Sciences Board, 1980, p. 8, Appendix C). The *AEGR* habitat proved too expensive to recertify (Manager E), but HURL operated the *Makali'i*, providing access to depths of 400 m (1200 ft.), visibility for a pilot and one observer through six 5-inch viewports, and 4–6 hour dive times—between 1981 and 1987. The *Makali'i* launch system was a unique ‘Launch, Recovery, Transport Platform’ (LRT), which was a towable, submersible barge that avoided ship-based launch difficulties at the rougher air/sea interface (In-Depth Images Kwajalein, 1981) (Figure 4-3).

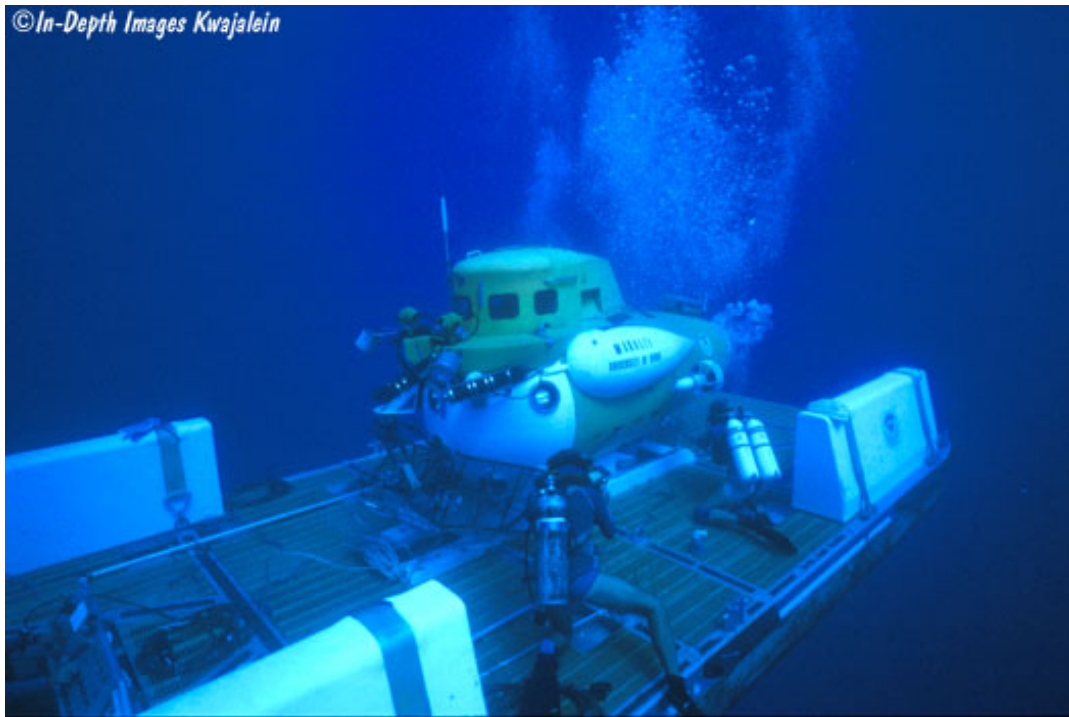


Figure 4-3 *Makali'i* submersible on Launch, Recovery, Transport platform (www.underwaterkwaj.com).

In 1986, HURL acquired the *Pisces V*, a Canadian HYCO submersible built in 1973, and began conducting research dives with her (from the LRT) in 1987 (Dixon, 2015; Kerby, 1991). The *Pisces* submersibles were built for undersea ‘intervention’ (oil field maintenance, undersea cable installation, inspection of underwater structures), have a depth capability of 2000 m, visibility for a pilot and two passengers through three 6-in viewports, and an 8–10 hour dive duration. In order to enable HOV operations beyond the towing capability of the LRT, HURL purchased and refitted a dedicated support ship, the *R/V Ka'imikai-o-Kanaloa (KOK)*, which began operations with the *Pisces V* in 1993. HURL acquired a sister submersible in 2000, the *Pisces IV*, from the Canadian Ministry of Defense, ostensibly for parts but ultimately as an operational HOV that provided self-

rescue and additional research and outreach capabilities (Engineer N). By 2012, HURL had recorded more than 1900 dives with the 3 HOVs (Hawai'i Undersea Research Laboratory, 2012). HURL also used a small 914 m (3000') ROV, the *RCV-150*, between 1998 and 2011, primarily for video surveys. In 2013, HURL acquired a 6000 m work-class ROV, named the *Lu'ukai*, built by Deep Ocean Exploration and Research (Hawai'i Undersea Research Laboratory, 2016; UH Marine Operations, 2013).

The discontinuation of funding from NURP, in 2013, resulted in a period of inactivity for the HOVs, during which the LRT was renovated, and HURL actively sought alternative mission activity. A potential expedition in partnership with Chinese scientists led to support from the University of Hawaii to bring the *Pisces IV* and *V* back to operational status. The Chinese expedition was cancelled, but HURL took advantage of the readiness of the subs to conduct NOAA missions from the LRT, and a few dives sponsored by National Geographic and Conservation International (Scientists Q, M, Engineer N). The HURL and University of Hawaii scientists who had used the *Pisces* submersibles have been engaging in ROV initiatives and operations, including testing of the new *Lu'ukai* ROV, and participation in NOAA Ocean Exploration missions with the 6000 m-capable ROV *Deep Discoverer (D2)* (Scientists G, M, Q).

Information about HURL is available publicly on the HURL website and in DESSC and other conference reports; additional data was acquired from grant records, and interviews and communications with eleven managers, scientists and engineers familiar with *Pisces* operations.

4.2.1 QUADRANT A: TECHNICAL FACTORS

Maneuverability was the most frequently cited technical advantage of the *Pisces* submersibles. Work at sites frequented by the submersibles—the Lo’ihi volcano and along vertical coral walls—requires fine dexterity among overhangs and strong currents:

The *Pisces* subs are particularly effective on atoll wall environments where there are steep (even vertical or overhung) walls with caves and karst features like stalactites waiting to snatch tethers. Also, since the walls are so steep, that requires the support ship for an ROV to be right off the fringing reef and breakers. With the subs, they can be launched and recovered in deeper water farther off by driving themselves in and out. (Scientist M)

After comparing deep ROV capabilities with *Pisces*, a pilot noted that

It’s a good thing ROVs can stay down longer, because it takes 3 or 4 times longer to do something as it does with the *Pisces*...if you’re looking for something and you miss it, you can’t just spin on a dime and go back. You’ve got all this gear in the water. (Engineer N)

The ability of the HOV to sit quietly on site to observe marine life also led to discoveries about fish and endangered monk seal behavior (Scientists Q, T). This capability was described by a *Pisces* pilot: “Human-operated submarines such as the *Pisces* are ‘like this really graceful hot air balloon that can just hang there perfectly,’ (pilot Terry Kerby) said. ‘You can get in irregular, unstable terrain and hang inches away from it’” (Wong, 2014).

The prevalence of steep coral atolls in the Pacific region, which suited the maneuverability advantage of the *Pisces* submersibles, has been a positive impact for operations. The depth rating of the subs has been largely positive; although NOAA's *D2* ROV was selected for recent deep exploration activity, the HOVs' 2000 m capability addressed a particular niche (Smith, 2005). "In some cases (*D2*) avoided ranges we dove *Pisces* to so as not to duplicate the exploration. *D2* can go much deeper, but they do not like to dive nearly as shallow as we are willing to go with *Pisces*" (Scientist M). (This resistance to shallow diving is due to overheating of the non-deployed umbilical cable on the deck of the surface ship when working at depths shallower than about 300 m (Engineer M)).

The reliability of the *Pisces* operation has always been positive, primarily due to the diligence of the crew. The *Pisces V* required end-of-life replacement of viewports in 2016 (Engineer N), but overall the HOVs have exhibited high dependability, especially when compared with early-system integration challenges of the new HURL ROV (Scientist M, Engineer N). The absence of connectivity to the surface has, also recently, been highlighted as a negative impact in comparison with recent NOAA ocean exploration telepresence missions in the Pacific region that were conducted with the *D2* ROV (NOAA Ocean Exploration, 2016).

4.2.2 QUADRANT B: OPERATIONAL FACTORS

The cost to maintain and operate the *Pisces* submersibles emerged as the most impactful of operational factors. Capital costs for the HOVs were low: HURL paid

\$500,000 for the *Pisces V* in 1985 and \$80,000 for *Pisces IV* in 2000; “(*Pisces V*) cost \$4 million to build in 1972...and would cost \$50 million to build today” (Dixon, 2015). The operation is run efficiently with a small, capable staff, but dedicated ship costs and leased pier space increases the university’s funding requirement. The LRT platform has been renovated for service, but remains limited to local operations (Scientist M, Engineer N, PBS UnderH2Oshow, 2013).

The HURL business model relied primarily on NURP funding (discussed in Section 4.2.4), and has faced challenges expanding beyond that support source. HURL managers have made numerous efforts to broaden the base of support for the *Pisces* program, including the traditional NOAA, NSF and Navy contacts, as well as “private sector, deep sea mining, ‘National Geo[graphic]s of the world,’ National Energy Lab, wind energy, deep water cable routes, Australia and New Zealand [partners], and munitions disposal...irons in the fire, if you will, all of which got quenched” (Manager Q). University of Hawaii (UH) leadership has been supportive with respect to maintaining the *R/V KOK* and acquiring the new ROV, but faces difficult decisions in the face of funding limitations (Manager Q). HURL has maintained a productive inter-university partnership with UH’s Hawaii Mapping Research Group (HMRG), but the opportunity to cross-employ *Pisces* engineers and pilots with other university initiatives has been less practical than at WHOI (likely due to the smaller number of ocean engineers, and possibly the off-campus location of the *Pisces* support facility at Makai Research Pier).

The relatively remote location of HURL has proven both positive and negative; it provides ready access to Pacific research sites, but increases the cost of activity beyond the reach of its support ship and reduces the number of potential partners. In 2005, HURL successfully conducted a South Pacific cruise that involved international partnerships, but other initiatives to reach eastward did not come to fruition (Manager G, Scientists Q, W). With respect to expanding the HURL business model, one manager noted, “we’re a little island out in the Pacific, and we have a limited dragnet of where we can go” (Manager Q).

The environmental characteristics of the Hawaiian research sites—especially steep, complex topography—have increased the value of the maneuverability of the HOVs. HURL has maintained ABS certification and an unblemished safety record.

4.2.3 QUADRANT C: FUNCTIONAL FACTORS

Although funding for the *Pisces* operations, including an annual number of *R/V KOK* sea days, was provided by NURP, research missions themselves were funded by other organizations including other NOAA offices, NSF, state, cultural, and industry partners. HURL conducted proposal reviews to select the missions that were to receive support; priority research topics for these missions were provided by NURP in an annual research guidance memorandum for all the Centers (Manager G). These missions were primarily biological studies in the Hawaiian Islands region, and included research and installation of instrumentation on the emerging Lo’ihi seamount. Studies consisted predominantly of small ecosystem examinations (Figure 4-4).

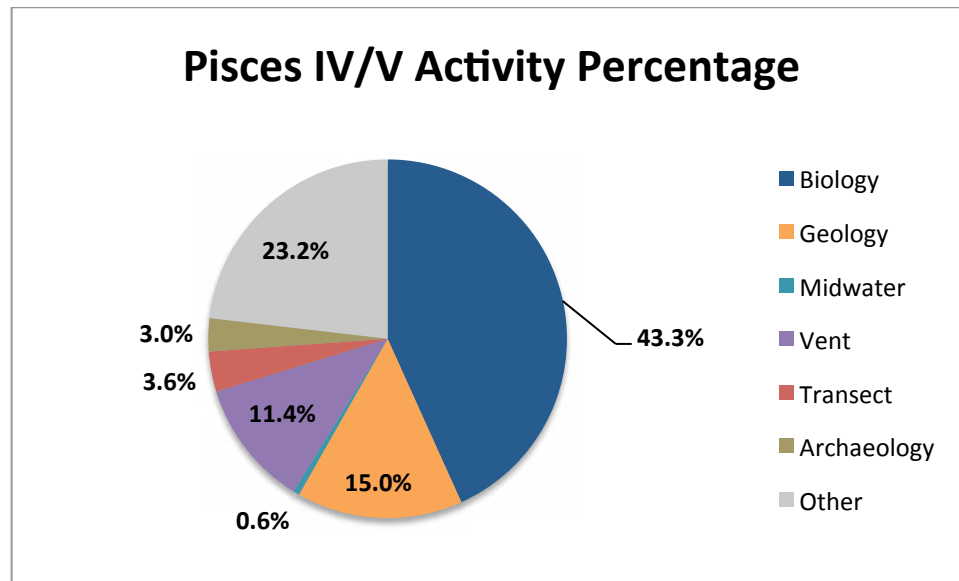


Figure 4-4 Percentage of *Pisces IV* and *V* dive activity by discipline (902 dives) 1985–2012.

The HURL funding model allowed for participation in other non-research activities, including archeological and salvage investigations, outreach activities, and identification of local chemical weapons sites under the “Hawai’i Undersea Military Munitions Assessment” (HUMMA) Project (Edwards, n.d.) (Scientist Q).

With the loss of NURP funding, the researchers lost data collection access to their worksites. Since there were limited alternatives for infrastructure with similar capabilities, “in general [that] work is just no longer being done” (Scientist M). “I don’t see putting instruments out this year because I don’t see getting them back. So that’s stopping me from doing the kind of work I’m trying to move forward with” (Scientist T). Others shifted focus of their work: a potential series of regional dives to study growth, life history and environmental correlations of deep sea corals was considered using the *Pisces* submersibles from the LRT platform but—in large part because the HOVs weren’t

operationally ready—NOAA’s Deep Sea Coral program funded deeper exploration ROV dives onboard the NOAA Ship *Okeanos Explorer* (Scientists M, T). A deep-sea coral scientist familiar with the region discussed considerations between the deep and shallow operational applications:

We’re definitely getting something out of [the deep ROV work]...but we go to [other U.S. Pacific territories] and talk to local communities about where to dive with *Okeanos*, and by and large almost all of the requests we get are for depths well within 2000 m: they want to look at bottom fisheries, deep corals, things that are of economic relevance to their agencies. (Scientist T)

4.2.4 QUADRANT D: SOCIETAL FACTORS

The termination of NURP funding, absence of support from the larger UNOLS community, and a relatively isolated and unfulfilled business model emerged as negatively impactful factors for *Pisces* operations. NURP provided infrastructure and research funding that was fairly stable despite congressional direction (Manager G), but once that funding disappeared, other support has been challenging to obtain.

NSF mission funding that included *Pisces* submersible infrastructure faced the obstacles previously noted—those costs would be included in the science proposals, and were not available from the NSF infrastructure fund—but HURL faced the additional challenge that the *Pisces* support ship R/V *KOK* was never accepted into the UNOLS program. The reasons for this exclusion emerged as funding limitations regarding support of existing UNOLS ships, uncertainty with respect to ship safety (risk perception), personal friction/differences, the absence of high-level incentives for interagency

collaboration, and a degree of resource protectionism (Managers A, B, C, E, G, J, Scientists M, T, Q). The latter is illustrated by an interviewee's statement: "I think people defend their cookies very, very tightly, and what they don't realize is that by competing, they're in bad shape... What these subs should be doing is closing ranks and building a strong story for themselves" (Scientist T).

The science priorities presented in the initial HURL NURP Center proposal included

...research (on) the areas of food from the sea, ocean energy, marine resource management, human performance in the sea, development of more effective work and habitation systems, marine environment management and, finally, basic research with potential long-term payoffs. (Ocean Sciences Board, 1980, p. 8, Appendix C)

Neither these goals nor the later work that was frequently cited as significant HURL research accomplishments—biological investigations in support of fisheries studies and examinations of the Lo'ihi volcano (Riley, 2016)—significantly influenced funding, however. A scientist who investigated environmental effects on corals surmised that the discontinuation of the NURP program was an indication that that ecosystem work was no longer a top priority (Scientist T), but in reality, the design of NURP as a provider of undersea infrastructure rather than as a discipline-specific program whose goal was to address particular marine research problems (such as the NOAA's Ocean Acidification or Deep Sea Coral program) makes it challenging to substantiate the contribution of research priorities to the overall funding of the program.

Personal championship has played a large role in the history of HURL. The Director of HURL from shortly after its establishment in 1980 until 2002, Dr. Alexander Malahoff, provided the personal energy and attention that was behind acquisition of the HOVs and the *R/V KOK* support ship (Scientist Q, Managers E, G). His influence was also described as a ‘double-edged sword,’ however, with positive results locally and congressionally and less positive results with NOAA and NSF (Scientists M, Q, T, Managers C, E, G). The leader of the *Pisces* operating team since 1981, pilot Terry Kerby, has provided steady operational expertise and leadership (Managers G, E, Scientists G, M, Q, T) to the point that the Director of the National Deep Submergence Facility has been quoted as saying: “You can’t replace a Terry Kerby with a robot” (Dixon, 2015).

Much of the persistence of the HURL operation could be traced to the commitment of the State of Hawaii, primarily in the form of Congressional support. As described by a HURL scientist, the inspirational aspect of the HOVs was a driver for this support:

The [Congressional] delegation saw Hawaii as a leading place for this marine technology: a new world with offshore energy and fish farms and mining and floating hotels and tourist submersibles, and we [HURL] were going to be a part of that. (Scientist Q)

The recent efforts to continue HOV operations in the face of financial difficulties has also brought positive media attention (Braun, 2016; Dixon, 2015; Wong, 2014).

Pisces scientists remain motivated about the human perspective and excitement of conducting research in an HOV, while recognizing the advantages of unmanned tools and the changing technological times (ThinkTech Hawaii, 2014), for example:

I was kind of wondering how much [being there] matters to kids these days or the public even in general. If you'd have told me when I was a kid that 'oh, someday you'll grow up and you can sit in front of a computer screen and watch,' I don't know that I would have been inspired to go. I was watching Jacques Cousteau out on the ship and diving and stuff. But things are different now and I don't know if it has the same impression. (Scientist M)

4.2.5 *PISCES ANALYSIS AND IMPACT MAP*

The *Pisces*' story displays characteristics of Technical replaceability (quadrant A), in that its activities have been and are largely being replaced by ROV technology, but strong Social (quadrant D) and Operational (quadrant B) factors have also had an impact. With respect to its primary funding supporter, New York Times reporter Chris Dixon (2015) observed that "[NURP] was phased out in favor of an unpiloted, internet-connected virtual model that includes on-call scientists around the world," and quotes NOAA leadership: "We realized we can't afford to do it all...so we had to ask, what are we doing and how can we have it be inclusive? So scientists who can't dive—they have a presence through telepresence" (Dixon, 2015, pp. 6–7). An illustration of the degree and character of the impact of factors as described above is presented in Figure 4-5.

The HURL business model suffered from exclusion from UNOLS, and from its geographical isolation (quadrant B) from other potential sponsors. The UNOLS exclusion

can be attributed to financial considerations, but it was also widely acknowledged that personal-level conflicts also contributed to this rejection (Scientist Q, Managers B, C).

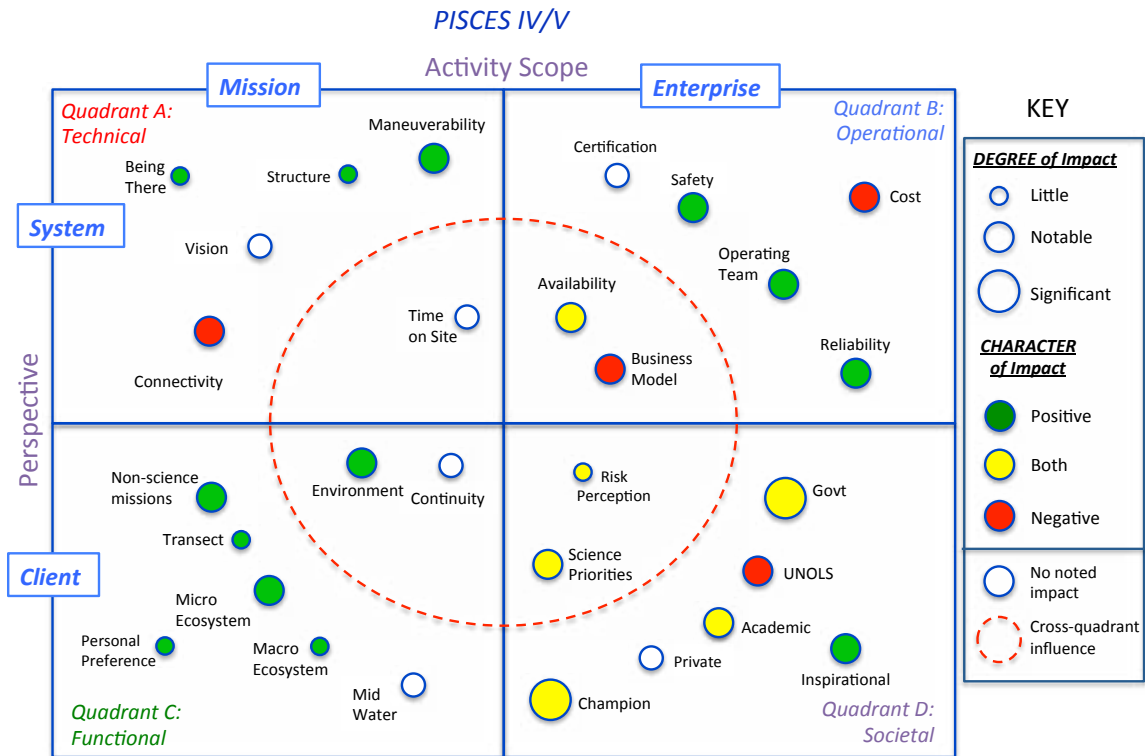


Figure 4-5 PISCES IV/V Impact Map.

Each of the impact factors that emerged during research could be captured within the model framework. Investigation into the quadrant factors has provided insight into causality. The new 6000 m ROV was not initially purchased with the intent of replacing the *Piscis* submersibles, but of replacing the older *RC-150* ROV, taking advantage of a

potential emerging deep sea mining market, and, in the long run, shifting from an ROV-augmented HOV operation to an HOV-augmented ROV program (Manager Q). The opportunistic activity indicates a situation of infrastructure push rather than scientific pull, but also illustrates the challenge of balancing the need for expensive equipment for relatively limited research activity.

4.3 *JOHNSON SEA LINK I AND II*: HARBOR BRANCH OCEANOGRAPHIC INSTITUTE

In 1971, J. Seward Johnson Sr., of Johnson & Johnson corporation, established the Harbor Branch Foundation, Inc. “for research in the marine sciences and for the development of tools and systems for underwater oceanographic research” (Harbor Branch Foundation, 1978). Edwin Link, inventor of the Link flight simulator and designer of the *Johnson Sea Link (JSL)* submersibles, was Vice President, trustee, and active participant in the Foundation’s research and development activities.

The Foundation constructed and operated a marine research facility, originally the Johnson Science Laboratory and ultimately Harbor Branch Oceanographic Institute, located on Link Port channel near Ft Pierce, Florida. Harbor Branch scientists conducted Foundation-supported work in marine science, ecology and engineering, aquaculture, biomedical collection and assay, and outreach and education (Scientist L, S). After Johnson Sr.’s death in 1983, the Foundation received a \$20 million endowment, and Johnsons’ son, J. Seward Johnson Jr., a sculptor, became director of the Foundation (J. D.

Reed, 2002; Weber, 2013). Financial difficulties ensued, and scientists were required to begin competing for external research grants (Scientists K, S).

Harbor Branch Oceanographic Institute has since received grant research funding from NOAA, NSF, and ONR, and in 2007 became part of Florida Atlantic University (Harbor Branch, n.d.). In 2009, HBOI led a consortium that became a new NOAA Cooperative Institute for Ocean Exploration, Research and Technology (CIOERT), which was established in part as a transition of the NURP program (Manager G). Infrastructure casualties of the financial struggles included the sale of three research vessels and mothballing of three submersibles: the 2 *JSL*s and a Perry submersible, the *Clelia* (Scientist K, L, Engineer L). Although the submersibles remain in storage at Link Port, they are no longer maintained. These HOVs conducted 9407 dives between 1971 and 2011 (Reed & Frank, 2011).

In the absence of the *JSL* submersibles, scientists have turned to primarily to ROVs to conduct deep-sea coral and ocean exploration work (Scientists K, L). Much of the biomedical collection work that was accomplished by the *JSL*, however, has not been resumed (Scientist K).

Activity summaries of the *JSL* submersibles can be found in Forman (1999), Liberatore *et al.* (1997), and Reed and Frank (2011). Other case study information was gathered from interviews and personal communication with *JSL* scientists, engineers and managers, and from personal experience.

4.3.1 QUADRANT A: TECHNICAL FACTORS

The JSL submersibles provided unique technical capabilities with respect to the panoramic visibility provided by the acrylic sphere, and the ability to hover and conduct work in mid-water (Liberatore *et al.*, 1997). The subs also included a separate pressurized sphere that enabled lock-out saturation diving, which requires lengthy decompression times that increase with mission depth. Saturation diving was discontinued in the mid-late 1980s due to a combination of factors, including changes in leadership and in-house science users, sale of a specialized support vessel, and increase of depth capability of the HOVs to 3000 ft. (Alistair Dove, 2011; Liberatore, personal communication, September 4, 2016). The capabilities that emerged as most missed by *JSL* scientists were the ability to access and maneuver in high current environments, and to conduct mid-water studies (Scientists K, L, P, S).

Deep-sea coral researchers face one of the more challenging marine research environments in and near the Gulf Stream and around the coast of Florida. In conditions of 4–5 knot surface currents, even the large research ROVs have been unable to descend through the current to the worksite (Scientist L). At the bottom, currents are typically slight, so HOVs—once through the interface and at the worksite—are no longer influenced by the stronger surface and mid-water column currents. As described by one scientist familiar with these operations:

The main problem with the ROV [is that you're] typically drifting along, hopefully not too fast, getting photo and video, but if you want to stop to get a sample...you at most have 30 seconds to work while the catenary is being pulled

out, while the ship is trying to station keep; even with good [shipboard dynamic positioning capability] it's hard for ship to station keep in 3 knot current. You don't go wherever you want...you go south to north. If I see a pot of gold 500 feet away, it's bye-bye. (Scientist L)

The unique ballast system of the *JSL* submersibles—which were designed with the ability to adjust to the variable weight demands of lock-out divers—allowed pilots to hover in mid-water, giving scientists who study pelagic organisms access to that ecosystem that was otherwise unavailable. This dexterity also provided other benefits:

A good pilot could actually use the currents around the sub to fold a siphonophore before he tucked it into the detritus sampler on the front of the sub. We're talking about things that were unbelievably fragile and you would never be able to handle them any other way. (Scientist P)

Although the acrylic sphere also provides a unique capability for panoramic vision, this value was not emphasized as much for research purposes as might have been expected. One *JSL* scientist suggested that this might be because “we took that for granted. Once you compare *JSL* with *Alvin* or *Mir*, you realize the limitation of looking through the portholes” (Scientist K). During missions sponsored by NOAA's Office of Ocean Exploration, two separate mission comments regarding the submersibles relayed that although the HOVs provided a “first-hand look” or “fish-eye's view”, “equally important were the sampling activities that took place” (Sedberry, 2004; Wyanski, 2003). The *JSL* submersibles were also noted as being more comfortable than the deeper HOVs: “sitting up for several hours is way more comfortable than lying prone” (Scientist K).

HBOI scientists have embraced the connectivity provided by ROVs. Those who have transitioned to using an ROV for habitat research found that the real-time ability for surface-based personnel to annotate the video for species and habitat characteristics has become an immensely valuable asset:

For the data we're collecting the ROV is wonderful because we have all this input immediately after the cruise; in a week [we] can have a 300-page report documenting everything we saw...I couldn't do that from a sub dive, get that level of detail. I've got all these people collecting data at once. (Scientist L)

The HBOI organization has also embraced the capability of telepresence with the installation of a NOAA-linked Exploration Command Center on campus, and active participation in NOAA's Office of Ocean Exploration missions (Scientist K).

4.3.2 QUADRANT B: OPERATIONAL FACTORS

The negative impact of cost in the case of the *JSL* submersibles was closely related to the reliance of the HOVs on a dedicated support vessel, which was decommissioned as part of an overall reduction of ships and infrastructure that occurred during Harbor Branch's transition to Florida Atlantic University (Scientist K).

The location of HBOI proved beneficial due to its proximity to marine habitats of interest off the coast of the southeastern United States and around Florida. More than three-fourths of *Johnson Sea Link* submersible dives were conducted in the Caribbean, Gulf of Mexico, and off the southeastern U.S. coast (*JSL Diving Logs*). The ability to focus on these areas was in fact instrumental to discovery and research (and subsequent implementation of management protocols) of the *Lophelia* deep-sea coral banks along the

southeastern U.S. coast (Reed & Franks, 2010). Environmentally, the prevalence of high currents in these areas increased the value of the HOVs' maneuverability (Scientist L).

Assessment of the business model reveals a longitudinal change from positive private support to a challenging public/private transition period to a more stable, multi-source partnership model. Although established after the loss of the HOVs, the CIOERT HBOI partnership has included participation from more than five different NOAA offices and 11 universities (NOAA Ocean Exploration, 2015). Like HURL, HBOI is relatively limited in the size of a local engineering staff, although the FAU partnership provides access to additional expertise in the Miami region, approximately 2 hours south of the HBOI campus.

After the 1973 fatal accident (Forman, 1999), lessons learned were incorporated into community HOV safety guidance (MTS Undersea Vehicle Committee, 1974), and the JSL operation became a leader in HOV safety, experiencing no further serious incidents (Engineer L). Nevertheless, the impact of the accident was still cited by a program manager decades later: "the problem they had at Harbor Branch...it took years to get over that" (Manager C). With respect to reliability and operating team expertise,

[The *JSL* subs] were just amazing, amazing workhorses. I don't think enough has been said about the team and the personnel that surrounded those submersibles—which is what really made them hugely productive—and that skill set is gone.

(Scientist P)

4.3.3 QUADRANT C: FUNCTIONAL FACTORS

The *JSL* submersibles specialized in mid-water studies and small ecosystem examinations (Figure 4-6).

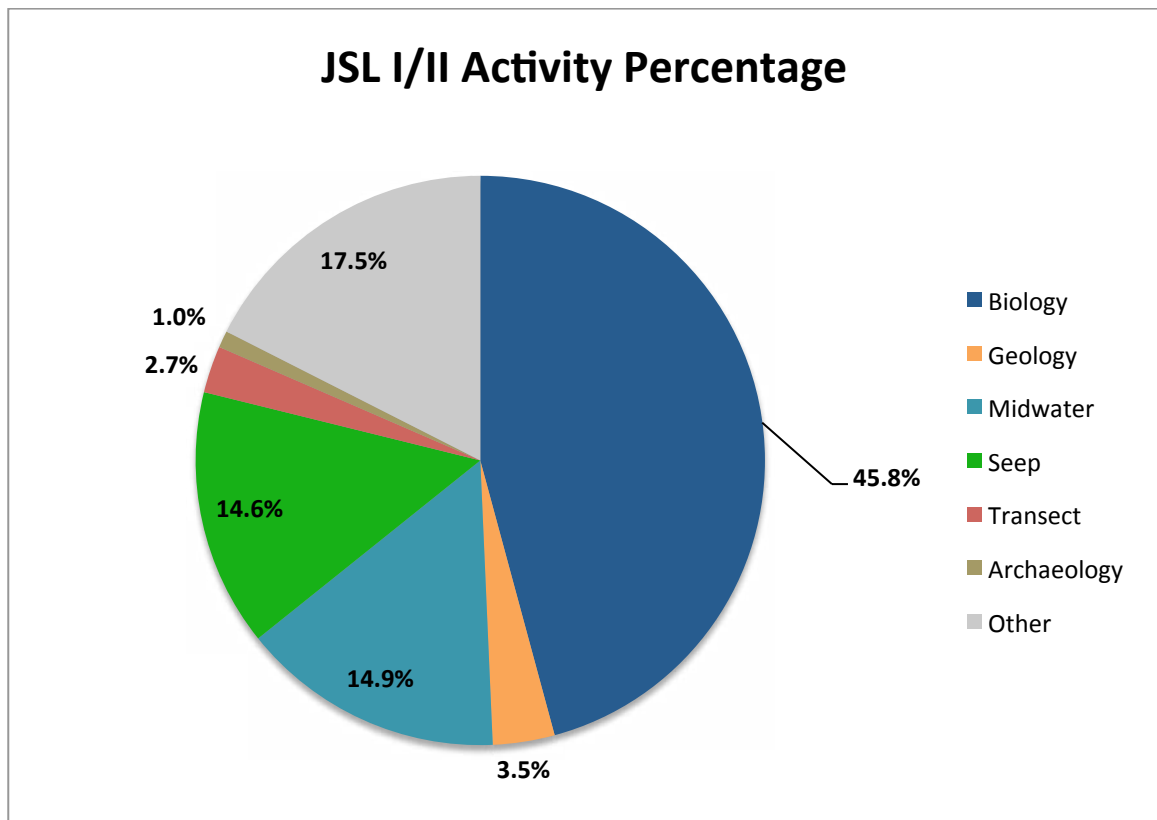


Figure 4-6 Percentage of *Johnson Sea Link I* and *II* dive activity by discipline (5667 dives 1985–2009).

Between 1985 and 2010, HBOI submersible activity was focused primarily on biological research, including collection of biological samples for biomedical assay (~12% overall), deep-sea coral habitat investigations, and mid-water studies (Harbor

Branch, 2009). NOAA's Office of Ocean Exploration supported 13 missions that used the *JSL* submersibles between 2001–2009; eight of these conducted exploration and sampling in the Gulf Stream high-current regime off the southeastern U.S. coast and three focused on mid-water bioluminescence (NOAA Ocean Exploration, 2016). Work was conducted in response to a combination of interests from HBOI, NSF, NOAA and other scientists.

4.3.4 QUADRANT D: SOCIETAL FACTORS

The most notable factor of the support for Harbor Branch Oceanographic Institution and *JSL* operations is the wide range of sponsorship sources. Champions Seward Johnson and Edwin Link were responsible for the establishment and early success of HBOI, but the personal decisions of later institution leaders led to a series of shifts away from HOV and marine infrastructure support (Reed, 2002). Dr. Shirley Pomponi championed use of the HOVs on the national stage, and at one point led a Shallow Submergence Committee within DESSC (DeSSC, 2002). As private support waned, public support arose from federal sources in the form of competitive project awards from NOAA, NSF, and other state sponsors. The 2007 incorporation of HBOI into Florida Atlantic University (FAU) has enabled the Institution to continue its work, although investment has been in shore-based rather than ship-based research infrastructure (Harbor Branch, 2010). This investment decision is represented as a 'significant negative academic' impact because it directly resulted in the sale of the *JSL* support ship, and retirement of the submersibles (Scientist K).

The amount of support from NOAA was influenced by program dynamics within the two primary funders, NURP and the Office of Ocean Exploration. NURP support was

available only from the regionally distributed Center funds, and faced competition with other Center-sponsored infrastructure priorities (Manager G). After five years of active use of the *JSL* submersibles for ocean exploration, the Office of Ocean Exploration's budget shifted from competitive awards to support for in-house infrastructure in the mid-2000s (Manager G, N).

The Harbor Branch vessels were members of UNOLS, but obtaining research funding from NSF for *JSL* submersible work faced the challenges previously described regarding increased cost of non-NSF sponsored infrastructure (Scientist K, Manager C).

Despite the impact of deep-sea coral habitat discovery and characterization on fisheries management, the research priority of *JSL* work did not in the end appear to exert much impact on the decision to retire the HOVs (Scientists K, L). Although research conducted using the *JSL* submersibles initially addressed the needs of primarily HBOI scientists, by 2011 more than 100 scientists from more than 75 organizations had conducted work from Harbor Branch vessels, with two dozen 'recent major users' of the *JSL* cited in 2011 (Reed & Frank, 2011).

The panoramic view provided by the *JSL* submersibles was an asset with respect to the inspirational draw of the vehicles. The HOVs were sought after for underwater video footage, and made appearances in numerous documentaries and anchored an active educational and public outreach program (Reed & Frank, 2011).

4.3.5 JOHNSON SEA LINK ANALYSIS AND IMPACT MAP

Like the HURL operation, both Technological (quadrant A) and Societal (quadrant D) factors influenced *JSL* sustainment. Private events and personal decisions

during the second generation of Johnson leadership led to financial challenges; new leadership responded to these financial challenges with decisions to divest of sea-going infrastructure that were a mix of financial analysis and personal preference. Public support was impacted by NOAA and NSF policies as described above. An illustration of the degree and character of the impacts described above is presented in Figure 4-7.

Each of the impact factors mentioned in research was captured within the model framework. Research activity (quadrant C) was influenced by location (quadrant B) and funding source (quadrant D). Causality between Technological and Societal factors is difficult to determine. Technological replacement of *JSL* activity with ROVs was primarily a result of adaptation by scientists to the loss of the HOVs rather than a conscious decision to by researchers choose an alternate technology, while Societal influence in the form of an individual in a program leadership position exerted more proactive, tangible impact in replacing the HOVs with remote technology.

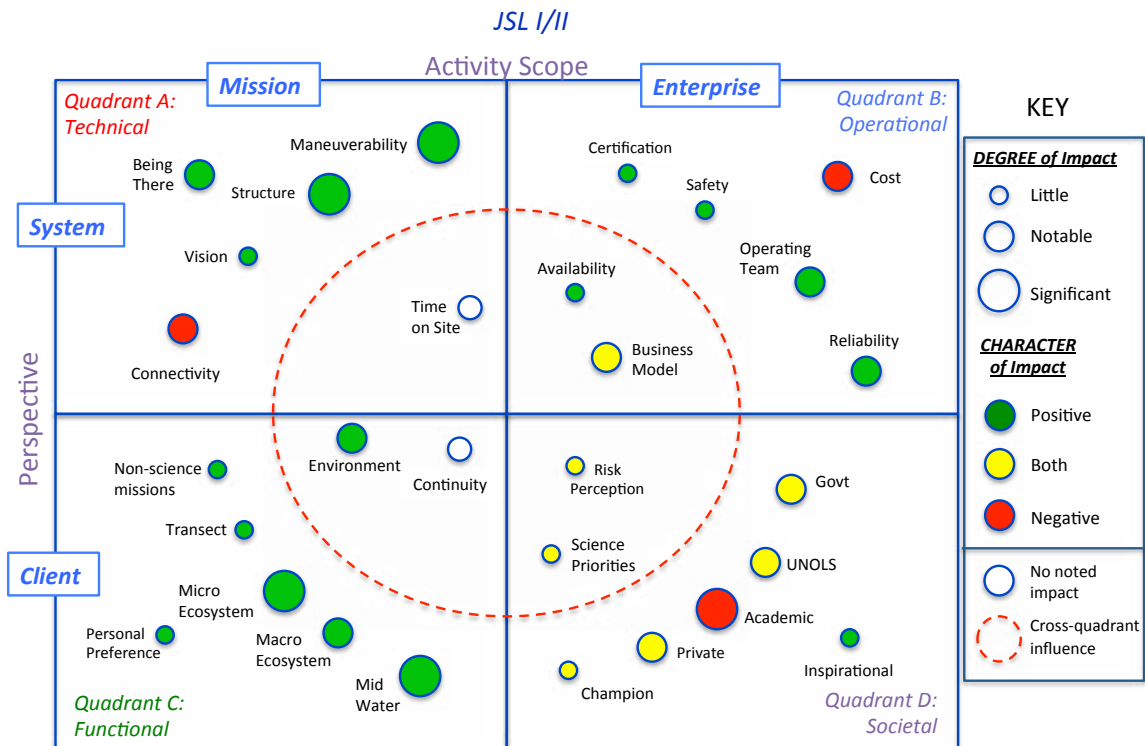


Figure 4-7 JSL I/II Impact Map.

4.4 DELTA OCEANOGRAPHICS

Entrepreneur Doug Privitt of Torrance, CA, began building submersibles in the 1950s; between 1970 and 1990, his *Nekton* series (*Alpha*, *Beta*, *Gamma*) were workhorses for underwater survey and science (Forman, 1999). Cylindrical in design and rated to 1000 ft. depth, these HOVs were designed “to break off fragments of rock, have good visibility for seafloor mapping, be able to dive off many kinds of support vessels, and be economical to use” (Slater, 2015, p. 62). Privitt replaced his *Nekton* series with the

improved *Delta* submersible and established Delta Oceanographics, which used *Delta* to conduct more than 7500 marine science and other dives between 1982 and 2009 (Delta Oceanographics, 2015; M. M. Yoklavich & O’Connell, 2008). The *Delta* provided an increase in depth to 1200 ft. (365m), faster speed, and better visibility than its predecessors.

Activity of the *Delta* is well documented in Yoklavich & O’Connell (2008), Slater (2015), and Forman (1999). The HOV was an important resource for fisheries survey efforts off Alaska and the U.S. West Coast, and also conducted archaeological expeditions to Lusitania, Sampson and other wrecks. The *Delta* has also been included in more than a decade of analysis of the value of video tools for marine and fisheries science (Green, Lowry, & Yamanaka, 2014; Harvey & Cappo, 2000, p. Appendix 1; NOAA, 2014; Reynolds, Greene, Woodby, Kurland, & Allee, 2008; Somerton & Glendhill, 2005; M. M. Yoklavich et al., 2015), including specific comparisons with ROVs (Laidig et al., 2013; Laidig & Yoklavich, 2016; O’Connell & Carlile, 1994). Other case study information is derived from interviews and personal communications with 12 scientists, managers, and engineers familiar with the *Delta* system. The *Delta* website remains accessible (www.deltaoceanographics.com).

Delta Oceanographics discontinued operations in 2009. Since then, several fisheries researchers have been actively engaged in evaluating the suitability of other HOVs (Yoklavich et al., 2013; Scientist R, Manager S), and in obtaining a replacement HOV with similar features to those of *Delta* (Scientists H, I, R). One fisheries monitoring

survey group that previously relied on *Delta* has fully transitioned to ROV use (Green, Stahl, & Kallenberger, 2013).

4.4.1 QUADRANT A: TECHNICAL FACTORS

The technical characteristics of the *Delta* that were cited as most valuable during interviews were the view provided by the flat side-looking viewports, maneuverability, and ruggedness.

The value of the view was directly related to the task of identification and quantification of fish. Advantages include the ability to:

...distinguish a cryptic fish from the background...measure many small species that otherwise would have been difficult to detect in video footage alone...look in multiple directions in contrast to the single, fixed direction of a video camera [which] creates greater opportunity to detect and identify fishes within the transect area, (Laidig & Yoklavich, 2016, p. 393)

and “to count yelloweye rockfish with an extremely low probability of counting the same fish multiple times” (O’Connell & Carlile, 1994, p. 200). Based on these observations, groundfish scientists have suggested that:

Consequently, an ROV may not be the vehicle of choice to assess the importance of nursery grounds, predator-prey interactions, or ecosystem functions, all of which require an ability to detect and identify small fish species. (Laidig & Yoklavich, 2016, p. 394).

The value of improved stereo still and video cameras, however, has been noted as a significant capability for estimating fish length (Laidig & Yoklavich, 2016). A scientist

who has transitioned to use of ROVs for groundfish surveys noted that, despite being able to see farther horizontally from the *Delta* submersible than from an ROV, the use of stereo cameras on the ROV had the advantage of “taking away the error of human measurement” (Scientist F).

Maneuverability, whether the ability to stay close to the bottom on a constant transect or maneuver freely around underwater objects, was also a quality of *Delta* that its users valued. During a comparison study between *Delta* and a Benthos Undersea Systems Technology MiniROVER MKI ROV, “The sub... allowed transects to be run in a relatively straight line. [It] was also much more maneuverable than the ROV [which failed to operate] in the rough terrain” (O’Connell & Carlile, 1994, p. 200). ROV work around an oil platform that was performed when visibility was too poor for *Delta* use resulted in data that was used for a report, but not considered academically publishable (Scientist H), in large part due to uncertainty of the ROV location: “It’s hard to estimate the area being surveyed by an ROV...[it] gets yanked away, 25 minutes later, you’re back on site” (Scientist H).

Geologists were particularly appreciative of the ruggedness of the HOV:

The senses that you get, the sounds that you hear through the submersible...I use all of this stuff. If I want to find out what the seafloor is made of, I’ll have the submersible dive to the bottom and scrape across it, and I can hear whether it’s sand, gravel, mud or what have you. (Scientist E)

This scientist also expressed a desire to use the *Delta* for a unique study that required prolonged presence on the bottom in a sediment wave field in order to view the intertidal

behavior of sand lances, a task he did not feel any other system was capable of accomplishing (Scientist E).

The rugged environment that was targeted by *Delta*'s fisheries scientist and geologist increased the value of *Delta*'s structural and maneuverability characteristics. The submersible was also relatively robust with respect to sea state limitations, depending on the size of the support vessel and other factors:

DELTA typically can be used up to a Beaufort Sea State of 4–5, but this is difficult to quantify because its use also depends on periodicity and direction of the sea swells, wind direction relative to swell direction, and atmospheric visibility coupled with the experience of a particular support crew. (M.M. Yoklavich & O'Connell, 2008)

4.4.2 QUADRANT B: OPERATIONAL FACTORS

Cost was identified as “the biggest issue when selecting a survey tool for future projects,” by members of the fisheries survey community, including researchers, who used the *Delta* submersible (Yoklavich et al., 2015, p. 21). This report cited a \$6,000–\$10,000/day cost for leasing an HOV, \$10,000–\$15,000/day to lease an ROV, and \$500–\$6000/day to operate an ROV that is owned by the user (Yoklavich et al., 2015). A scientist faced with replacing fisheries assessment work formerly conducted using *Delta* noted that other HOV options were more expensive (@\$30,000/day with support vessel), while an alternative small ROV with vessel solution was a more affordable \$4,000/day (Scientist F). A small ROV also “requires less specialized vessel support than the submersible” (O'Connell & Carlile, 1994, p. 200).

The leasing business model was effective in sustaining the Delta Oceanographics operation during its tenure. Further discussion of the funding sources is included in the section on Societal impact (Section 4.4.4).

The *Delta* maintained ABS certification, and included safety features such as the use of compressed air for ballast tanks, which precluded the need for electrical power to ascend; and detachable tail section and external weights, which allowed for escape if fouled underwater (Forman, 1999; Slater, 2015). *Delta* was free of major safety incidents throughout its tenure (Delta Oceanographics; 2016, Engineer D). An overall sense of safety with respect to the submersible was credited to its simplicity:

Delta was such a simple machine, a safe machine. I liked the submersible because [I] felt comfortable, safe. I knew if something happened I could get up; (Scientist E)

“*Delta* (was) a very, very simple tool, it’s really difficult to get yourself in trouble” (Scientist J); and

In my humble opinion, the simplicity of that made it safe. The batteries, the tail would come off if you got caught in a net. You know, they wanted to live as much as anybody. (Manager E)

The small size and ruggedness of *Delta* allowed its operators to use a launch practice that did not require the submersible to be lifted over the side while occupied, enabling use of a wide range of small vessels of opportunity that were equipped with dynamic, load-tested, cranes (Slater, 2015; M. M. Yoklavich & O’Connell, 2008).

UNOLS safety guideline requirements, however, require that “If the handling system will

ever be utilized while the HOV is occupied in the lift/launch/recovery/deck-transfer modes, it must be rated for such service by ABS, NAVSEA, or another appropriate classification society” (UNOLS, 2009b, p. 13, 2009a). Cranes thus certified are typically available on larger, more expensive vessels. One *Delta* operation was cancelled in 2005 because of this policy (Manager C, Engineer D).

The *Delta* was easily shipped from its home base in Torrance, CA to operational locations around the world, with ease of shipping being “no different than having a generator that you’re going to use” (Scientist J). Dive location was therefore driven more by the mission demand than by convenience of the home location: prior to 1995, almost half of its dives were in locations other than off the U.S. West Coast and Alaska; after 1995 and the rise of usage by the west coast groundfish community, 91% of dives were offshore of either Alaska, California, or the northwestern United States (Figure 4-8, derived from *Delta* dive logs).

4.4.3 QUADRANT C: FUNCTIONAL FACTORS

Quantitative transects for fisheries research and assessment were by far the most impactful and frequent activity conducted by researchers using the *Delta* (Figure 4-9). As expressed by one fisheries scientist:

[*Delta*] drove the continental shelf fisheries in situ studies for several decades.

[At] western ground fish conferences, talk after talk after talk from Alaska to southern California, even British Columbia would have pictures of the *Delta* in their talks. It got so it was almost humorous. Its loss was a huge impact; it was a standardized piece of equipment that we were using coast-wide. (Scientist O)

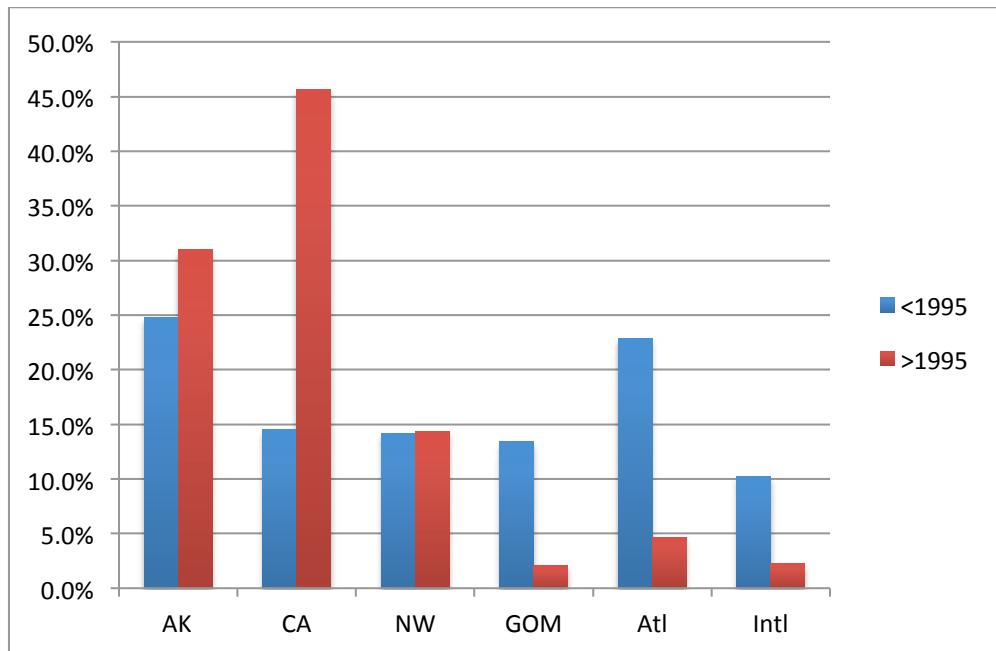


Figure 4-8 *Delta* Dives by Region: <1995=3722 dives, >1995=3518 dives
 (AK-Alaska, CA-California, NW-U.S. Northwest, GOM-Gulf of Mexico, Atl-U.S. Atlantic coast, Intl - International). Figures derived from *Delta* logbooks.

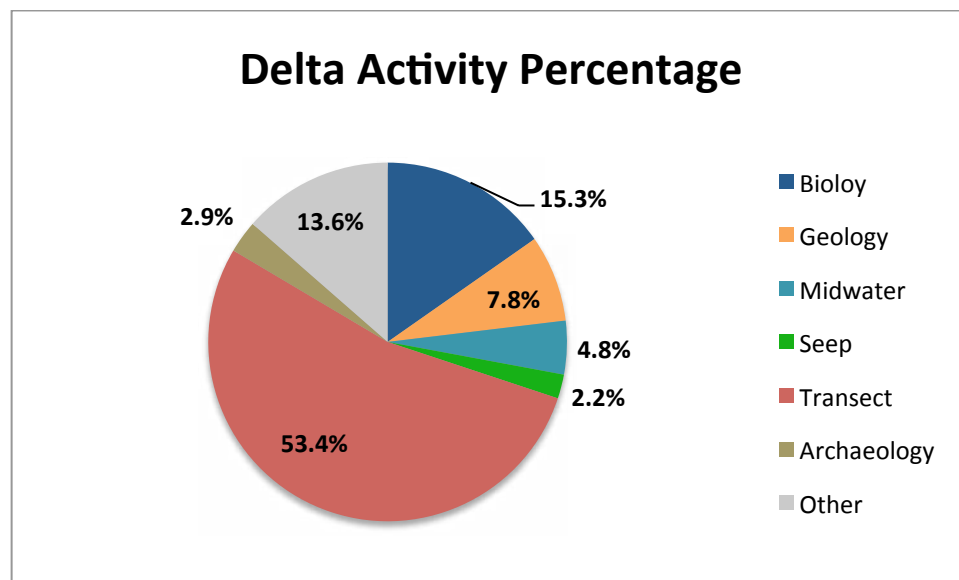


Figure 4-9 Percentages of *Delta* dive activity by discipline (6958 dives 1982-2009).

In a 2015 “*Visual Survey Tools*” report, HOVs were marked ‘high’ in capabilities that supported species-habitat association studies (Yoklavich et al., 2015, p. 31). One scientist also noted the value of *Delta*’s capability to characterize the broader ecosystem: “What we’ve lost with *Delta* and these smaller submersibles is the sort of shallow, continental shelf, upper slope exploration capability” (Scientist E). Non-science missions were more important in early years of *Delta* use, when the submersible conducted industrial surveys and salvage operations. Requirements for continuity of survey method also play a positive role in the use of *Delta*, both in the past and for current studies that must establish comparative factors for technologies that have replaced it (for example, comparing fish densities estimated from surveys conducted with an ROV and *Delta* (Laidig & Yoklavich, 2016)).

A scientist who has implemented ROV’s for groundfish surveys noted that the nature of the mission contributed to the success of the transition:

I asked myself, why aren’t people using this [ROV technology] more actively? Part of it is that we already had a methodology established, so we were just swapping out vehicles. We had a really clear goal going into it—a responsibility to provide a stock assessment to the federal government, it’s pretty cut and dry—I don’t know if others were tasked the same. (Scientist F)

More information on this transition is presented in Green, Stahl, & Kallenberger (2013).

4.4.4 QUADRANT D: SOCIETAL FACTORS

“As John Holland was to submarines in the late 1890s, so Doug Privitt is to submersibles in the 1990s” (Forman, 1999).

Two societal forces exercised primary impact on the success and decline of *Delta*: the support and then relinquishment of the submersible by the builder and owner, and the multi-disciplinary community of scientists that developed around its use. Although Mr. Privitt was responsible for the development and success of his submersibles, each *Delta* user interviewed asserted that the company discontinued operations as a result of matters regarding internal business disagreements and Mr. Privitt's personal situation (Scientists D, E, H, J, O, R, Engineers D, O). These matters resulted in the sale of the *Delta* in 2011; as of this writing it has not reemerged as an operational asset (Engineer D, O).

The importance of the community of scientists that formed around use of the *Delta* was described in literature (M. M. Yoklavich & O'Connell, 2008), and apparent in the variety of multi-authored publications based on *Delta*-collected data, passenger information in the logs, and in direct quotes and frequent cross-referral to each other that occurred during interviews:

All the time we were doing—a number of us have talked about this—a grass roots collegial thing that happened where groups of fisheries scientists off Alaska, Oregon, and California started to work together to explore and quantify habitat for demersal fish. (Scientist O).

As a geologist described:

In order to be able to participate in their [fisheries scientists'] projects, I needed to go down and run line transects myself and count fish...sort of pay my dues, then I would have time available to explore and pick up rocks and look at my geology

and various features and things that didn't need the rigor of counting fish.

(Scientist E)

Federally, NOAA funding from the West Coast NURP center, which supported a significant portion of *Delta* operations, was reduced in 2006 and ultimately eliminated with the discontinuation of NOAA's Undersea Research Program (NURP) in 2014 (Manager G). Funding was not received from NSF due to the crane certification issue described previously. Most *Delta* operations during its last 10+ years of operation were sponsored by State (Alaska, California, Washington, Oregon) and other agency organizations such as NOAA NMFS and the Packard Foundation (Scientist R, Engineer D; *Delta* logs).

Inspirationally, whereas *Delta* users reported that they were attracted by the adventurous aspect of diving in *Delta*, and appreciated the opportunity for non-scientists to visit the marine environment, they overall expressed more practical preferences for the submersible. Several scientists recalled the positive impact of a series of demonstration dives on the area fishermen, journalists and family members who participated (Scientists D, E, H, W, R), for example: "The fishermen especially came back and said it wasn't at all what they thought it was like [on the bottom]" (Scientist R). A scientist who had adapted fisheries surveys to ROV use acknowledged that:

I think that there's just always something more sexy about doing submersible research, and you do have that human observation aspect. I've been in a submersible, and there's nothing like seeing what's underwater at 1000 feet; the human wonder factor, that's pretty hard to beat. Would I rather go in a

submersible and see that than sit in an office, absolutely. But from a practical standpoint, the ROV has been a very good resource for us. Objectively, there are definitely advantages and disadvantages to both; I think you make the best decision with what you can do. (Scientist F)

4.4.5 DELTA ANALYSIS AND IMPACT MAP

The *Delta* demonstrates a case of societal (D) obsolescence, notably personal factors that led to the sale of the HOV, with secondary impacts from the increased use of technological (A) replacements and an extrinsic, physical (B) impact, i.e. the crane certification requirement. Portfolio-style assessments in the field of visual survey tools continue to mature and provide relative value information on *Delta*-like submersible capability (Yoklavich et al., 2015), Manager S, Scientist R). Each factor that arose was captured within the quadrant construct.

Although technological replacements (ROVs) are being used to conduct former *Delta* activities, (quadrant A) it was evident that this use came about as a response to the absence of the submersible; ROVs were not proactively selected as a preferred alternative by HOV users:

Under most circumstances, a manned submersible is far superior to an ROV, certainly an ROV that is in a reasonable price range...The one time I used an ROV, circumstances dictated that I absolutely had to, and it was adequate.

(Scientist H)

Scientists also expressed a sense of academic resilience with respect to infrastructure choice:

I’ve sort of gone backwards. [Losing *Delta* was] sort of like losing your right arm—you go to your left arm...you learn, but it isn’t as efficient as having both. So basically we’re handicapped. We’re not out of business, we wouldn’t be good scientists if we were out of business by losing a tool, but nevertheless, it’s more difficult...we’re losing things on this. (Scientist E)

An illustration of the degree and character of the impact of factors as described above is presented in Figure 4-10.

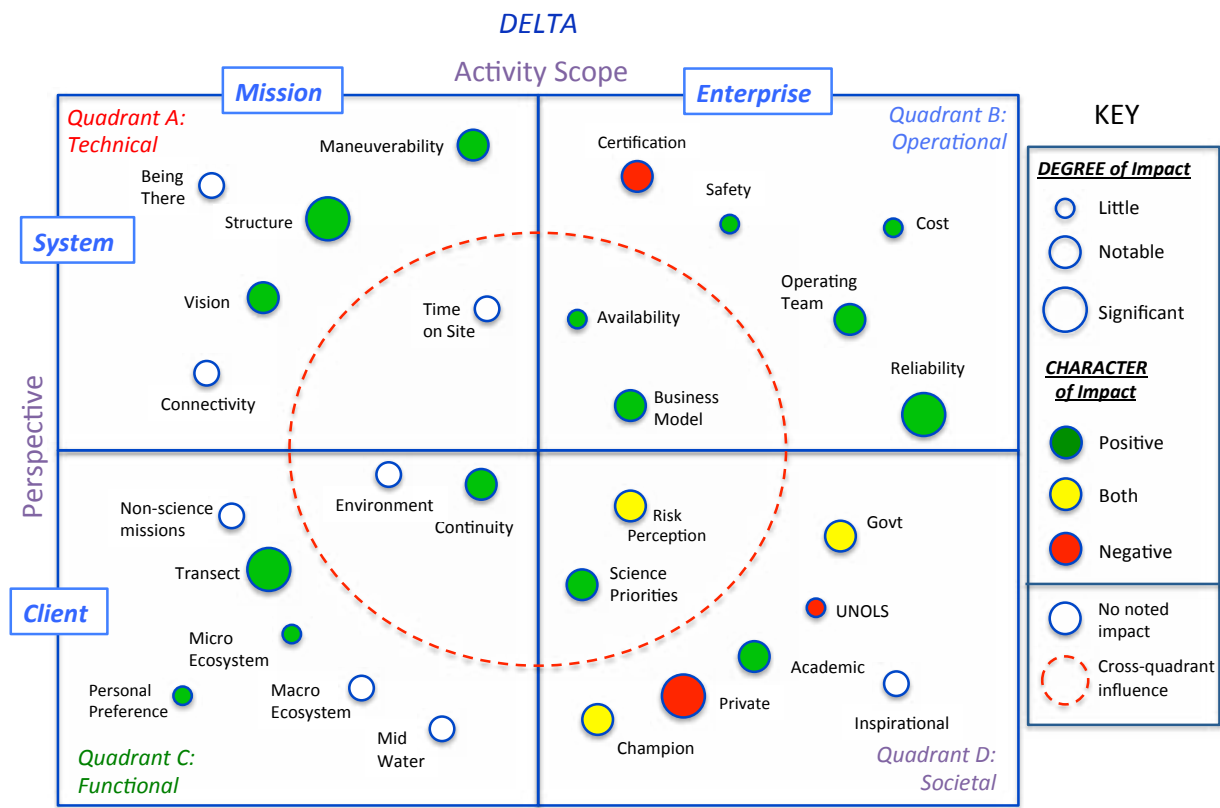


Figure 4-10 *Delta* Impact Map.

4.5 *AQUARIUS* UNDERSEA LABORATORY

As a further test of the model's ability to capture factors of sustainment, the *Aquarius* Undersea Laboratory was also examined. The *Aquarius* is a saturation diving habitat, which allows divers to remain underwater for extended periods of time (typically 7–14 days), sleeping and eating in a dry habitat secured to the ocean floor (Kohanowich & Potts, 2010; Shepard, Dinsmore, Miller, Cooper, & Wicklund, 1996) (Figure 4-11).

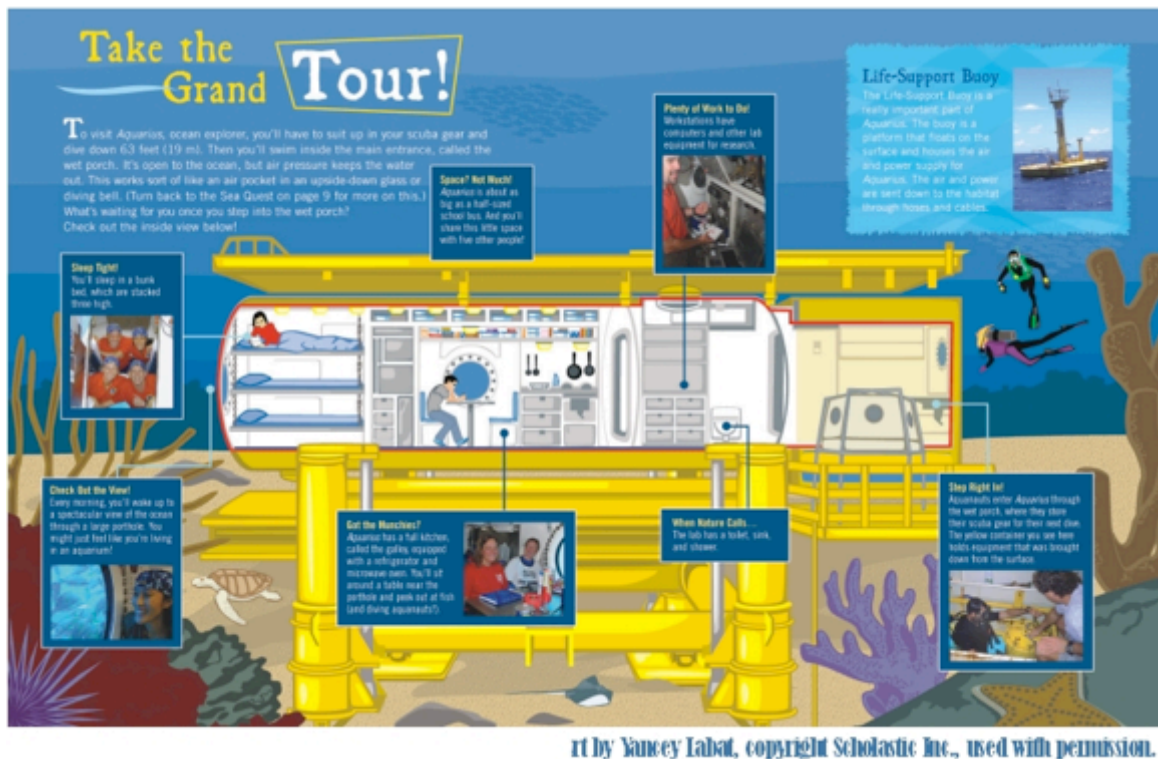


Figure 4-11 *Aquarius* undersea laboratory drawing (Yancey Labat, © Scholastic, Inc.).

Resembling a large Air Stream[®] trailer, *Aquarius* is located in 60 feet of water in a reef environment off Key Largo, Florida. For a full description and video of the facility see <https://Aquarius.fiu.edu/about/facilities/>). The *Aquarius* (originally intended to be christened the *George F. Bond* after the leader of the Navy's *Sealab* program), replaced NOAA's *Hydrolab* habitat, and was the post-1980 NURP program's first and only operating saturation habitat (S. L. Miller & Cooper, 2000). It was owned by NOAA and operated by the University of North Carolina, Wilmington (UNCW) until the expiration of its NOAA grant in 2012. Florida International University (FIU) began operating the facility for NOAA in 2013, and requested and received ownership from NOAA in 2014 (Potts, 2016). Whereas the factors developed for the undersea system model in Chapter 3 do not strictly apply to the *Aquarius*, they do provide a guideline for a first order evaluation.

This analysis of *Aquarius* was derived from numerous online newspaper and magazine articles, summary publications (Kohanowich & Potts, 2010; Miller & Cooper, 2000; Potts, 2016; Shepard et al., 1996), information available online at <https://Aquarius.fiu.edu/> and https://www.nasa.gov/mission_pages/NEEMO, program grant records, and personal experience.

4.5.1 QUADRANT A: TECHNICAL FACTORS

The primary advantage of the *Aquarius* laboratory is the ability to bring the senses and manipulative dexterity of a human diver to a 45–110 foot deep research site for an extended period of time. The *Aquarius* was designed to allow periodic changes of location with the support of a surface barge, but this ultimately proved too costly—the

barge was sold and the system has remained on site at Conch Reef since 1993 (with a single removal and replacement for maintenance) (Shepard et al., 1996). During strategic sessions held regarding the value of the *Aquarius* through the years, this lack of mobility was frequently cited as a drawback (UNCW SBTDC, 2007). The *Aquarius* staff did take advantage of its near-shore location to install advanced communications capabilities, which pioneered telepresence activity with schools, aquaria, and even the International Space Station (Malik, 2007).

4.5.2 QUADRANT B: OPERATIONAL FACTORS

The operating cost for an *Aquarius* saturation mission is comparable to a small research vessel; currently \$14,500/day, with a \$16,380 mission preparation and training fee (Florida International University, 2014). These costs pertain to the maintenance of a shore base, small boats, and the requirement to maintain a team of uniquely qualified personnel on site.

The *Aquarius* business model faced unique challenges during the facility's tenure under NURP. During the years the *Aquarius* was operated by UNCW, the sponsoring institution and the facility were located in different states. This resulted in difficulties with respect to Congressional support, as well as reducing opportunities for staff rotation opportunities. The status of the habitat as a NOAA-owned facility ensured consistent core funding and helped with the establishment of Navy and NASA partnerships, but presented complications with respect to seeking additional private sponsorship. The transfer of ownership of the facility to FIU has changed these factors, and is allowing FIU to explore a new business model.

The *Aquarius* had no blemishes on its safety record until 2009, when a staff member using advanced rebreather diving technology perished during a dive excursion from the habitat (Commercial Diver Network, 2009). The resulting investigation revealed conflicts between industrial and scientific diving practices, which delayed resumption of missions and resulted in an additional surface recompression chamber support requirement (*Aquarius* grant program documents).

4.5.3 QUADRANT C: FUNCTIONAL FACTORS

NURP funded both the *Aquarius* infrastructure and research conducted using the facility; it therefore addressed primarily NOAA-related research goals for fisheries, ecosystem management and coral conservation purposes. Its longevity on site provided an opportunity to record longitudinal data. In the face of reduced research support in the late 1990s, the *Aquarius* staff engaged other partners for research, and developed a Five-Fold Mission philosophy: ‘Scientific Research,’ ‘Training,’ ‘R&D of Undersea Technology,’ ‘Coral Reef & Ocean Observation,’ and ‘Ocean Education and Outreach’ (Florida International University, n.d.). Partnerships with the Navy have provided training, technology testing, and maintenance benefits for both parties (Kohanowich & Potts, 2010). NASA began conducting NASA Extreme Environment Mission Operations (NEEMO) missions in 2001, and completed their 21st mission in August, 2016 (Loff, 2016). Other mission activity since 2014 has included some privately sponsored research and FIU outreach and education, as well as research activities conducted in cooperation with NASA missions (Scientist Y).

4.5.4 QUADRANT D: SOCIETAL FACTORS

Public support for *Aquarius* has had both positive and negative impacts throughout its history. NURP provided funds to establish the facility, and the consistency of that funding sustained the infrastructure and supported valuable research for many years. Once overall NURP program funding was reduced, however, scientists who were used to the advantages of a NOAA-subsidized research source were less able to find alternate sponsorship for their work. Other federal (NASA and Navy) support has been positive, but potential projects submitted to NSF faced the non-NDSF infrastructure cost issues described previously. Private investment has contributed significantly to *Aquarius*' success at FIU (Gamarra, 2015).

The inspirational draw of *Aquarius* is in part due to its status as the last of a long history of saturation habitats (Barth, 1999; Hellwarth, 2012; J. W. Miller & Koblick, 1995; Wicklund, 2012). An ingredient of FIU's interest was this attraction that the facility provides for marine science students (Huffington Post, 2013; Mikulski, 2013; TEDx Talks, 2013). Champions for *Aquarius* have included a range of chief scientists, facility managers, and researchers.

With respect to science priorities, although the research that was addressed with *Aquarius* while it was a NOAA-sponsored facility included important marine science and conservation questions—ecosystem connectivity, coral and sponge biology and resilience, coral restoration—NOAA program managers continually struggled to make the case that the results were worth the investment in the facility (Manager G).

4.5.5 AQUARIUS ANALYSIS AND IMPACT MAP

An illustration of the degree and character of the impacts described above is presented in Figure 4-12. All of the factors that arose during the research could be addressed within the quadrant construct.

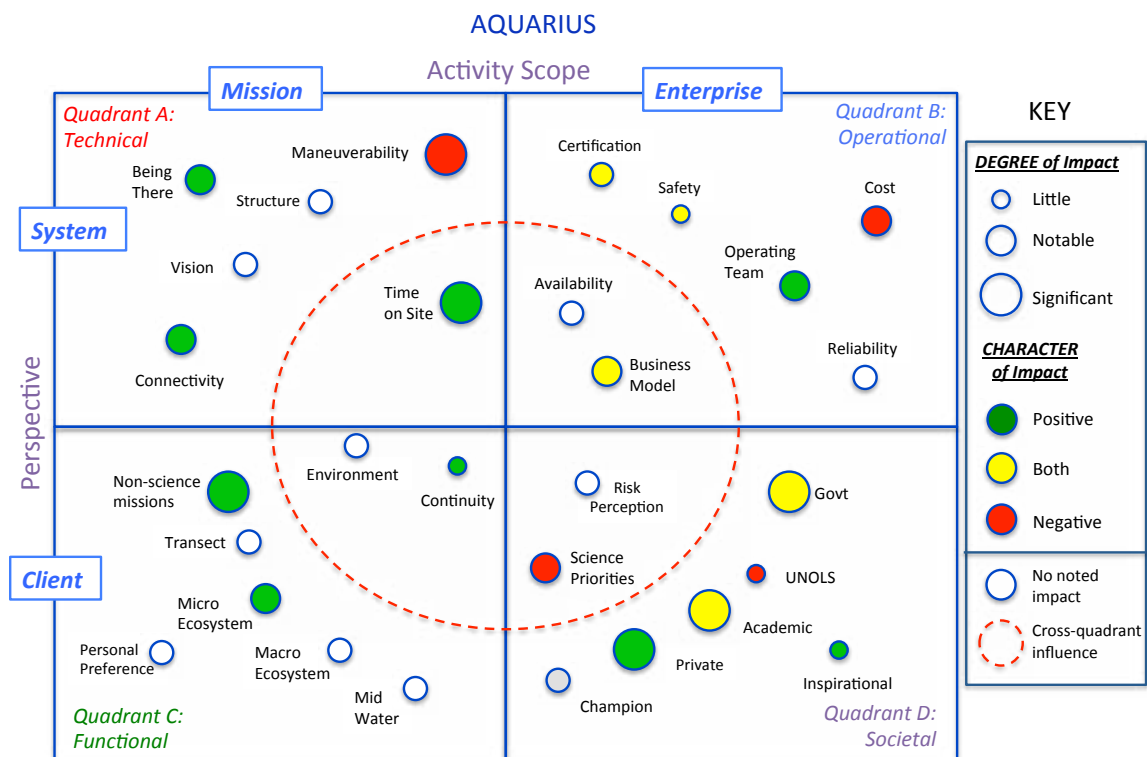


Figure 4-12 *Aquarius* Impact Map.

The primary impacts on *Aquarius* sustainment have been Functional (quadrant C) factors—its mobility limitations (quadrant A) negatively impacted its value to research.

Alternative uses (NASA and Navy) have allowed the facility to remain in operation so that some degree of marine research and education may continue. The *Aquarius* operation struggled with, but largely overcame, safety/certification challenges (quadrant B). Like the systems described above, Societal impacts have had a strong role in the sustainment of the *Aquarius* undersea laboratory; in large part its adoption by FIU is due to inspirational (quadrant D) motivations of FIU leadership and a private benefactor.

4.6 CASE STUDY OBSERVATIONS

The case studies validated the quadrant model in that the model was able to capture each of the impact factors of U.S. HOV sustainment that arose from literature and interview research. The assessments also provided insight on overall trends within quadrants, and on inter-quadrant relationships.

4.6.1 TECHNICAL

With respect to technical capabilities, the maneuverability of HOVs emerged as the most consistently positive factor (in an inverse sense, the lack of maneuverability was a notable negative in the case of *Aquarius*). The visual capabilities of technology have surpassed human vision at the level necessary for most marine research—humans still see greater distances in the visual spectrum, but zoom capability, high definition, stereo and infrared capabilities have become more valued for most work. The connectivity provided by an umbilical has introduced advantages for ROVs (that translate to negative HOV impacts) at two levels—first at the shipboard level, where more scientists can engage in a mission on site, and, when coupled with telepresence broadcast capability, at a game-

changing level of inclusion of scientists and private citizens. This latter capability has led to the development of a new discipline of interactive ocean exploration.

4.6.2 OPERATIONAL

Cost was an important aspect of all cases, with surface support vessel and manpower costs as consistent factors for each instance. Certification has become more exacting and more important, especially for publicly funded operations. Evaluation of the business model, an important ingredient of success, revealed a reliance on societal sponsorship that was perhaps the strongest inter-quadrant dependency noted during the study.

4.6.3 FUNCTIONAL

The functional research factors as developed provided a general indication of what type of research function for which the HOV was most, or uniquely, important (e.g., transects for *Delta*, mid-water research for *JSL*, micro ecosystem studies for *Alvin*), and indicated the degree to which non-science missions helped augment the operation. The role of research activity from a multiple-mission standpoint (consistent with the Ocean Studies Board (2011) recommendation to prioritize infrastructure based on “...(3) ability to contribute to other missions or applications” (p. 2)) was evident, but not fully developed at this stage of the model investigation.

4.6.4 SOCIETAL

The strength of societal factors was a notable result across all of the case studies. Characteristics of the sponsoring organizations were central to success in each instance. The influence of individuals—champions, program managers, and operators—also arose as a significant factor. An experienced program manager expressed the inherent nature of this influence succinctly: “There just has to be some built in biases, because people are people” (Manager C).

Consideration of inspirational impacts led to questions about the role of larger societal issues related to the emergence of virtual reality (represented by James Cameron’s film *Avatar*).

4.6.5 SUMMARY

Overall, the case study analyses validated the quadrant approach. Factors beyond the scientific usefulness of a type of infrastructure were shown to have exerted significant impact on the sustainment of each system, and the model captured all issues that emerged within the identified quadrants and factors. The interrelationships and dependencies between quadrants that were identified during the establishment of factors were also demonstrated during the case studies.

The model’s ability to visualize case study factors both individually and as compared with one another was useful for the purposes of this analysis, and also led to approaches that have potential to provide more insight into the dynamics and causality of sustainment. These include investigations into the sufficiency of the impact of factors in

each quadrant—for an operation to succeed, does every quadrant need to have a certain amount of positive impact; can factors within a single quadrant overwhelm those of others; and is there a tipping point of successful factors? This study does not attempt to answer these questions, but the fact that these questions can now be asked and investigated within a framework is a beneficial outcome of the model.

Although identification of how to avoid obsolescence was not a research goal of this study, the information lends insight into factors that are likely to be important for continued sustainability of research HOVs. Connectivity, launch costs, and safety certification arose as key, tangible issues. The evolving capabilities of autonomy and virtual reality will influence future technological comparisons as well as the societal attraction of human-occupied research vehicles. Political and personal dynamics must be considered on local and national levels. *Trieste* pilot and veteran of national submersible policy discussion, Dr. Don Walsh, recently confided that:

I strongly believe that the key to exploring the 80-90% of the World Ocean that remains unexplored is the unmanned submersible, primarily the [autonomous underwater vehicle] AUV. However there will always be some room for manned submersibles, mostly because human presence in the depths invokes fascination with the public. There is one of ‘us’ doing it, not a robotic machine. I asked Roger Revelle once ‘Why man?’ He said, ‘It is because you cannot surprise an instrument.’ (Walsh, personal correspondence, 2016)

CHAPTER FIVE : DISCUSSION

The undersea marine research infrastructure quadrant study investigated three questions:

- 1) Does an assessment model exist, or can one be developed, that incorporates the full range of causative factors into the evaluation of undersea marine research infrastructure?
- 2) How can such model be best illustrated and applied?
- 3) What does a test of this model tell us about U.S. human-occupied research submersible sustainment?

Whereas much can be learned from past national-level ocean research infrastructure studies, none take into account the full range of factors that influence the obsolescence or sustainment of this infrastructure, especially behavioral elements. The undersea marine research infrastructure (UMRI) quadrant assessment model presented here was designed to not only capture technical, operational, functional and societal factors that impact effectiveness, but to provide a framework for investigation into and relative quantification of these impacts. The case studies conducted here indicate that this model is indeed useful for this purpose, and shows promise for further development.

The sections below present a discussion of results and recommendations of the study, as well as of the applicability of the model from a user standpoint.

5.1 UMRI QUADRANT MODEL

5.1.1 *STRENGTHS*

The UMRI model provides an assessment tool that breaks out of the linear requirements-resources approach that has been used in past assessment efforts. This new approach provides whole-system insights and recognition of inter-system dependencies that would not have otherwise been identified. Societal factors, in particular, which have not been included in traditional ocean research assessments, emerge as particularly important in the ultimate success or failure of infrastructure sustainment. The model is particularly effective in serving as a framework to systematically develop and conduct further investigation within defined categories, and in stimulating investigation into multi-factor causality.

With respect to suitability for quadrant analysis, the pursuit of a valuation technique for undersea research infrastructure meets the guidance provided by Rao (2009) in “How to Draw and Judge Quadrant Diagrams”. The four quadrant labels—Technical, Operational, Functional, and Societal impacts—represent four distinct, “evocative labels” that describe specific, experiential, observable patterns (Rao, 2009).

The identification of scope of activity (mission and enterprise) and perspective (system and client) as axes provided definitions that enabled clear assignment of factors to each of the four quadrants. Whereas some factors were subject to influence by factors in different quadrants—e.g., the system-specific, enterprise-level ‘business model’ factor (quadrant B) relies heavily on client-driven support factors (quadrant D)—this

relationship could be displayed within the quadrant construct, and did not contest the home placement of the factor.

An important benefit of quadrant models is the ability to identify common characteristics of a situation and provide recommendations that are likely to be most effective in those circumstances. Leaman et al.'s (2010) recommendations for managing building obsolescence—"Fit and forget, Implement and manage, Implement and internalize, and Risk and freedom" (p. 572)—and Conlan et al.'s (2014) qualities of political Pathways—"Chief Sponsor," "Incubation Period," "Enactment Time," "Degree of Consensus," and "Partisanship" (p. 6, Table 1.2)—are examples of these products.

The UMRI quadrant enables visualization and identification of types of actions that are required to improve or maintain sustainment of a system (or to discontinue these efforts). Managers are able to identify a range of impacts, their strengths and interrelationships; and assess the appropriate amount of effort to be applied to each (examples might include reconsideration of expenditures for higher resolution cameras when research goals require stereo capability, or investment in certification when risk perception is particularly negative). The titles of the quadrants—Technical, Operational, Functional, and Societal Impact—suggest the direction of recommendations for these actions, a few examples of which are presented in Section 5.1.3.

The axes also lead to identification of the responsible actors or implementers for each category of factors: 'Engineers' for Technical factors; 'Managers' (operations directors, program supervisors, pilots and operators) for Operational factors; 'Scientists' for Functional factors, and 'Leaders'—whether policy, program, or private—for Societal

factors (Figure 5-1). These actor identifications are not intended to be exclusive, but to represent a general category of responsibility.

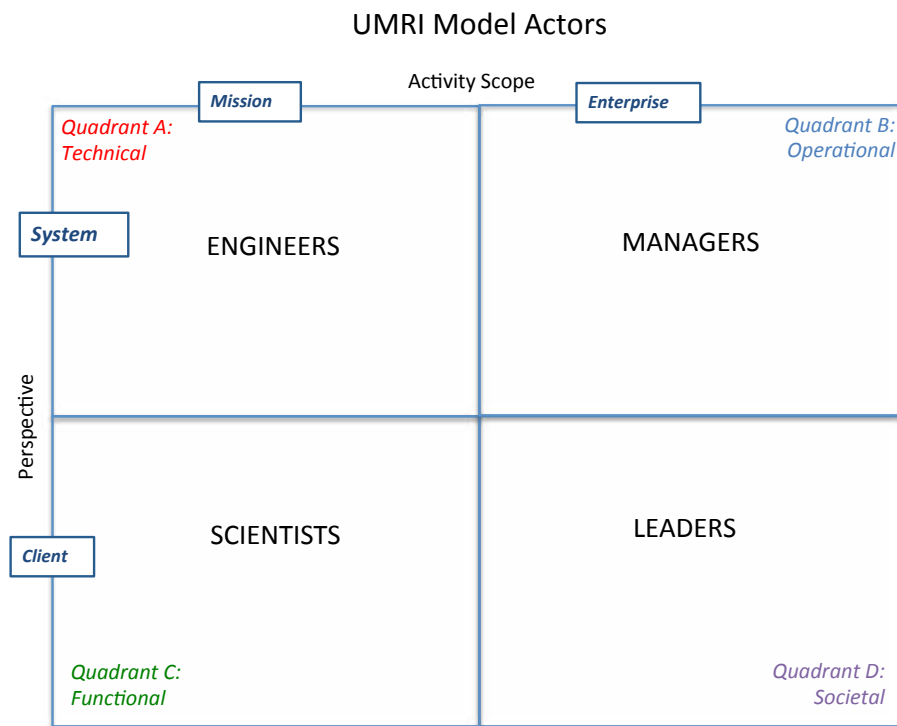


Figure 5-1 Suggested actors for recommendations within each quadrant.

Implementation of the model required development and assessment of an illustrative mechanism that would enable identification of factors, quantification of impact, and comparison of results. The pertinent measures of impact emerged as strength (minimal or significant) and character (positive or negative) of influence, with a third aspect of cross-quadrant effects. The use of circles within the quadrant diagram was

selected because this technique offered three degrees of display: strength (circle size), character (color), and interrelationship to other factors (quadrant placement).

A five-point Likert scale for both strength and character was initially tested, but resulted in an overly complex map that served more to obfuscate trends than to clarify them; the three-option alternative proved effective in representing the information in a clearer, more manageable way. The use of a ‘both positive and negative’ assignment in the degree scale was valuable in indicating areas that called for additional—and often conditional—attention.

The use of a central boundary to denote inter-relationships by quadrant position was an effective means to highlight those relationships that were most meaningful. The table used at the end of each case study to assign and explain these quadrant relationships was useful as a tool to develop this aspect of factor qualities. Whereas each factor could, conceptually, be assessed with respect to these inter-relationships, it was judged that the effort required and resulting complexity would conflict with the goal of clarifying an already-multifaceted process.

The ability to visually compare the various factors was beneficial in single and multi-dimensional ways. As intended, it provided a snapshot of a studied system that suggested which factors were most influential in the sustainment of that system, and indicated which areas were worthy of further examination. An additional advantage that emerged was the ability to compare the impacts of specific factors between systems. The practice of comparing these results added to the robustness of the analysis and presented

new perspectives of relative value (i.e., how did the importance of science priority vary between case studies.)

The UMRI model also enables a holistic approach to infrastructure assessment in consideration of the overall sufficiency of factors, as identified in Section 4.6.5—how much positive impact is required in each of the quadrants to maintain operations? How many quadrants may exhibit negative characteristics before obsolescence becomes a concern?

5.1.2 LIMITATIONS

Whereas the quadrant model meets the goals of the study, a few considerations regarding its implementation require consideration. The selection of the impact factors was not a straightforward process. New factors emerged throughout the analysis, as well as different alternatives for level of specificity in categorizing these factors. This was beneficial in that it required a thoroughness and willingness to examine factors from different perspectives, but it also demonstrated a degree of subjectivity inherent in the model implementation. The analysis of the impact of those factors during the case studies was also a relatively subjective, iterative process that required a significant degree of cross-quadrant and cross-case study comparative analysis and reflection.

A particularly complex aspect of the model design was the development of the Functional (quadrant C) factors. Relationships between the value of a technological capability (quadrant A) and research activity (quadrant C); and research activity (quadrant C) and science priority (quadrant D) reflect inherent challenges of the linear requirements-to-resources national assessment approach. The activities identified for

quadrant C of this study are proxies for a more complex trail of how well a system collects data, and how vital those data are to answering research questions. They allow initial testing of the model, but they are not sufficiently rigorous for fully understanding research-infrastructure cause and effect interactions. The model design does, however, provide an opportunity to parse the discussion into specific ingredients of these relationships.

The model illustration is limited in its ability to represent longitudinal changes in factor impacts (for example, shifts in supporter commitment over time). The use of a ‘both positive and negative’ alternative for character allowed for identification of such a situation, but does not reflect whether the impact alternated for a single factor with time, and how that might have changed, or whether it represented a combination of conflicting sub-factor values within the category. At this stage, these characteristics must be addressed in explanatory comments.

Causality remains an elusive characteristic. The model does not directly address determination of causality, but the level of investigation that is required to populate the quadrant during case studies sets the groundwork for further insights into cause and effect.

The selection of U.S. human-occupied research submersibles was satisfactory for this initial study in that it provided a consistent system variable, allowed for exploration of differences in the factors on an organizational level, and provided a unique social factor—the value of human presence as an inspirational factor—to include in the assessment. This aspect may weight the results toward a stronger social impact than what

might be found when investigating unmanned systems, however, so therefore may also be considered as a limitation of the study.

As with any quantitative management display, there is a risk of over-reliance on an illustrated representation of data. Even with a more rigorous analysis, care should be taken to define the limitations and intentions for use of the results.

5.1.3 MODEL RECOMMENDATIONS

The quadrant model developed here shows potential for application to U.S. marine research infrastructure valuation activities. The following activities are recommended to reinforce the theory and hone the application of the model.

- (A) Directly test the model with the submersible science community. Queries should be made both for specific case studies, and as to evaluation of the effectiveness of the model. Survey and panel techniques should be considered to augment interview methodology.
- (B) Expand the case studies to include comparable ROV and other UMRI systems. Inclusion of a comparable ROV research operation would enable an evaluation of social factors while maintaining similar functional drivers. The NDSF's *Alvin* and *Jason* provide an example with built-in controls as far as organizational support. Ultimately, examination of other systems that are used for different suites of research questions—for example, AUVs, gliders, and ocean observing systems—would provide increased depth of insight into a variety of factors.

- (C) Conduct targeted analyses to explore methods of investigating and determining cause and effect of factors on sustainment.

5.2 UNDERSEA MARINE RESEARCH INFRASTRUCTURE

The quadrant model developed here is intended to apply to undersea marine research infrastructure; the case studies focused on the characteristics of U.S. human-occupied submersible operations, but revealed insights and suggested follow-up pursuits that apply to the broader field of UMRI. The examination of HOVs, and comparisons to ROVs, made during the case studies led to a number of recommended studies that will contribute to insight regarding factors that influence the sustainment of U.S. undersea marine research infrastructure. These recommendations will involve a combination of qualitative and quantitative methodology, and are presented here.

5.2.1 QUADRANT A

Recommendations for further study to define aspects of technical value include:

- (D) Direct comparison field studies of technical capabilities. One potential venue for assessing technical performance that appeared infrequently (except for fisheries visual survey tool efforts) was direct comparison field studies between different technologies. Whereas expense of these studies is likely a deterring factor, focused or opportunistic efforts to directly compare maneuverability, sampling and panorama video capabilities in other research fields would be useful. Comparative data may also be deduced from operations that are similar: the “Expedition to the Deep Slope” series of

NOAA Ocean Exploration missions (NOAA Ocean Exploration, 2006, 2007) used *Alvin* and *Jason* to perform similar research in 2006 and 2007, respectively.

- (E) The fields of Human Robot Interaction (HRI), Cognitive Task Analysis (CTA) (Usability Body of Knowledge, n.d.), and virtual reality also present an opportunity for more comparative experimentation about research data collection value.

5.2.2 QUADRANT B

Several additional avenues can add to insight regarding operational factors, and are timely with respect to the emergence of public/private partnerships for oceanographic research:

- (F) Assess potential of private HOV sponsorship and operation to contribute to national oceanographic enterprise. The emerging capability of private shallow HOVs was introduced during this study and the increasing use of these vehicles for research purposes (Nekton Mission, 2016; Undersea Hunter, n.d.-a) offers a timely, potentially valuable avenue of investigation.
- (G) Assess potential of private ROV operations to contribute to the national oceanographic enterprise. This capability has been implemented by the Schmidt Ocean Institute since 2013 (Schmidt Ocean Institute, n.d.)
- (H) Evaluation of cost per unit observation for a particular system and/or discipline. Determination of cost per unit observation is a philosophically

attractive but daunting task; further investigation into costs is a task that would be best suited at an implementation rather than an academic level.

5.2.3 *QUADRANT C*

Functional factors contain perhaps the most inherent complexity of any aspect of the quadrant model. The following recommended studies are intended to help parse the assessment of value of a type of infrastructure to a research goal.

- (I) The conduct of *discipline-specific* analyses of the relationships between research questions, data required to answer those questions, activities that collect that data, and research infrastructure that performs those activities can provide insight into the complexity of research infrastructure value. Research disciplines with the most potential for such further study include those that have well developed research plans, engage a variety of undersea data collection technologies, and are supported by a cohesive research community. Based on an initial review of the research topics that emerged during this investigation, the following fields of study emerged as most promising for this effort: deep sea corals, hydrothermal vents, ground fisheries assessment, ocean exploration, and biodiversity observation.
- (J) Such studies should also consider incorporating work done by the existing NOAA Observing System Integrated Analysis effort (Office of Technology, Planning and Integration for Observation, n.d.), where appropriate.
- (K) Explore techniques to capture multi-mission value of systems to research goals.

5.2.4 *QUADRANT D*

Many of the results from investigation into societal impact of human-occupied research submersible use suggests further study on a broader ocean enterprise scale, but a few avenues offer valuable insight to system-specific operations:

- (L) Investigate value of in-person versus virtual experience for tomorrow's oceanographers. Studies on the impact of inspirational attractions of infrastructure, whether manned or virtual, for recruitment of scientists, could be conducted in partnership with other educational research efforts.
- (M) Risk perception and its impact on sustainment were difficult to ascertain during this preliminary test of the model. Future studies could provide more depth and insight into this aspect.

5.3 NATIONAL SUBMERSIBLE SCIENCE AND OCEANOGRAPHIC ENTERPRISE

The factors identified and discussed in this study describe a national research system in which none of the effecting (i.e., funded, implementing) agencies are singularly responsible for the success of the full range of undersea marine research infrastructure on a national level. The prevalence of societal impact seen in this study may suggest that the distributed nature of the U.S. federal oceanographic research infrastructure system—despite active interagency cooperation mechanisms—allows for a higher level of organizational protectionism and personal influence on the national enterprise than would

be present in a more centralized regime. An observation made by a submersible scientist during interviews for this study provides an illustration of this concern:

If someone looked into [the question]: ‘are we spending our deep-sea research money the best way possible?’ people would ask ‘why are we not doing this much more cost effectively with the assets that are stationed out in the Pacific?’ And there wouldn’t be a good answer for that, there really wouldn’t be. (Scientist T)

Consideration of centralized versus distributed systems for research oversight is not new: the establishment of NSF after World War II included 5 years of deliberation on, among other issues, geographic distribution of research funds (Greenberg, 2001; Task Force on Science Policy, 1986); a special issue of *Technology in Society* (1986) was dedicated to a debate on the establishment of a “Department of Science and Technology” (Bugliarello & Schillinger, 1986); and national-level ocean panels have made numerous recommendations to address this dispersion of authority in the oceanographic sciences (Commission on Marine Science, Engineering, and Resources, 1969; Merrell, Katsouros, & Bienski, 2001; Safina & Chasis, 2004; Watkins, 2004). This impact has also been observed with respect to other types of infrastructure.

This study suggests that the decentralized result is still impacting the state of undersea research infrastructure sustainment in the United States, as observed by one scientist/manager: “I see ROVs and AUVs going down the same [distributed] path—the interest is not in protecting the overall system technology, but in protecting the [specific named ROVs and AUVs]” (Scientist K).

Along similar lines, the differences between agency practices and characteristics, especially between NSF and NOAA, had significant impact on the various operations. The influence of champions also arose as an important factor in infrastructure success and failure. Like Malcolm Gladwell's (2008) assessment of factors behind the accomplishments of extremely successful people, or "outliers," the components and circumstances of this influence are both likely a complex mixture that includes legacy, opportunity, and skill. This influence emerged during this case study on HOVs, but would be strongest when applied at the U.S. ocean technology enterprise level.

Another theme that emerged during this study was a difference in perspective between managers and scientists. This was discussed to some extent on the issue of safety considerations, but it was also evident with respect to a desire for a variety of types of undersea systems, and satisfaction with relatively mature, simple systems as expressed in the field, in contrast to a managerial need to balance limited funds in support of expensive systems.

Information assessed during this quadrant analysis led to recommendations for further study of the dynamics of support for both submersible science infrastructure, and for the overall ocean research enterprise.

5.3.1 RECOMMENDED STUDIES: SUBMERSIBLE SCIENCE

(N)Comparatively examine the factors that impact U.S. undersea marine research infrastructure (UMRI) support for NSF and NOAA. Further understanding of the dissimilarities between the two primary U.S. federal agency sponsors of undersea marine research infrastructure - through review of personnel

procedures, congressional influence, organizational structure, and other elements - would provide insight into the nature of success of the respective efforts.

(O) Study and compare international UMRI enterprises to US organization (on national, UMRI, submersible-scales). A study of international submersible operations, including the German *Jago*; French *Nautilus*; Russian MIR; Japanese *Shinkai 6500*; and Chinese *Jiaolong* would provide a different perspective on factors that influence successful government sponsored research infrastructure, and would contribute to studies on the value of centralized or distributed government oversight of programs.

(P) Separately assess specific characteristics of success for shallow and deep-sea research and exploration. This investigation noted past submersible science community recommendations concerning shallow undersea research infrastructure (DeSSC, 1999; Ocean Studies Board, 2004; UNOLS, 1990). The termination of NOAA's Undersea Research Program (NURP) in 2014 has changed the character of sponsorship of these systems. Further investigation into this gap offers an opportunity for more effective national undersea infrastructure management.

5.3.2 RECOMMENDED STUDIES: OCEAN ENTERPRISE

(Q) Influence of champions on ocean research enterprise. The role of champions in oceanographic research is notable (Jacques Cousteau, James Cameron, Carl Wunsch, Bob Ballard, Sylvia Earle, John Delaney) but not well understood.

Further investigation should not only seek to define individual roles in development of technologies, but in the ability to sustain efficient, effective operations.

- (R) Compare effectiveness of strong interagency coordinating bodies on research productivity. The matter of the decentralization of U.S. oceanographic research authority is a complex issue that requires additional research in governmental affairs and science, technology, and society policy fields. The waxing and waning of strong interagency coordinating bodies (i.e. 1970's National Advisory Committee on Oceans and Atmosphere (NACOA); 1980's agency-level activity; and 2000's National Ocean Council (NOC)) presents an opportunity to compare degree of centralized oversight with a measure of productiveness of ocean research.
- (S) Analyze adoption of recommendations from past oceanographic infrastructure reports. Within the oceanographic community, an analysis of the effectiveness of past ocean research priority reports that considers the factors that impacted the success or failure of recommendations that came from these efforts can help further advise future portfolio efforts.
- (T) Investigate the role of innovative technologies in inspiring new research, as compared to the role of research requirements in influencing the development and sustainment of tools to meet those needs. An investigation of this type would provide a perspective for decision-making when support for new technologies competes with that for existing 'workhorse' technologies. The

impact of fluorometers on phytoplankton studies is a well-documented example (Leeuw, Boss, & Wright, 2013) of technology-inspired research. Telepresence and real-time communication technologies have enabled a new interactive ocean exploration-form of marine research that is continuing to evolve, and that presents a particularly timely focus area.

Figure 5-2 captures all study recommendations.

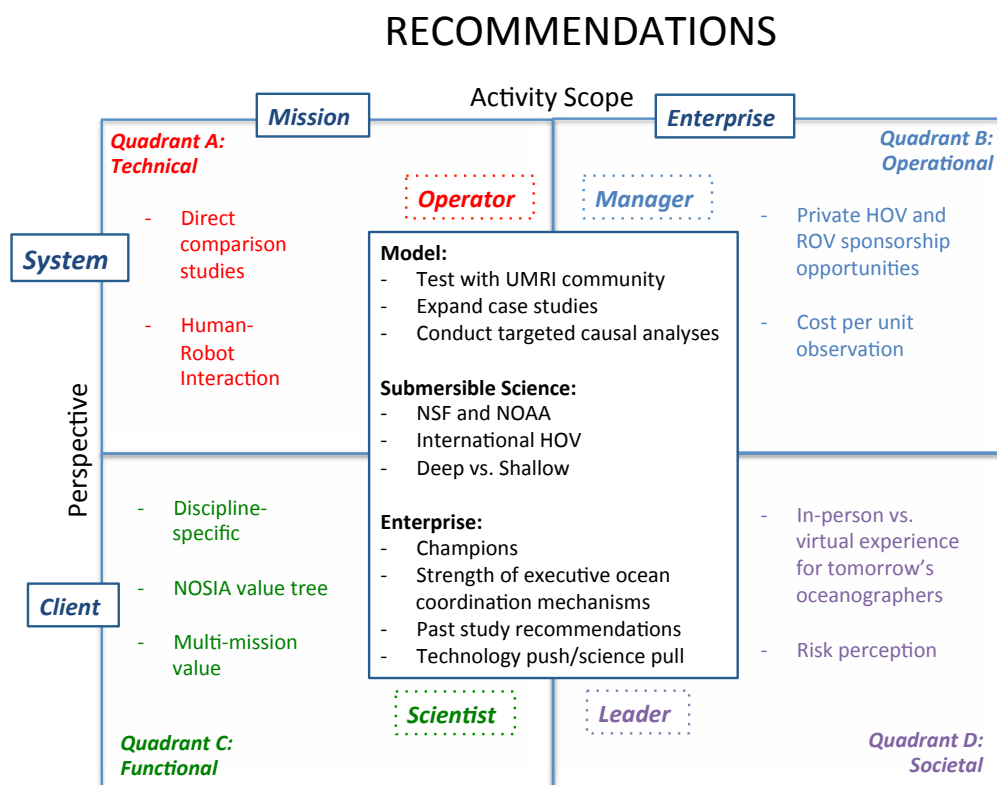


Figure 5-2 Recommendations for further study by quadrant.

5.4 FINAL THOUGHTS

Assessment of undersea infrastructure requirements on a national level is a valuable but complex undertaking. This study provides a model that parses this inherent complexity into four distinct categories of influence. This framework contributes to furthering research infrastructure assessment activity in three respects:

- (1) Simplification. Categorization enables the identification and pursuit of focused, bounded studies as distinct ingredients of a larger process;
- (2) Comparison. Visual mapping of factors stimulates and enables causal comparison between the varieties of impacts.
- (3) Societal consideration. The model includes an assessment of behavioral and social influences, which has not previously been considered in marine infrastructure studies.

The inclusion of societal impacts is a particularly important, if challenging, finding. Unlike hypothesis-driven scientific investigations, in which the ‘observer effect’ is to be carefully noted and avoided, the observer—or decision-maker—for infrastructure assessment is an integral part of the social science system. In some respects, the oceanography community has recognized the importance of people—and the serendipitous opportunities that are caused by people—to the success of scientific and technological pursuits (Briscoe, 2003), but it has not yet incorporated these factors into its evaluation techniques.

The model presented here was initiated to aid managers in including these considerations during national-level research infrastructure assessments. Its present form

may prove complex for institutional use at this time, but provides a template for deliberation of the full range of influential factors. Other audiences for this tool may be technology champions, who could use this ‘360’ approach to plan for success of new initiatives; operations leaders concerned with sustainment of their existing efforts, and program managers, who can become better equipped to defend or yield support for the infrastructure for which they are responsible.

APPENDIX 1: U.S. SUBMERSIBLE SCIENCE AND INFRASTRUCTURE STUDIES

Date	Title	Sponsoring Organization
1956	Proceedings on the Symposium on Aspects of Deep-Sea Research	National Academy of Sciences
@	https://searchworks.stanford.edu/view/1168934	
1959	Oceanography: 1960 to 1970. Chapter 7: Engineering Needs for Ocean Exploration	National Academy of Sciences Committee on Oceanography
@	http://babel.hathitrust.org/cgi/pt?id=mdp.39015021230027;view=1up;seq=3	
1965	Undersea Vehicles for Oceanography	Interagency Committee on Oceanography ICO Pamphlet no. 18
@	http://scilib.ucsd.edu/sio/hist_oceanogr/undersea-vehicles5.pdf	
1972	UNOLS First Annual Report: Appendix IV – Report of Working Group for University Submersibles	UNOLS
@	https://www.unols.org/sites/default/files/1972_ar.pdf	
1974	Future Facilities Requirements of the University National Oceanographic Laboratory System	UNOLS
@	https://www.unols.org/sites/default/files/197410ffr_searchablesearchable.pdf	
1980	Oceanlab Concept Review	National Academy of Sciences
1980	The Undersea Research Program of the National Oceanic and Atmospheric Administration	NOAA Memorandum
1981	Technology and Oceanography: An Assessment of Federal Technologies for Oceanographic Research and Monitoring	Office of Technology Assessment
@	Google document	
1982	UNOLS Submersible Science Study	University National Oceanographic Laboratory System

@	https://www.unols.org/sites/default/files/Submersible_Science_Study_1982searchable_lo_res.pdf	
1986	The Marine Research Community and Low-Cost ROVs and Submersibles: Needs and Prospects: Summary of a Workshop	Center for Ocean Management Studies, the University of Rhode Island in cooperation with Marine Technology Society
1990	Submersible Science Study for the 1990's	A Submersible Science Committee of the University-National Oceanographic Laboratories System
@	https://www.unols.org/sites/default/files/199011des_searchable_lo_res.pdf	
1994	The Global Abyss: An Assessment of Deep Submergence Science in the United States	UNOLS Deep Submergence Science Committee
1996	Undersea Vehicles and National Needs	National Research Council
@	http://www.nap.edu/catalog/5069.html	
1999	Discovering the Oceans: Developing Submergence SCience for Next Decade - "DESCEND" Workshop Proceedings	UNOLS Deep Submergence Science Committee
@	http://www.unols.org/meetings/1999/199910dcd/descend_proceedings.pdf	
2004	Future Needs in Deep Submergence Science: Occupied and Unoccupied Vehicles in Basic Ocean Research	National Research Council
@	http://www.nap.edu/catalog/10854.html	
2011	Critical Infrastructure for Ocean Research and Societal Needs in 2030	National Research Council
@	http://www.nap.edu/catalog.php?record_id=13081	
2015	Sea Change: 2015-2025 Decadal Survey of Ocean Sciences	National Research Council
@	http://www.nap.edu/catalog.php?record_id=21655	
2016	DESCEND 2 Workshop January 14-15, 2016	DESSC
@	http://projects.iq.harvard.edu/descend2	

@ = online availability

APPENDIX 2: INVESTIGATIVE RESOURCES

A2.1 BACKGROUND DOCUMENTS

A2.1.1 SUBMERSIBLE RECORDS OF EXCURSIONS

Data concerning the daily details of undersea technology use are recorded in operational logs. Specific log content varies by operation, but typically the data includes date, location, time, depth, personnel and purpose of the dive, or excursion. Availability and completeness of these logs also vary by research operation. The WHOI logs for the undersea vehicles of the National Deep Submergence Facility are a readily available example of this resource (Woods Hole Oceanographic Institution, 2016e). Other submersible-specific compilations (Hawai'i Undersea Research Laboratory, 2012; Kaharl, 1990; J. K. Reed et al., 2005; M. Yoklavich & O'Connell, 2008) provide a resource to examine submersible excursion activity.

A2.1.2 SCIENTIFIC ARTICLES BASED ON DATA COLLECTED BY SUBMERSIBLES

In 1970, a study of the 346 research papers that resulted from submersible research to that date provided a comprehensive picture of the value of submersibles to various fields of marine research (Ballard & Emery, 1970). Today, although data is much more available electronically, the volume of such papers makes such a task formidable. Review of a number of subsets of this data can be considered depending on the research

approach, including: papers citing use of a specific submersible, addressing a specific scientific discipline, or sponsored by a particular funding source. In addition to providing descriptive information of submersible use, these research papers can also indicate scientific value through citation analysis. Such a study must consider the differences between citation services (Harzing & van der Wal, 2008; Kendall, 2016) as well as issues introduced by new open access journals (AAström, 2008).

A2.1.3 PUBLISHED ANECDOTAL DATA

Submersible engineers, pilots, scientists, and managers have commented on the value of HOVs in books, magazine articles and conference papers for more than 50 years (List of journals, conferences).

A2.1.4 OPERATIONAL COMPARISONS

Published comparisons between undersea research tools have been conducted primarily in the field of visual survey tools for fisheries (M. M. Yoklavich et al., 2015).

A2.1.5 ORGANIZATIONAL STUDIES AND REPORTS

Included in Appendix 1.

A2.2 INTERVIEW TEMPLATES

Each interview was tailored to address the interviewee's experience and background using the below template questions. The questions varied for interviews with submersible scientists, policymakers, and engineers and pilots.

A2.2.1 SUBMERSIBLE SCIENTIST QUESTIONS

What research work have you conducted using manned submersibles for data collection? Which submersibles?

What capabilities of the submersible were most valuable for your work?

Were there considerations other than these that influenced your selection of the submersible, i.e. cost, convenience, etc.?

What has the impact of losing (sub) been on your work? Have there been unexpected/unanticipated impacts?

Are you now using a different technology to do the same work that you used to do with a manned submersible? If so, what is different about the way you collect your data now? Have you seen any impact/what impacts have you seen on your research using the unmanned technologies?

What are the advantages and disadvantages of the alternative technology(ies) compared to the manned submersible(s)?

What are your thoughts on the value of manned submersibles? Do they still have a role in marine science data collection? For which tasks are they best suited?

Has the loss of the opportunity to dive in a submersible affected your recruitment of student researchers?

Can you comment on the importance of these capabilities for the undersea data collection work that you do?

Vision: peripheral vision, 3D, panorama view, high definition

Engineering: Ability to operate in strong currents, maneuver on the bottom or in the water column, length of bottom time, ability to collect samples, distance covered on the bottom

Cognition: Spatial awareness, ability to respond to changing situations on site

A2.2.2 POLICYMAKER QUESTIONS

How was submersible science funded at your agency?

Can you tell me about the factors that influenced that funding?

Can you talk about the recommendations of (Submersible Science Reports that the interviewee was familiar with.)

The 2004 NAS “Future Needs” report recommended that NSF/OCE “should establish a small pool of additional funds (on the order of 10 percent of the annual budget for NDSF) that could be targeted specifically to support the use of non-NDSF vehicles.”

Can you talk about the implementation of this recommendation, and the factors that influenced this recommendation?

How did safety considerations impact funding decisions?

What influenced whether infrastructure was included in the UNOLS system?

Can you tell me about the DESSC shallow submersible committee?

A2.2.3 ENGINEER/PILOT QUESTIONS

The value of manned and unmanned vehicles for research has been discussed at length. Can you tell me your impressions of which factors are most relevant today in light of new technologies?

What safety features and procedures are used in your operation?

What new technologies do you see emerging that have the most promise for undersea research?

APPENDIX 3: NASA HUMAN SPACEFLIGHT RATIONALES

In one of the first U.S. policy statements regarding manned spaceflight, the Space Science Board of the National Academy of Science stated:

From a scientific standpoint, there seems little room for dissent that man's participation in the exploration of the Moon and planets will be essential...Man can contribute critical elements of scientific judgment and discrimination...which can never be fully supplied by his instruments, however complex and sophisticated they may become. (Berkner, 1961, p.2)

Since then, many studies have been conducted on the value of and plans for manned spaceflight (Space Studies Board, 2014; Space Studies Board, n.d.; U.S. Human Spaceflight Plans Committee, 2009) as well as human-robot interactions and replacement considerations from operational and technological aspects (Cooper & O'Donnell, 2000; Google Scholar, 2016; Rodriguez & Weisbin, 2003).

The most recent comprehensive study on the rationales for human spaceflight, *"Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human space Exploration"* by a National Academy of Sciences Committee on Human Spaceflight, identifies and discusses seven rationales for manned space activities that

present an informative overview of the scope of investigation into manned and unmanned research overall. These rationales, and the conclusions reached by the Committee, are:

1. Economic and Technological Impacts: while “it is clear that the NASA human spaceflight program...has stimulated economic activity...it is impossible to develop a reliable comparison of the returns on spaceflight versus other government R&D investment.”

2. National Security and Defense: “...the direct contribution of human spaceflight in this realm has been and is likely to remain limited.”

3. National Stature and International Relations: “Being a leader in human space exploration enhances international stature and national pride” and “...can benefit from international cooperative efforts. Such cooperation has important geopolitical benefits.”

4. Education and Inspiration: “Many who work in space fields report the importance of (space missions as) inspiration, although it is difficult to separate the contributions of human and robotic spaceflight.”

5. Scientific Exploration and Observation: “The relative benefits of robotic versus human efforts in space science are constantly shifting as a result of changes in technology, cost, and risk. The current capabilities of robotic planetary explorers...are such that although they can go farther, go sooner, and be much less expensive than human missions to the same locations, they cannot match the flexibility of humans to function in complex environments, to improvise, and to respond quickly to new discoveries. Such constraints may change some day.”

6. Survival: “It is not possible to say whether human off-Earth settlements could eventually be developed that would outlive human presence on Earth and lengthen the survival of our species. That question can be answered only by pushing the human frontier in space.”

7. Shared Human Destiny and Aspiration: “The urge to explore and to reach challenging goals is a common human characteristic...Some say that it is human destiny to continue to explore space. While not all share this view, for those who do it is an important reason to engage in human spaceflight.”

The study concludes that: “No single rationale seems to justify the value of pursuing human spaceflight.” But “The fact that no one of these rationales alone provides the key to why the nation should support human spaceflight does not mean that collectively they are not strong.” P. 70

Further details from the *Pathways* assessment and other space-related documents are included in appropriate sections of this work.

REFERENCES

- AAström, F. (2008). Citation patterns in open access journals. *Unpublished Project Report: The OpenAccess.se Program, The National Library of Sweden*. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.218.1602&rep=rep1&type=pdf>
- Aburto-Oropeza, O., Caso, M., Eisman, B., & Ezcurra, E. (2011). *Log of the deep sea*. Instituto Nacional de Ecologia. Retrieved from https://issuu.com/eezcurra/docs/bitacora_baja_resolucion
- Alucia. (2016). Alucia the ship. Retrieved July 25, 2016, from <http://aluciatheship.com/>
- American Society of Mechanical Engineers. (2007). Safety standard for pressure vessels for human occupancy, ASME PVHO-1-2007. American Society of Mechanical Engineers. Retrieved from <https://www.asme.org/products/codes-standards/pvho1-2012-safety-standard-pressure-vessels-human>
- Amin, A. A. (2015, August 31). Seven steps in predicting equipment lifecycle: Using obsolescence management. Retrieved August 30, 2016, from <http://www.plantengineering.com/single-article/seven-steps-in-predicting-equipment-lifecycle-using-obsolescence-management/547c3ac6da4cc7097fc02cea10c097cf.html>
- Aristotle. (350AD). *Metaphysics*. Massachusetts Institute of Technology. Retrieved from <http://classics.mit.edu/Aristotle/metaphysics.1.i.html>
- Assistant Secretary of Defense for Research and Engineering. (2011, May 13). *Technology Readiness Assessment (TRA)*. Assistant Secretary of Defense for Research and Engineering. Retrieved from <http://www.acq.osd.mil/chieftecnologist/publications/docs/TRA2011.pdf>
- Auster, P. J. (1997). Rov technologies and utilization by the science community. *Marine Technology Society. Marine Technology Society Journal*, 31(3), 72.
- Bajarin, T. (2016, January 19). Why virtual reality isn't just for gamers. *Time*. Retrieved from <http://time.com/4185505/virtual-reality-gamers/>

- Ballard, R. D., & Emery, K. O. (1970). *Research submersibles in oceanography, by R.D. Ballard and K.O. Emery*. Washington D.C.: Marine Technology Society.
- Ballard, R. D., & Hively, W. (2000). *The eternal darkness: a personal history of deep-sea exploration*. Princeton NJ: Princeton, New Jersey Press.
- Ballard, R. D., & McConnell, M. (1995). *Explorations: my quest for adventure and discovery under the sea*. New York: Hyperion. Retrieved from <https://www.amazon.com/Explorations-Quest-Adventure-Discovery-Under/dp/0786860421>
- Barth, B. (1999). *Sea dwellers: the humor, drama, and tragedy of the U.S. Navy Sealab programs*. Doyle Publishing Company.
- Beebe, W. (1934). *Half mile down*. New York: Harcourt, Brace and Company.
- Berkner, L. V. (1961, March 31). Policy positions on (1) man's role in the national space program and (2) support of basic research for space science. National Academies Press. Retrieved from <http://www.nap.edu/catalog/12427/policy-positions-on-1-mans-role-in-the-national-space-program-and-2-support-of-basic-research-for-space-science-march-27>
- Bigelow, H. B. (1931). Report of the Committee on Oceanography of the National Academy of Sciences.
- Bijker, W. E., Hughes, T. P., & Pinch, T. (1987). *The social construction of technological systems*. Cambridge, Mass: MIT Press. Retrieved from <https://mitpress.mit.edu/books/social-construction-technological-systems-0>
- Blascovich, J., & Bailenson, J. (2011). *Infinite reality: avatars, eternal life, new worlds, and the dawn of the virtual revolution*. New York: William Morrow.
- Blidberg, D. R. (2001). The development of autonomous underwater vehicles: a brief summary. In *IEEE International Conference on Robotics and Automation, 2001. Proceedings 2001 ICRA* (Vol. 1). Seoul, South Korea: IEEE. <https://doi.org/10.1109/ROBOT.2001.933107>
- Bluebird Marine Systems. (2013). Submersibles. Retrieved October 26, 2016, from <http://www.bluebird-electric.net/submersibles.htm>
- Boe, R. (2013, January 28). On the line: public safety risk management: the normalization of deviance (if it can happen to NASA, it can happen to you). Retrieved from <http://lmcontheline.blogspot.com/2013/01/the-normalization-of-deviance-if-it-can.html>

- Bogorff, R., & Jacobs, B. (2006). The mysterious disappearance of Nova University's Research Vessel Gulf Stream. In *NSU Books and Book Chapters, Book 3* (p. 27). Nova Southeastern University. Retrieved from [Http://nsuworks.nova.edu/nsu_books/3](http://nsuworks.nova.edu/nsu_books/3)
- Bonde, D. (2013). Qualitative interviews: when enough is enough. Research by Design. Retrieved from <http://www.researchbydesign.com.au/media/RBD-WhitePaper-Margin-of-Error.pdf>
- Borne, L. (2015). Unmanned vehicles 2015 buyers guide: mid-year update. Ocean News and Technology. Retrieved from <https://www.oceannews.com/buyersguide>
- Boutros, N., Shortis, M. R., & Harvey, E. S. (2015). A comparison of calibration methods and system configurations of underwater stereo-video systems for applications in marine ecology. *Limnology and Oceanography: Methods*, 13(5), 224–236. <https://doi.org/10.1002/lom3.10020>
- Bowen, A. D., & Walden, B. B. (1992). Manned Versus Unmanned Systems: A Complementary Approach. *Marine Technology Society Journal*, 26(4), 79–80.
- Brahim, N., Gueriot, Daniel, & Solaiman. (2011). 3D reconstruction of underwater scenes using DIDSON acoustic sonar image sequences through evolutionary algorithms. In *OCEANS, 2011 IEEE - Spain* (pp. 1–6). <https://doi.org/10.1109/Oceans-Spain.2011.6003666>
- Brass, C. T. (2012). *Changes to the Government Performance and Results Act (GPRA): overview of the new framework of products and processes* (CRS Report for Congress No. R42379) (p. 36). Washington D.C.: Congressional Research Service.
- Braun, D. M. (2016, August 7). Sylvia Earle revisits Hawaii's deep frontier. Retrieved September 1, 2016, from <http://voices.nationalgeographic.com/2016/08/07/sylvia-earle-revisits-hawaiiis-deep-frontier/>
- Breul, J. D. (2007). GPRA - a foundation for performance budgeting. *Public Performance and Management Review*, 30(3), 312–331. <https://doi.org/10.2753/PMR1530-9576300301>
- Briscoe, M. G. (2003). Science, technology, and people. *Oceanography*, 16(1), 4–10.
- Briscoe, M. G. (2013, March). *Setting Research Priorities*. Presented at the Ocean Studies Board.
- Broad, W. J. (2013, March 26). James Cameron to donate deep-sea craft to Woods Hole Institute. *The New York Times*. Retrieved from

<http://www.nytimes.com/2013/03/26/science/earth/james-cameron-to-donate-deep-sea-craft-to-woods-hole-institute.html>

Bugliarello, G., & Schillinger, A. G. (1986). Special Issue: A Department of Science and Technology - In the National Interest? *Technology in Society*, 8(1–2), 1–148.

Building Research Board. (1993). *Fourth Dimension in Building: Strategies for Avoiding Obsolescence*. Committee on Facility Design to Minimize Premature Obsolescence, Building Research Board, National Research Council.

Bureau of Ocean Energy Management. (2016). BOEM Research and Studies. Retrieved February 23, 2016, from <http://www.boem.gov/Marine-Minerals-Research-and-Studies/>

Busby, R. F. (1976). *Manned submersibles*. Office of the Oceanographer of the Navy. Retrieved from <http://archive.org/details/mannedsubmersibl00busb>

Busby, R. F. (1979). *Remotely operated vehicles*. U. S. Government Printing Office. Retrieved from <http://archive.org/details/remotelyoperated00rfa>

Business Dictionary. (n.d.-a). Definition of champion. Retrieved July 3, 2016, from <http://www.businessdictionary.com/definition/champion.html>

Business Dictionary. (n.d.-b). Definition of life cycle management. Retrieved January 5, 2016, from <http://www.businessdictionary.com/definition/life-cycle-management.html>

Cambridge in Colour. (n.d.). Cameras vs. the human eye. Retrieved August 25, 2015, from <http://www.cambridgeincolour.com/tutorials/cameras-vs-human-eye.htm>

Cameron, J. (2013, January 14). Don't give up on piloted dives. *Newsweek*. Retrieved from <http://www.newsweek.com/james-cameron-responds-robert-ballard-deep-sea-exploration-63183>

Cameron, J. (n.d.). *Deepsea challenge*. Retrieved from <http://www.deepseachallenge.com/>

Campbell Institute. (2014). *Risk perception: theories, strategies, and next steps* (p. 12). National Safety Council. Retrieved from <http://www.nsc.org/CampbellInstituteandAwardDocuments/WP-Risk%20Preception.pdf>

Campbell, S. M. (2009). On the absence of obsolescence. *IEEE Annals of the History of Computing*, 31(4), 120–119.

- Campbell, S. M. (2012, December 6). Scott Campbell. Retrieved August 29, 2016, from <https://uwaterloo.ca/systems-design-engineering/people-profiles/scott-campbell>
- Cantrell, L. (2015, March 25). Use of NOAA's NOSIA-II effort for undersea marine research tool assessment.
- Carnell, M., & Shank, S. (2016, July 3). The champion's role in successful six sigma deployments. Retrieved from <https://www.isixsigma.com/new-to-six-sigma/roles-responsibilities/champions-role-successful-six-sigma-deployments/>
- Catalog, T. (2014, May 9). 7 badass things that technology will never make obsolete. Retrieved from <http://thoughtcatalog.com/joe-choi/2014/05/7-badass-things-that-technology-will-never-make-obsolete/>
- Chidami, S., Guénard, G., & Amyot, M. (2007). Underwater infrared video system for behavioral studies in lakes. *Limnology and Oceanography: Methods*, 5(10), 371–378. <https://doi.org/10.4319/lom.2007.5.371>
- Christ, R. D., & Wernli, R. L. S. (2013). *The ROV manual: a user guide for remotely operated vehicles*. Butterworth-Heinemann.
- Cicala, R. (2012, November 17). The camera versus the human eye. Retrieved May 28, 2016, from <http://petapixel.com/2012/11/17/the-camera-versus-the-human-eye/>
- Clark, H. L. (2000). Technology development for ocean sciences at NSF. In *50 Years of Ocean Discovery: National Science Foundation 1950 - 2000*. National Academies Press (US). Retrieved from <http://www.ncbi.nlm.nih.gov/books/NBK208802/>
- Clear, J. (2014, April 7). How to be more productive by using the “Eisenhower Box.” Retrieved October 28, 2016, from <http://jamesclear.com/eisenhower-box>
- Commercial Diver Network. (2009, May 7). Research diver accident results in death in Florida Keys. Retrieved September 7, 2016, from <http://cdiver.net/news/research-diver-accident-results-in-death-in-florida-keys/>
- Commission on Marine Science, Engineering, and Resources. (1969). *Our nation and the sea. A plan for national action* (p. 305). Washington D.C.: United States Government Printing Office.
- Committee on Oceanography. (1959). *Oceanography, 1960 to 1970*. Washington: National Academy of Sciences, National Research Council. Retrieved from <http://catalog.hathitrust.org/Record/001273498>

- Committee on Science, Engineering and Public Policy. (1933). *Technology, and the federal government: national goals for a new era* (National Academy Press) (p. 68). Washington D.C.: National Academy of Sciences.
- Committee on Science, Engineering and Public Policy. (1999). *Evaluating federal research programs: research and the Government Performance and Results Act*. National Academy Press. Retrieved from <http://www.nap.edu/catalog/6416/evaluating-federal-research-programs-research-and-the-government-performance-and>
- Committee on Science, Engineering and Public Policy. (2006). *Advanced research instrumentation and facilities* (National Academy of Sciences). Washington D.C.: National Academy of Sciences. Retrieved from <http://www.nap.edu/catalog/11520/advanced-research-instrumentation-and-facilities>
- Committee on Undersea Warfare. (1957). *Proceedings of the symposium on aspects of deep-sea research*. Washington, D.C.
- Conlan, T. J., Posner, P. L., & Beam, D. R. (2014). *Pathways of power: the dynamics of national policymaking*. Washington D.C.: Georgetown University Press. Retrieved from https://www.amazon.com/Pathways-Power-Dynamics-Policymaking-Government/dp/1626160392#reader_1626160392
- Cooper, B., & O'Donnell, J. (2000, July 26). Robot associate study. Oceaneering Advanced Technologies.
- Corke, P. I. (1996). *Visual control of robots: high-performance visual servoing* (Vol. 2). Research Studies Press (John Wiley). Retrieved from <http://www.petercorke.com/bluebook/book.pdf>
- Covey, S. R. (1989). *The 7 habits of highly effective people: powerful lessons in personal change*. Free Press. Retrieved from https://www.amazon.com/Habits-Highly-Effective-People-Powerful/dp/1451639619/ref=asap_bc?ie=UTF8
- CQ Almanac. (1966). Reorganization of oceanography program. *Congressional Quarterly*, 1967, 22nd ed, 661–63.
- Craven, J. P. (1983). The extension of human performance in the sea. In *Subtech '83: The Design and Operation of Underwater Vehicles* (Vol. Keynote Presentation, p. 10). Society of Underwater Technology.
- Craven, J. P. (1990). The geopolitical significance of a deepest ocean presence. *Marine Technology Society Journal*, 24(2).

- Craven, J. P. (2002). *The silent war: the cold war battle beneath the sea* (Reprint edition). New York: Simon & Schuster.
- Csikszentmihalyi, M. (1990). *Flow: the psychology of optimal experience* (1 edition). New York: Harper Perennial Modern Classics.
- Davis, C. (2014, March 16). Triton subs designed to dive deep for adventure and research. Retrieved April 6, 2016, from <http://www.palmbeachdailynews.com/news/lifestyles/companys-triton-subs-designed-to-dive-deep-for-adv/nfDbK/>
- de Solla Price, D. (1963). *Little science big science*. Columbia University Press. Retrieved from <http://derekdesollaprice.org/little-science-big-science-full-text/>
- de Witte, D., & Tauss, C. (2016). The obsolescence management portal. Retrieved August 19, 2015, from <http://www.obsolescence.com/>
- Decker, M. (2000). Replacing human beings by robots. how to tackle that perspective by technology assessment. In D. J. Grin & P.-D. D. A. Grunwald (Eds.), *Vision Assessment: Shaping Technology in 21st Century Society* (pp. 149–166). Springer Berlin Heidelberg. Retrieved from http://link.springer.com/chapter/10.1007/978-3-642-59702-2_7
- Decker, M. (2006, October 18). Ethics of human interaction with robotic, bionic, and AI systems. Retrieved August 19, 2015, from <http://ethicbots.na.infn.it/meetings/firstworkshop/abstracts/decker.htm>
- DeepFlight. (n.d.). High performance personal submarines. Retrieved September 2, 2016, from <http://www.deepflight.com/>
- Delaney, J. (2010). *Wiring an interactive ocean*. Retrieved from https://www.ted.com/talks/john_delaney_wiring_an_interactive_ocean?language=en
- Delta Oceanographics. (2014). Submersible Logs Delta Oceanographics 1981 - 2009.
- Delta Oceanographics. (2015, April 23). DELTA dive logs. Not Published.
- Delta Oceanographics. (n.d.). Delta Oceanographics. Retrieved June 2, 2016, from <http://www.deltaoceanographics.com/index.html>
- DeSSC. (1993, July 13). UNOLS deep submergence science committee draft terms of reference. Retrieved from <https://www.unols.org/sites/default/files/199306desmi.pdf>

- DeSSC. (1994). *The global abyss: an assessment of deep submergence science in the United States*. University National Oceanographic Laboratory System.
- DeSSC. (1999). *Discovering the Oceans; DEveloping Submergence SCienceE for the Next Decade “DESCEND” Workshop Proceedings*. Arlington VA: UNOLS. Retrieved from http://www.unols.org/meetings/1999/199910dcd/descend_proceedings.pdf
- DeSSC. (2002). *Spring 2002 DeSSC meeting minutes*. WHOI: UNOLS. Retrieved from https://www.unols.org/sites/default/files/DESSC%20Minutes%205_02.pdf
- DeSSC. (2005, June 14). 2005 DeSSC spring meeting minutes. Retrieved from <https://www.unols.org/event/meeting/2005-dessc-spring-meeting>
- DeSSC. (2016a). *DESCEND2 benthic report*. Retrieved from https://descend2blog.files.wordpress.com/2016/04/open_ocean_benthic_rev1.pdf
- DeSSC. (2016b, January). DESCEND2 background. Retrieved June 8, 2016, from <http://projects.iq.harvard.edu/descend2/background>
- DeSSC. (2016c, January 14). DESCEND-2 workshop. Retrieved April 1, 2016, from <http://projects.iq.harvard.edu/descend2>
- DeSSC. (2016d, January 14). DESCEND-2 workshop documents. Retrieved April 1, 2016, from <http://projects.iq.harvard.edu/descend2/documents-pdfs>
- Dickey, T. D. (1990). Physical-optical-biological scales relevant to recruitment in large marine ecosystems. In *Large Marine Ecosystems, Patterns and Processes* (K. Sherman, L.M. Alexander, B.D. Gold, Vol. Chapter 7, pp. 82–89). Washington D.C.: American Association for the Advancement of Science. Retrieved from <http://www.opl.ucsb.edu/tommy/pubs/Dickeyscales1990.pdf>
- Dickey, T. D. (1991). The emergence of concurrent high-resolution physical and bio-optical measurements in the upper ocean and their applications. *Reviews of Geophysics*, 29(3), 383–413.
- Dinsmore, R. P. (1996, October 25). A 25 year history of UNOLS: Appendix X, UNOLS annual meeting minutes. UNOLS. Retrieved from <http://archive.unols.org/meetings/1996/199609anu/199609anuap10.html>
- Dixon, C. (2015, September 14). Do humans have a future in deep sea exploration? *The New York Times*. Retrieved from <http://www.nytimes.com/2015/09/15/science/piloted-deep-sea-research-is-bottoming-out.html>

- Donovan, S., & Holdren, J. P. (2015, July 9). Multi-agency science and technology priorities for the fy2017 budget. Memorandum fo the Heads of Executive Departments and Agencies. Retrieved from <https://www.whitehouse.gov/sites/default/files/omb/memoranda/2015/m-15-16.pdf>
- Dove, A. (2011). *Don Liberatore on the history of the Johnson Sea Link submersible*. Retrieved from <https://www.youtube.com/watch?v=830PA7PpeWQ>
- Dragland, A. (2016, January 7). Eagle-eyed subsea camera. *Gemini Science News*. Retrieved from <http://gemini.no/en/2016/01/marine-ressurser-kan-snart-forvaltes-bedre/>
- Edwards, M. (n.d.). HUMMA Project. Retrieved June 17, 2016, from <http://www.hummaproject.com/>
- Eisenhower, D. D. (1954, August). *Dwight D. Eisenhower: Address at the Second Assembly of the World Council of Churches, Evanston, Illinois*. Presented at the Second Assembly of the World Council of Churches, Evanston, IL. Retrieved from <http://www.presidency.ucsb.edu/ws/?pid=9991>
- Esaias, W. E. (1981). Remote sensing in biological oceanography. *Oceanus*, 24, 32–38.
- Executive Order 13547. Stewardship of the Ocean, Our Coasts, and the Great Lakes (2010). Retrieved from <https://www.whitehouse.gov/files/documents/2010stewardship-eo.pdf>
- Farr, N. (2013, June 24). Optical communications. Retrieved December 31, 2015, from <http://www.who.edu/website/optical-communications/>
- Fecht, S. (2011, April 8). Graham Hawkes talks deep flight challenger. Retrieved September 2, 2016, from <http://www.popularmechanics.com/technology/engineering/extreme-machines/questions-for-graham-hawkes-the-man-who-built-the-deep-flight-challenger-submersible>
- Finkle, E. (1985). *NOAA's Office of Undersea Research fiscal year 1984 report*. NOAA Office of Undersea Research. Retrieved from http://www.aoml.noaa.gov/general/lib/CREWS/Cleo/St.%20Croix/salt_river149.pdf
- Florida International University. (2014). 2014 Aquarius Reef Base Day Rates. Retrieved August 28, 2016, from https://aquarius.fiu.edu/working-with-aquarius/rate_details_2014.pdf

- Florida International University. (n.d.). Aquarius. Retrieved September 2, 2016, from <https://aquarius.fiu.edu/>
- Forman, E. H., & Gass, S. I. (2001). The analytic hierarchy process—an exposition. *Operations Research* 49(4): 469-486. *Operations Research*, 49(4), 469–486.
- Forman, W. (1999). *The history of american deep submersible operations* (Vol. 1st Edition). Best Publishing Company.
- Forrest, A. L., Laval, B. E., Lim, D. S. S., Williams, D. R., Trembanis, A. C., Marinova, M. M., ... McKay, C. P. (2010). Performance evaluation of underwater platforms in the context of space exploration. *Exploring Other Worlds by Exploring Our Own: The Role of Terrestrial Analogue Studies in Planetary Exploration*, 58(4), 706–716. <https://doi.org/10.1016/j.pss.2009.08.007>
- Forum Energy Technologies. (n.d.). Tether Management Systems. Retrieved August 15, 2016, from http://www.f-e-t.com/our_products_technologies/subsea-solutions/tether-management-systems-tms/
- Fox, T. (2014, June 4). Calit2 : Researchers at UCSD’s CISA3 Use 3D Visualization Technique to Document Underwater Cave, Paleoamerican Remains. Retrieved May 29, 2016, from <http://www.calit2.net/newsroom/article.php?id=2349>
- Free Dictionary. (n.d.). Definition of sustainment. Retrieved July 3, 2016, from <http://www.thefreedictionary.com/sustainment>
- Frey, D. (1991). Learning the Ropes: My Life As a Product Champion. *Harvard Business Review*, 69(5), 46–52.
- Fryer, P., Fornari, D., Perfit, M., Von Damm, K., Humphris, S., Fox, P. j., & Lippsett, L. (2002). Being there: The continuing need for human presence in the deep ocean for scientific research and discovery. *Eos, Transactions American Geophysical Union*, 83(46), 526–533. <https://doi.org/10.1029/2002EO000363>
- Gamarra, I. (2015, July 7). Tech pioneer and entrepreneur honored with FIU’s 2015 Lifetime Achievement Award. Retrieved from <https://news.fiu.edu/2015/07/fiu-college-of-business-to-award-tech-pioneer-and-entrepreneur-manuel-d-medina-the-2015-lifetime-achievement-award/90090>
- Garber, S. (2015, December 15). Style guide for NASA history authors and editors. NASA. Retrieved from <http://history.nasa.gov/styleguide.html>
- Garson. (2014, May 9). What is important is seldom urgent and what is urgent is seldom important | quote investigator. Retrieved from <http://quoteinvestigator.com/2014/05/09/urgent/>

- General Electric. (n.d.). Dull, dirty, dangerous - it's robot work. Retrieved January 30, 2016, from <https://www.ge.com/digital/blog/dull-dirty-dangerous-its-robot-work>
- GEOMAR. (2016, February 6). Helmholtz Centre for Ocean Research, Kiel. Retrieved September 14, 2016, from <http://www.geomar.de/en/research/>
- Geyer, R. A. (1977). *Submersibles and their use in oceanography and ocean engineering*. Elsevier. Retrieved from <https://www.elsevier.com/books/submersibles-and-their-use-in-oceanography-and-ocean-engineering/geyer/978-0-444-41545-5>
- Global Sub Dive. (2015, December 2). Project Baseline submersible and research vessel featured on pbs. Retrieved from <http://globalsubdive.com/project-baseline-submersible-research-vessel-featured-pbs/>
- Google Scholar. (2016). NASA human robotic systems - Google Scholar. Retrieved May 30, 2016, from <https://scholar.google.com/scholar?q=nasa+human+robotic+systems>
- GoPro. (n.d.). GoPro spherical solutions. Retrieved August 22, 2016, from <https://gopro.com/spherical>
- Green, K., Lowry, D., & Yamanaka, L. (2014). *Proceedings of the Visual Survey Methods Workshop* (p. 79). Sand Point, Seattle, WA: U.S. Canada Technical Sub-Committee (TSC) of the Canada-U.S. Groundfish Committee. Retrieved from http://www.psmfc.org/tsc2/docs/TSC_Visual_Survey_Methods_Workshop_Proceedings_5_14_2014.pdf
- Green, K., Stahl, J., & Kallenberger, M. (2013). *2013 Demersal shelf rockfish remotely operated vehicle survey* (Alaska Department of Fish and Game Divisions of Sport Fish and Commercial Fisheries No. Regional Operational Plan CF.1J.2013.09). Retrieved from <http://www.adfg.alaska.gov/fedaidpdfs/ROP.CF.1J.2013.09.pdf>
- Greenberg, D. S. (2001). *Science, money, and politics*. University of Chicago Press. Retrieved from <http://www.press.uchicago.edu/ucp/books/book/chicago/S/bo3629423.html>
- Hackett, E. J., Amsterdamska, O., Lynch, M., & Wajcman, J. (2008). *The handbook of science and technology studies*. (E. J. Hackett, O. Amsterdamska, M. Lynch, & J. Wajcman, Eds.). Cambridge, USA: The MIT Press. Retrieved from <https://mitpress.mit.edu/books/handbook-science-and-technology-studies>
- Hanson, L. C. (1986). *The marine research community and low-cost ROVs and submersibles : needs and prospects* /. Kingston, R.I. : University of Rhode Island Center for Ocean Management Studies.

- Hanson, L. C. (1989). From low-cost vehicles to the deepest ocean: The process. *American Academy of Underwater Sciences: Diving for Science*. Retrieved from <http://dSPACE.rubicon-foundation.org/xmlui/handle/123456789/10166>
- Harbor Branch. (2009). Harbor Branch Oceanographic Institute submersible logs, 1985 - 2009.
- Harbor Branch. (2010, April). Harbor Branch Bulletin. Retrieved from http://fau.edu/hboi/pdf/ebulletins/HBOI_ebulletin_0410.pdf
- Harbor Branch. (n.d.). A mission: ocean discovery. Retrieved June 18, 2016, from <http://www.fau.edu/hboi/community/modexhibit2016.php>
- Harbor Branch Foundation. (1978). Harbor Branch Profiles.
- Harvey, E., & Cappel, M. (2000). *Video sensing of the size and abundance of target and non-target fauna in Australian fisheries - a National workshop* (Workshop Proceedings No. 2000/187). Australia: Australian Institute of Marine Science. Retrieved from <http://www.aims.gov.au/pages/research/video-sensing>
- Harzing, A., & van der Wal, R. (2008). Google Scholar as a new source for citation analysis. *Ethics in Science and Environmental Politics*, 8, 61–73. <https://doi.org/10.3354/esep00076>
- Hawai'i Undersea Research Laboratory. (2012). Hawai'i Undersea Research Laboratory: Applying innovative deep-sea technologies toward research, service, and stewardship in the Pacific region. Retrieved from https://www.soest.hawaii.edu/HURL/science/HURL_2012_tabloid_brochure_v7.pdf
- Hawai'i Undersea Research Laboratory. (2014). Hawai'i Undersea Research Laboratory, submersible logs, 1981 - 2014.
- Hawai'i Undersea Research Laboratory. (2016). Hawaii Undersea Research Laboratory (HURL): Submersible assets. Retrieved August 27, 2016, from <http://www.soest.hawaii.edu/HURL/subops/>
- Heirtzler, J. R., & Andel, T. H. V. (1977). Project FAMOUS: Its origin, programs, and setting. *Geological Society of America Bulletin*, 88(4), 481–487. [https://doi.org/10.1130/0016-7606\(1977\)88<481:PFIOPA>2.0.CO;2](https://doi.org/10.1130/0016-7606(1977)88<481:PFIOPA>2.0.CO;2)
- Hellwarth, B. (2012). *Sealab: America's forgotten quest to live and work on the ocean floor*. Simon and Schuster.

- Henderson, J., Pizarro, O., Johnson-Roberson, M., & Mahon, I. (2013). Mapping submerged archaeological sites using stereo-vision photogrammetry. *International Journal of Nautical Archaeology*, 42(2), 243–256. <https://doi.org/10.1111/1095-9270.12016>
- Hightower, J. D., Smith, D. C., & Wiker, S. F. (1986). *Development of remote presence technology for teleoperator systems*. DTIC Document. Retrieved from <http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA191898>
- Hilts, P. J. (2014, September 29). Marine archaeology goes high-tech. Retrieved January 19, 2016, from <http://blogs.scientificamerican.com/expeditions/marine-archaeology-goes-high-tech/>
- Hoffman, C. (2005, June 1). The mad genius from the bottom of the sea. *WIRED*. Retrieved from <http://www.wired.com/2005/06/craven/>
- Hollings, F., & Magnuson, W. G. National Advisory Committee on Oceans and Atmosphere, 33USC857-13 (1971). Retrieved from <https://archive.org/stream/nationaladvisor00trangoog#page/n5/mode/2up>
- Hourigan, T. F., Etnoyer, P. J., McGuinn, R. P., Whitmire, C., Dorfman, D. S., Dornback, M., ... Sallis, D. (2015). *An Introduction to NOAA National Database for Deep Sea Coral and Sponges* (NOAA Technical Memorandum No. NOS NCCOS 191) (p. 27). Silver Spring MD: NOAA. Retrieved from http://data.nodc.noaa.gov/coris/library/NOAA/CRCP/other/other_crcp_publications/DeepSeaCoralRT/Intro_Natl_DB_for_DSCS.pdf
- Huffington Post. (2013, January 9). Thrilling news for ocean research. *The Huffington Post*. Retrieved from http://www.huffingtonpost.com/2013/01/09/fiu-aquarius-reef-base-florida-international-university_n_2440054.html
- Human-Robot Interaction Conference. (2006, March 2). Human-Robot Interaction Conference. Retrieved May 30, 2016, from <http://humanrobotinteraction.org/2006/>
- IEEE. (1995). *IEEE Standard Glossary of Computer Networking Terminology* (p. 0_1-). Retrieved from <http://ieeexplore.ieee.org/mutex.gmu.edu/stamp/stamp.jsp?arnumber=467542>.
- In-Depth Images Kwajalein. (1981). Makali'i sumbersible. Retrieved June 17, 2016, from <http://www.underwaterkwaj.com/enew/makalii.htm>
- INFORMS. (2016, March 4). What is operations research? Retrieved March 4, 2016, from <https://www.informs.org/About-INFORMS/What-is-Operations-Research>

- Interagency Working Group on Facilities. (2007). *Federal oceanographic fleet status report* (p. 52). Interagency Working Group on Facilities, Joint Subcommittee on Ocean Science and Technology. Retrieved from <http://www.nopp.org/wp-content/uploads/2010/03/IWG-F-Fleet-Status-Report-Final.pdf>
- Interagency Working Group on Facilities and Infrastructure. (2013). *Federal oceanographic fleet status report*. Retrieved from https://www.whitehouse.gov/sites/default/files/federal_oceanographic_fleet_status_report.pdf
- Interagency Working Group on Ocean Acidification. (2014). *Strategic plan for federal research and monitoring of ocean acidification*. Silver Spring, MD: NOAA. Retrieved from <ftp://ftp.oar.noaa.gov/OA/IWGOA%20documents/IWGOA%20Strategic%20Plan.pdf>
- International Association of Classification Societies. (2011, March). Classification societies: What, where, how? Retrieved from http://www.iascs.org.uk/document/public/explained/Class_WhatWhy&How.PDF
- International Society on MCDM. (2016, March 4). Mission of the Society: Multiple Criteria Decision Making. Retrieved March 4, 2016, from <http://www.mcdmsociety.org/content/mission-society>
- Investopedia. (2003, November 25). Definition: portfolio management. Retrieved March 4, 2016, from <http://www.investopedia.com/terms/p/porfoliomangement.asp>
- Ishibashi, S. (2009). The stereo vision system for an underwater vehicle. In *OCEANS 2009 - EUROPE* (pp. 1–6). <https://doi.org/10.1109/OCEANSE.2009.5278314>
- Jabr, F. (2010a, August 5). Gleaning the gleam: A deep-sea webcam sheds light on bioluminescent ocean life. *Scientific American*. Retrieved from <http://www.scientificamerican.com/article/edith-widder-bioluminescence/>
- Jabr, F. (2010b, August 5). Gleaning the Gleam: A Deep-Sea Webcam Sheds Light on Bioluminescent Ocean Life. Retrieved May 23, 2016, from <http://www.scientificamerican.com/article/edith-widder-bioluminescence/>
- Joint Subcommittee on Ocean Science and Technology. (2007). *Charting the course for ocean science in the United States for the next decade: an ocean research priorities plan and implementation strategy*. Washington D.C.: National Science and Technology Council. Retrieved from <https://www.whitehouse.gov/sites/default/files/microsites/ostp/nstc-orppis.pdf>

- Journal of Human-Robot Interaction. (n.d.). Journal of Human-Robot Interaction. Retrieved May 30, 2016, from <http://humanrobotinteraction.org/journal/index.php/HRI/index>
- Kahan, D. M. (2008). Cultural cognition as a conception of the cultural theory of risk. In *Handbook of risk theory*. Rochester, NY: Social Science Research Network. Retrieved from <http://papers.ssrn.com/abstract=1123807>
- Kaharl, V. A. (1990). *Water baby: the story of Alvin* (First Edition edition). New York: Oxford University Press.
- Kantor, G., Fairfield, N., Jonak, D., & Wettergreen, D. (2008). Experiments in navigation and mapping with a hovering AUV. In C. Laugier & R. Siegwart (Eds.), *Field and Service Robotics* (pp. 115–124). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-75404-6_11
- Kasser, J. E. (2015). Applying holistic thinking to the problem of determining the future availability of technology. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, PP(99), 1–1. <https://doi.org/10.1109/TSMC.2015.2438780>
- Kendall, S. (2016). So which is better: PubMed, Web of Science, or Google Scholar? Retrieved March 3, 2016, from <http://libguides.lib.msu.edu/pubmedvsgoogle scholar>
- Kerby, T. (1991). The use of a diver-operated launch, recovery and transport (LRT) vehicle for operations of the submersible *Pisces V*. *American Academy of Underwater Sciences, International Pacifica Scientific Diving*. Retrieved from <http://dspace.rubicon-foundation.org/xmlui/handle/123456789/9357>
- Kilduff, P., Carmichael, J., & Latour, R. (2009). *Guide to Fisheries Science and Stock Assessments*. Atlantic States Marine Fisheries Commission. Retrieved from <http://www.asmfc.org/files/Science/GuideToFisheriesScienceAndStockAssessments.pdf>
- Kim, M. (2015, February 18). The good and the bad of escaping to virtual reality. *The Atlantic*. Retrieved from <http://www.theatlantic.com/health/archive/2015/02/the-good-and-the-bad-of-escaping-to-virtual-reality/385134/>
- Klevebrant, H., & Svensson, S. (1983). Stereo TV for underwater work and inspection. In *Subtech '83: The Design and Operation of Underwater Vehicles* (pp. 269–277). London: The Society for Underwater Technology.
- Kodak. (n.d.). Kodak SP360 action camera. Retrieved August 22, 2016, from <http://kodakpixpro.com/Americas/cameras/actioncam/sp360/>

- Kohanowich, K. M., & Potts, T. A. (2010). NOAA's AQUARIUS Reef Base: entering a new decade. In *29th AAUS Symposium March 25-27, 2010*. Waikiki, HI.
- Kohnen, W. (2013). Review of deep ocean manned submersible activity in 2013. *Marine Technology Society Journal*, 47(5), 56–68.
- Kohnen, W. (2016a). Active manned submersibles by depth. Retrieved March 11, 2016, from <http://www.mtsmuv.org/active-manned-submersibles-by-depth/>
- Kohnen, W. (2016b). Manned submersibles - looking ahead. *Ocean News and Technology*, 2016(January), 8.
- Kohnen, W. (2016c, September 26). UI.
- Laidig, T. E., Krigsman, L. M., & Yoklavich, M. M. (2013). Reactions of fishes to two underwater survey tools, a manned submersible and a remotely operated vehicle. *Fishery Bulletin*, 111(1), 54–67. <https://doi.org/10.7755/FB.111.1.5>
- Laidig, T. E., & Yoklavich, M. M. (2016). A comparison of density and length of Pacific groundfishes observed from 2 survey vehicles: a manned submersible and a remotely operated vehicle. *Fishery Bulletin*, 114(4), 386–396. <https://doi.org/10.7755/FB.114.4.2>
- Lange, B. (2015). Seeing in 3-D. Retrieved May 29, 2016, from <https://www.whoi.edu/main/topic/imaging>
- Leaman, A., Stevenson, F., & Bordass, B. (2010). Building evaluation: practice and principles. *Building Research & Information*, 38(5), 564–577. <https://doi.org/10.1080/09613218.2010.495217>
- Leeuw, T., Boss, E. S., & Wright, D. L. (2013). In situ measurements of phytoplankton fluorescence using low cost electronics. *Sensors (Basel, Switzerland)*, 13(6), 7872–7883. <https://doi.org/10.3390/s130607872>
- Leonard, R. (2016, August 2). NEKTON releases 360 virtual reality video as its first exploratory mission deploys from Bermuda and Canada. Retrieved from <http://irishtechnews.net/ITN3/nekton-releases-360-virtual-reality-video-as-its-first-exploratory-mission-deploys-from-bermuda-and-canada/>
- Letessier, T. B., Kawaguchi, S., King, R., Meeuwig, J. J., Harcourt, R., & Cox, M. J. (2013). A robust and economical underwater stereo video system to observe antarctic krill (*euphausia superba*). *Open Journal of Marine Science*, 03(03), 148–153. <https://doi.org/10.4236/ojms.2013.33016>

- Liberatore, D., Askew, T., Tusting, R., & Olson, S. (1997). Harbor branch submersibles command a role in underwater scientific sampling. *Marine Technology Society. Marine Technology Society Journal*, 31(3), 55.
- Lim, D. (2015, November 23). NASA Exploration Operations Research.
- Link, M. C. (1973). *Windows in the Sea*. Washington D.C.: Smithsonian Institution Press.
- Loff, S. (2016, August 31). NEEMO—NASA Extreme Environment Mission Operations [Text]. Retrieved July 26, 2016, from http://www.nasa.gov/mission_pages/NEEMO/index.html
- Madin, K., & Lipsett, L. (2014). Trailblazer in the ocean. *Oceanus Magazine*, 51(1). Retrieved from <http://www.whoi.edu/oceanus/feature/trailblazer-in-the-ocean-depths>
- Madin, L. P. (1990). Overview - being there - the role of in situ science in oceanography. *Marine Technology Society Journal*, 24(2), 19–21.
- Mahaffie, J. (2009, December 4). Critical decisions—four-quadrant scenario analysis. Retrieved September 17, 2016, from <http://foresightculture.com/2009/12/04/critical-decisions-four-quadrant-scenario-analysis>
- Mai, T. (2015, July 31). Technology readiness levels. Retrieved August 30, 2016, from http://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html
- Malik, T. (2007, May 17). Space station astronaut calls undersea lab. Retrieved September 7, 2016, from <http://www.space.com/3819-space-station-astronaut-calls-undersea-lab.html>
- Mallet, D., & Pelletier, D. (2014). Underwater video techniques for observing coastal marine biodiversity: A review of sixty years of publications (1952–2012). *Fisheries Research*, 154, 44–62. <https://doi.org/10.1016/j.fishres.2014.01.019>
- Marine Board. (1996). *Undersea vehicles and national needs* (p. 116). Marine Board Commission on Engineering and Technical Systems, National Research Council National Academies Press. Retrieved from http://www.nap.edu/catalog.php?record_id=5069
- Marine Board Commission on Engineering and Technical Systems. (1990). *Safety of tourist submersibles*. National Academies.

- Markham, S. K., & Aiman-Smith, L. (2001). Product champions: truths, myths and management. *Research-Technology Management*, 44(3), 44–50.
<https://doi.org/10.1080/08956308.2001.11671429>
- Marouchos, A., Muir, B., Babcock, R., & Dunbabin, M. (2015). A shallow water AUV for benthic and water column observations. In *OCEANS 2015 - Genova* (pp. 1–7).
<https://doi.org/10.1109/OCEANS-Genova.2015.7271362>
- Mason, M. (2010). Sample size and saturation in PhD studies using qualitative interviews. *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research*, 11(3). Retrieved from <http://www.qualitative-research.net/index.php/fqs/article/view/1428>
- Mathaisel, D. F. X., Manary, J. M., & Comm, C. L. (2009). *Enterprise sustainability: enhancing the military's ability to perform its mission*. CRC Press.
- Matthews, J. N. A. (2016). Questions and answers with Carl Wunsch. *Physics Today*.
<https://doi.org/10.1063/PT.5.3032>
- Maxwell, J. A. (2013). *Qualitative research design: an interactive approach (3rd edition)*. SAGE.
- MBARI. (1997). *MBARI's First decade: a retrospective*. Moss Landing CA: Monterey Bay Aquarium Research Institute. Retrieved from <http://www.mbari.org/wp-content/uploads/2015/10/MBARI-retrospective.pdf>
- MBARI. (n.d.-a). Exploration and discovery. Retrieved April 6, 2016, from <http://www.mbari.org/about/making-an-impact/exploration-discovery/>
- MBARI. (n.d.-b). Monterey Bay Aquarium Research Institute. Retrieved October 25, 2016, from <http://www.mbari.org/>
- McGrath, A. (2010). Social implications for the “real” in virtual reality. Retrieved April 7, 2016, from <http://www.soc.hawaii.edu/leon/459s010/mcgrath/mcgrath-report1.htm>
- Merrell, W. J., Katsouros, M. H., & Bienski, J. (2001). The stratton commission: the model for a sea change in national marine policy. *Oceanography*, 14(2), 11–16.
- Merriam-Webster Dictionary. (n.d.). Definition of big science. Retrieved October 9, 2016, from <http://www.merriam-webster.com/dictionary/big+science>
- Merrick, R. L. (2013). NOAA Fisheries strategic plan overview 2013. Retrieved February 23, 2016, from <https://www.st.nmfs.noaa.gov/Assets/Strategic-Plans/NOAA%20Fisheries%20Stragetic%20Plan%20Overview%202013.pdf>

- Meyer, D., Isakower, A., & Mott, B. (2014). *An Ocean of Opportunities: 2015 Full Summary Report*. The Ocean Project. Retrieved from <http://theoceanproject.org/communication-resources/market-research/reports/#2015>
- Michel, D. (2016, August 24). ROV Costs.
- Midson, B. (2016, April 5). NSF Support of NDSF.
- Mikulski, L. (2013, January 4). President's spring 2013 welcome back message. Retrieved from <http://news.fiu.edu/2013/01/presidents-spring-2013-welcome-back-message/50339>
- Miller, J. W., & Koblick, I. G. (1995). *Living and working in the sea*. Five Corners Publications.
- Miller, S. L., & Cooper, C. (2000). The Aquarius underwater laboratory: America's "inner space" station. *Marine Technology Society Journal*, 34(4), 69–74.
- Mindell, D. A. (2015). *Our robots, ourselves: robotics and the myths of autonomy*. Viking.
- Mission Blue. (2013, June 24). Dive deep with subs 101. Retrieved from <https://www.mission-blue.org/2013/06/dive-deep-with-subs-101/>
- Monastersky, R. (2012). Deep-sea research: Dive master. *Nature*, 489(7415), 194–196. <https://doi.org/10.1038/489194a>
- Moore, M. H. (1997). *Creating public value: strategic management in government*. Harvard University Press. Retrieved from <http://www.hup.harvard.edu/catalog.php?isbn=9780674175587>
- Moore, M. H. (2013). *Recognizing public value*. Harvard University Press. Retrieved from <http://www.hup.harvard.edu/catalog.php?isbn=9780674066953>
- Moynihan, R. A., Reining, R. C., Salamone, P. P., & Schmidt, B. K. (2009). Enterprise scale portfolio analysis at the National oceanic and Atmospheric Administration (NOAA). *Systems Engineering*, 12(2), 155–168. <https://doi.org/10.1002/sys.20116>
- MTS MUV Committee. (2016). Manned Underwater Vehicles. Retrieved March 11, 2016, from <http://www.mtsmuv.org/>
- MTS ROV Committee. (2016a). ROV applications - propulsion. Retrieved June 22, 2016, from http://www.rov.org/rov_design_propulsion.cfm

- MTS ROV Committee. (2016b). ROV categories. Retrieved June 23, 2016, from http://www.rov.org/rov_categories.cfm
- MTS Undersea Vehicle Committee. (1968). *Safety and operational guidelines for undersea vehicles* (Vol. I). Washington: Marine Technology Society. Retrieved from <http://catalog.hathitrust.org/Record/008329634>
- MTS Undersea Vehicle Committee. (1974). *Safety and operational guidelines for undersea vehicles; book II*. (Vol. II). Washington: Marine Technology Society.
- MTS Undersea Vehicle Committee. (1979). *International safety standard guidelines for the operation of undersea vehicles* (Vol. III). Washington, D.C.: Marine Technology Society.
- Mueller-Parker, G. (2007). “Rotators” in the National Science Foundation’s geosciences directorate. *Eos, Transactions American Geophysical Union*, 88(18), 200–200. <https://doi.org/10.1029/2007EO180007>
- Murphy, H. M., & Jenkins, G. P. (2010). Observational methods used in marine spatial monitoring of fishes and associated habitats: a review. *Marine and Freshwater Research*, 61(2), 236–252.
- Nakamura, J., & Csikszentmihalyi, M. (2014). The concept of flow. In *Flow and the foundations of positive psychology* (pp. 239–263). Springer. Retrieved from http://link.springer.com/10.1007/978-94-017-9088-8_16
- NASA. (n.d.). Oceanography Science Mission Directorate. Retrieved October 15, 2016, from <https://science.nasa.gov/earth-science/focus-areas/oceanography>
- National Academy of Sciences. (1988). *Federal science and technology budget priorities: new perspectives and procedures* (p. 32). Washington DC: National Academy Press.
- National Deep Submergence Facility. (2016). Annual NSF Grant proposals 2007-2016.
- National Geographic. (2000). National Geographic: U.S. marine sanctuaries expeditions. Retrieved August 22, 2016, from <http://www.nationalgeographic.com/features/seas/>
- National Science Board. (2003). *Science and engineering infrastructure for the 21st century: the role of the National Science Foundation* (No. NSB 02-190) (p. 74). Washington D.C.: National Science Foundation. Retrieved from <https://www.nsf.gov/nsb/documents/2002/nsb02190/nsb02190.pdf>

- National Science Foundation. (1982). *Report of the decade: The International Decade of Ocean Exploration*. Retrieved from <http://www.divediscover.whoi.edu/ventcd/pdf/ReportofDecadePrologue.pdf>
- National Science Foundation. (2016a). Oceanographic facilities and equipment support. Retrieved July 6, 2016, from http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504848&org=OCE&from=home
- National Science Foundation. (2016b). Temporary/Rotator Programs. Retrieved July 6, 2016, from <https://www.nsf.gov/careers/rotator/>
- Nautilus Live. (2015). Nautilus live home page. Retrieved January 20, 2016, from <http://www.nautiluslive.org/>
- Nautilus Live. (n.d.). The tools of ocean exploration. Retrieved August 15, 2016, from <http://www.nautiluslive.org/tech>
- Naval Sea Systems Command. (1998). *P-9290 manual: system certification procedures and criteria manual for deep submergence systems* (No. 0910-NaN-018-2840). Washington D.C. Retrieved from http://traktoria.org/files/personal_submarine/standards/System_Certification_Procedures_and_Criteria_Manual_for_Deep_Submergence_Systems.pdf
- Naval Sea Systems Command. (2016, October 4). Naval vessel register - no name (DSV 2). Retrieved October 8, 2016, from http://www.nvr.navy.mil/SHIPDETAILS/SHIPSDETAIL_DSV_2.HTML
- Nekton Mission. (2016, July 24). Nekton deep ocean exploration [text/html]. Retrieved July 25, 2016, from <https://nektonmission.org/>
- Nixon, D. (1987). Liability issues in the operation of oceanographic research vessels in the United States. In *OCEANS '87* (pp. 826–829). <https://doi.org/10.1109/OCEANS.1987.1160773>
- Nixon, D. W. (2000). Recent developments in oceanographic research vessel law. In *OCEANS 2000 MTS/IEEE Conference and Exhibition* (Vol. 1, pp. 233–236 vol.1). <https://doi.org/10.1109/OCEANS.2000.881266>
- NOAA. (1980, March 31). The Undersea Research Program of the National Oceanic and Atmospheric Administration. U.S. Department of Commerce.
- NOAA. (1999). National Marine Sanctuaries - Sustainable Seas. Retrieved August 22, 2016, from <http://sanctuaries.noaa.gov/sse/sse.html>

- NOAA. (2010a). *NOAA strategic plan for deep-sea coral and sponge ecosystems: research, management, and international cooperation* (No. NOAA Technical Memorandum CRCP 11) (p. 67). Silver Spring, MD: NOAA Coral Reef Conservation Program. Retrieved from http://www.coris.noaa.gov/activities/deepsea_coral/dsc_strategicplan.pdf
- NOAA. (2010b, May 27). About NURP (archived). Retrieved July 7, 2016, from <https://web.archive.org/web/20100527091153/http://www.nurp.noaa.gov/About.htm>
- NOAA. (2012). NOAA Blue Book FY2013: Chapter 3 Office of Oceanic and Atmospheric Research. Retrieved from http://www.corporateservices.noaa.gov/nbo/fy13_budget_highlights/chapter3_OAR.pdf
- NOAA. (2013a). FY 2014 NOAA budget summary -. Retrieved from http://www.corporateservices.noaa.gov/nbo/fy14_bluebook/FINALnoaaBlueBook_2014_Web_Full.pdf
- NOAA. (2013b). Research and development at NOAA: environmental understanding to ensure america's vital and sustainable future. Retrieved February 23, 2016, from http://nrc.noaa.gov/sites/nrc/Documents/5YRDP/2013%20NOAA%205%20Year%20Plan_FINAL%20version.pdf
- NOAA. (2014). *Undersea Imaging Workshop* (Workshop Proceedings). Red Hook, NJ: NOAA Sea Grant NJ. Retrieved from <http://njseagrant.org/wp-content/uploads/2014/07/Undersea-Imaging-Workshop.pdf>
- NOAA. (2016). NOAA's Deep-Sea Coral Data Portal [Page]. Retrieved May 6, 2016, from <https://deepseacoraldata.noaa.gov/>
- NOAA NOSC. (2015, December). NOAA NOSIA-II Methodology Report v1.93. Retrieved from <https://nosc.noaa.gov/tpio/docs/NOSIA-II-Methodology-Report-v1.93-NOSC.pdf>
- NOAA NOSC. (2016). NOAA NOSIA-II Value Tree. Retrieved August 29, 2016, from https://nosc.noaa.gov/tpio/docs/NOSIA_value_tree_v3.pdf
- NOAA NURP. (2009a, March 16). NIUST. Retrieved September 6, 2016, from <http://www.nurp.noaa.gov/NIUST.htm>
- NOAA NURP. (2009b, July 22). NURP. Retrieved September 6, 2016, from <http://www.nurp.noaa.gov/>

- NOAA Ocean Exploration. (2002). Sustainable Seas Expedition. Retrieved August 22, 2016, from <http://oceanexplorer.noaa.gov/projects/02sse/welcome.html>
- NOAA Ocean Exploration. (2006, June). NOAA Ocean Explorer: expedition to the deep slope 2006. Retrieved September 8, 2016, from <http://oceanexplorer.noaa.gov/explorations/06mexico/welcome.html>
- NOAA Ocean Exploration. (2007, July). NOAA Ocean Explorer: expedition to the deep slope 2007. Retrieved September 8, 2016, from <http://oceanexplorer.noaa.gov/explorations/07mexico/welcome.html>
- NOAA Ocean Exploration. (2015, September). NOAA Ocean Explorer: coral ecosystem connectivity 2015: from Pulley Ridge to the Florida Keys: Background Resources. Retrieved August 27, 2016, from <http://oceanexplorer.noaa.gov/explorations/15pulleyridge/welcome.html>
- NOAA Ocean Exploration. (2016, February 28). NOAA Ocean Explorer: explorations. Retrieved February 28, 2016, from <http://oceanexplorer.noaa.gov/explorations/explorations.html>
- NOAA Ocean Exploration. (n.d.-a). NOAA Okeanos Explorer home. Retrieved January 20, 2016, from <http://oceanexplorer.noaa.gov/okeanos/welcome.html>
- NOAA Ocean Exploration. (n.d.-b). NOAA Ship *Okeanos Explorer*: deepwater wonders of Wake. Retrieved August 15, 2016, from <http://oceanexplorer.noaa.gov/okeanos/explorations/ex1606/background/plan/welcome.html>
- NOAA Ocean Exploration. (n.d.-c). *Okeanos Explorer* Seirios camera sled. Retrieved August 15, 2016, from <http://oceanexplorer.noaa.gov/okeanos/explorations/ex1103/background/seirios/seirios.html>
- NOAA Ocean Exploration. (n.d.-d). Telepresence technology. Retrieved August 22, 2016, from <http://oceanexplorer.noaa.gov/technology/commstech/telepresence/telepresence.html>
- NOAA Office of Oceanic and Atmospheric Research. (2014, May 15). Guide-to-FY2015-NOAA-Research-Funding.pdf. Retrieved from <https://research.usc.edu/files/2011/05/Guide-to-FY2015-NOAA-Research-Funding.pdf>
- Nolte, W. L. (2008). *Did I ever tell you about the whale?, or, measuring technology maturity*. IAP.

- NSF Ocean Sciences. (2015, May 11). NSF/Ocean Sciences reply to: NRC/NAS's "Sea Change (2015-2025 Decadal Survey of Ocean Sciences)." NSF. Retrieved from <https://www.nsf.gov/geo/oce/pubs/nsf-oce-sea-change-reply-may-11-2015.pdf>
- Nuytco Research, Ltd. (2016). Orcasub. Retrieved September 2, 2016, from <http://nuytco.com/products/orcasub/>
- Nuytco Research, Ltd. (n.d.). Phil Nuytten timeline. Retrieved September 2, 2016, from <http://nuytco.com/history/timeline/>
- Nuytten, P. (2005). *History of Nuytco* [.mp3] hard copy DVD.
- Nuytten, P. (2009, December 6). Super Aviator. Retrieved from <http://divermag.com/super-aviator/>
- Nuytten, P. (2012, January 25). Underwater Intervention.
- Nuytten, P. (2013, November 26). Submersible classification. Retrieved from http://www.psubs.org/pipermail/personal_submersibles/2013-November/001087.html
- Ocean News and Technology. (2016). A marine industry directory of unmanned vehicles 2016 buyers guide mid-year update. Retrieved from <http://digital.oceannews.com/publication/index.php?i=323984>
- Ocean Sciences Board. (1980). *Oceanlab Concept Review* (Technical Report). Retrieved from <https://books.google.com/>.
- Ocean Studies Board. (2000a). *50 years of ocean discovery: National Science Foundation 1950-2000*. Washington, D.C.: The National Academies Press.
- Ocean Studies Board. (2000b). *NSF Division of Ocean Sciences: senior science staff, rotators, ipas, and visiting scientists Appendix D*. National Academies Press (US). Retrieved from <http://www.ncbi.nlm.nih.gov/books/NBK208805/>
- Ocean Studies Board. (2004). *Future needs in deep submergence science: occupied and unoccupied vehicles in basic ocean research*. National Academies Press. Retrieved from <http://www.nap.edu/catalog/10854.html>
- Ocean Studies Board. (2009). *Science at sea: meeting future oceanographic goals with a robust academic research fleet*. Washington, D.C.: The National Academies Press.
- Ocean Studies Board. (2011). *Critical infrastructure for ocean research and societal needs in 2030* (p. 99). Washington D.C.: National Research Council, Ocean Studies Board. Retrieved from http://www.nap.edu/catalog.php?record_id=13081

- Ocean Studies Board. (2015). *Sea change: 2015-2025 decadal survey of ocean sciences*. Washington D.C.: National Academies Press. Retrieved from <http://www.nap.edu/catalog/21655/sea-change-2015-2025-decadal-survey-of-ocean-sciences>
- Oceaneering International. (2015, February 6). Top 10 ROV questions. Retrieved August 15, 2016, from <http://www.oceaneering.com/rovs/top-10-rov-questions/>
- OceanGate. (2014). OceanGate Battelle camera test. Retrieved August 22, 2016, from <http://www.oceangate.com/blog/2015-01-27-battelle-camera-test.html>
- OceanGate. (2016). MSLARS: Mobile Subsea Launch and Recovery System. Retrieved April 6, 2016, from <http://www.oceangate.com/submersibles/mobile-subsea-launch-recovery-system.html>
- O'Connell, V. M., & Carlile, D. W. (1994). Comparison of a remotely operated vehicle and a submersible for estimating abundance of demersal shelf rockfishes in the eastern Gulf of Alaska. *North American Journal of Fisheries Management*, 14(1), 196–201. [https://doi.org/10.1577/1548-8675\(1994\)014<0196:COAROV>2.3.CO;2](https://doi.org/10.1577/1548-8675(1994)014<0196:COAROV>2.3.CO;2)
- Office of Management and Budget. (1993). Government Performance Results Act of 1993. Retrieved from <https://www.whitehouse.gov/omb/mgmt-gpra/gplaw2m>
- Office of Naval Research. (2015). *Naval S&T strategy: innovations for the future force*. U.S. Navy Office of Naval Research. Retrieved from <http://www.onr.navy.mil/About-ONR/~media/Files/About-ONR/2015-Naval-Strategy-final-web.ashx>
- Office of Technology Assessment. (1981). *Technology and oceanography: an assessment of federal technologies for oceanographic research and monitoring*. (No. NTIS order #PB82-101718). U.S. Government Printing Office. Retrieved from <https://books.google.com/>
- Office of Technology, Planning and Integration for Observation. (n.d.). NOAA Observing System Integration Analysis (NOSIA-II). Retrieved November 16, 2015, from https://nosc.noaa.gov/tpio/main/nosia_main.html
- OSHA. (n.d.). Formulas for Calculating Rates. Retrieved May 13, 2016, from http://www.nmmcc.com/wp-content/uploads/FORMULAS_for_CALCULATING_RATES1.pdf
- OSTP. (2016). R&D Budgets. Retrieved June 7, 2016, from <https://www.whitehouse.gov/node/8290>

- Oxford English Dictionary. (2016). Definition of obsolete. *OED Online*. Oxford University Press. Retrieved from <http://www.oed.com.mutex.gmu.edu/view/Entry/129929>
- Oxford English Dictionary. (n.d.-a). Definition of little science. Retrieved October 9, 2016, from https://en.oxforddictionaries.com/definition/us/little_science
- Oxford English Dictionary. (n.d.-b). Definition of submersible. Retrieved October 26, 2016, from <https://en.oxforddictionaries.com/definition/submersible>
- PBS UnderH2Oshow. (2013). *How to launch a 13-ton submarine part 1*. Retrieved from <https://www.youtube.com/watch?v=Y7fgQgwsEMQ&feature=youtu.be>
- Perry, J. H. J. (1996). *Never say impossible: the life and times of an American entrepreneur*. Legacywords Pub.
- Peterson, G. (2010, February 24). Visualization: a history of Stommel diagrams. *Resilience Science*. Retrieved from <http://rs.resalliance.org/2010/02/24/a-history-of-stommel-diagrams/>
- Piltch, A. (2013, May 28). 12 obsolete technologies americans still use. Retrieved from <http://blog.laptopmag.com/12-outdated-technologies-refuse-to-die>
- Pinsel, M. I. (1982). *150 years of service on the seas: a pictorial history of the U. S. Naval Oceanographic Office from 1830 to 1980, volume I (1830-1946)*, (First Edition edition). U. S. Government Printing Office,.
- Plait, P. (2015, October 7). A lesson in crewed language. *Slate*. Retrieved from http://www.slate.com/blogs/bad_astronomy/2015/10/07/manned_spaceflight_time_to_change_the_language.html
- Potts, T. (2016, February 16). 50th anniversary of SEALAB II: the evolution of the AQUARIUS Reef Base program. Retrieved September 6, 2016, from <https://www.oceannews.com/news/2016/02/16/january-feature-50th-anniversary-of-sealab-ii>
- Press, F. (1988a). The dilemma of the golden age. *Eos*, 69(23), 633, 641–642.
- Press, F. (1988b). The Dilemma of the Golden Age. *Eos*, 69(23), 633, 641–642.
- Pritzlaff, J. A. (1972). Submersible safety through accident analysis. *Marine Technology Society Journal*, 6(3), 33–40.
- Puglise, K. A., & Kelty, R. (2007). *NOAA coral reef ecosystem research plan for fiscal years 2007 to 2011* (p. 140). Silver Spring, MD: NOAA Technical Memorandum CRCP 1. Retrieved from

http://test.coris.noaa.gov/activities/coral_research_plan/pdfs/coral_researchplan.pdf

- Rao, V. (2009, April 21). How to draw and judge quadrant diagrams. Retrieved February 24, 2016, from <http://www.ribbonfarm.com/2009/04/20/how-to-draw-and-judge-quadrant-diagrams/>
- Reed, J. D. (2002, June 30). Seward's follies. *The New York Times*. Retrieved from <http://www.nytimes.com/2002/06/30/nyregion/seward-s-follies.html>
- Reed, J. K., & Frank, T. (2011, March 10). Johnson-Sea-Link submersibles tools for research and discovery: Summary of users, publications, documentaries and testimonials. Retrieved from <https://fau.digital.flvc.org/islandora/object/fau%3A2731>
- Reed, J. K., & Franks, T. (2010, January 27). External review 2010, HBOI ship and submersible use.
- Reed, J. K., Shepard, A. N., Koenig, C. C., Scanlon, K. M., & Gilmore, R. G. J. (2005). Mapping, habitat characterization, and fish surveys of the deep-water Oculina coral reef Marine Protected Area: a review of historical and current research. In P. D. A. Freiwald & D. J. M. Roberts (Eds.), *Cold-Water Corals and Ecosystems* (pp. 443–465). Springer Berlin Heidelberg. Retrieved from http://link.springer.com/chapter/10.1007/3-540-27673-4_22
- Reeve, M. R. (2000). *A chronology of the early development of ocean sciences at NSF*. National Academies Press (US). Retrieved from <http://www.ncbi.nlm.nih.gov/books/NBK208837/>
- Reynolds, J., Greene, H., Woodby, D., Kurland, J., & Allee, B. (2008). Workshop Report: Marine Habitat Mapping Technology Workshop for Alaska, April 2-4, 2007, Anchorage, Alaska. In J. Reynolds & H. Greene (Eds.), *Marine Habitat Mapping Technology for Alaska* (pp. 237–266). Alaska Sea Grant, University of Alaska Fairbanks. Retrieved from <http://www.alaskaseagrant.org/bookstore/pubs/AK-SG-08-03.html>
- Riley, J. (2016). Lo'ihi Seamount. Retrieved July 24, 2016, from <http://www.geo.arizona.edu/geo5xx/geos577/projects/riley/Loihi%20Seamount%20Web%20Page.htm>
- Rodriguez, G., & Weisbin, C. R. (2003). A new method to evaluate human-robot system performance. *Autonomous Robots*, 14, 165–178.
- Rountree, R., Juanes, F., & Blue, J. E. (2002). Potential for the use of Remotely Operated Vehicles (ROVs) as a platform for passive acoustics. Presented at the An

- International Workshop on the Application of Passive Acoustics in Fisheries.
Retrieved from <http://seagrant.mit.edu/cfer/acoustics/exsum/blue/extended.html>
- Rutgers University. (2008, May 6). NURP:Mid-Atlantic Bight National Undersea Research Center. Retrieved September 6, 2016, from <https://marine.rutgers.edu/nurp/mabnurc.html>
- Sacks, P. A. (1995). The Ocean Research Vessel Act of 1965: An inequitable result suggests reevaluation. *Theses and Major Papers. Paper 296*. Retrieved from http://digitalcommons.uri.edu/ma_etds/296/
- Safina, C., & Chasis, S. (2004). Saving the oceans: Two major commissions have proposed far-reaching reform of ocean policy. It's time for Congress to act. *Issues in Science and Technology*, 21(1), 37–44.
- Sangeeta. (2013, July 6). Difference between aspiration and inspiration [Text]. Retrieved October 15, 2016, from <http://www.differencebetween.info/difference-between-aspiration-and-inspiration>
- Sapolsky, H. M. (1990). *Science and the Navy: the history of the Office of Naval Research*. Princeton Legacy Library. Retrieved from <http://press.princeton.edu/titles/4595.html>
- Schmidt Ocean Institute. (n.d.). Schmidt Ocean Institute. Retrieved October 27, 2016, from <https://schmidtocan.org/>
- Schon, D. A. (1963). Champions for radical new inventions. *Harvard Business Review*, 41(2), 77–86.
- Schudel, M. (2015, February 21). John P. Craven, scientist who directed top-secret Navy projects, dies at 90 - The Washington Post. Retrieved from https://www.washingtonpost.com/national/john-p-craven-scientist-who-directed-top-secret-navy-projects-dies-at-90/2015/02/21/50083a20-b935-11e4-a200-c008a01a6692_story.html
- Schweinle, A., & Bjornestad, A. (2009, December 23). Flow theory. Retrieved September 14, 2016, from <http://www.education.com/reference/article/flow-theory/>
- Sedberry, G. (2004, September 1). NOAA Ocean Explorer: estuary to the abyss. Retrieved August 18, 2016, from <http://oceanexplorer.noaa.gov/explorations/04etta/logs/summary/summary.html>
- SERPENT. (2016). SERPENT: Deep sea research using ROVs. Retrieved July 14, 2016, from <http://www.serpentproject.com/default.php>

- Shepard, A. N., Dinsmore, D. A., Miller, S. L., Cooper, C. B., & Wicklund, R. (1996). AQUARIUS undersea laboratory: the next generation. In Lang, MA, Baldwin, CC, eds. *Methods and Techniques of Underwater Research 1996*. Washington D.C.
- Shepherd, K., & Juniper, S. K. (1997). ROPOS: Creating a scientific tool from an industrial ROV. *Marine Technology Society. Marine Technology Society Journal*, 31(3), 48.
- Singh, H., Can, A., Eustice, R., Lerner, S., McPhee, N., & Roman, C. (2004). SeaBED AUV offers new platform for high-resolution imaging. *Eos, Transactions American Geophysical Union*, 85(31), 289–296.
<https://doi.org/10.1029/2004EO310002>
- Slater, D. R. A. (2015). *Views from the conning tower: the adventures of a deep-sea explorer* (2 edition). Slater.
- Slovic, P. (1987). Perception of risk. *Science*, 236(4799), 280–285.
<https://doi.org/10.1126/science.3563507>
- Slovic, P., Fischhoff, B., & Lichtenstein, S. (1985). Perilous progress: managing the hazards of technology. In *Perilous Progress: Managing the Hazards of Technology* (pp. 91–125). Boulder, CO: Westview.
- Smith, J. (2005). *Applying the Hawai“i Undersea Research Laboratory”s 25 years of deep submergence science support toward achieving the goals of the Ridge 2000 integrated studies sites*. Presented at the Ridge 2000 Report: Progress & Planning Community Meeting, Vancouver, BC, Canada. Retrieved from http://www.ridge2000.org/science/downloads/workshop_reports/R2KVancouver2005.final2.pdf
- Somerton, D. A., & Glendhill, C. T. (2005). *Report of the National Marine Fisheries Service workshop on underwater video analysis* (NOAA Technical Memorandum No. NMFS-F/SPO-68) (p. 77). National Marine Fisheries Service. Retrieved from http://www.afsc.noaa.gov/Publications/misc_pdf/NMFS%20FSP0-68.pdf
- Soule, A. (2015). *Response to the National Academy of Science Ocean Studies Board Decadal Survey of Ocean Science report*. Input provided from WHOI to NSF OCE.
- Space Studies Board. (1994). *A space physics paradox: why has increased funding been accompanied by decreased effectiveness in the conduct of space physics research?* National Academies Press. Retrieved from <https://www.nap.edu/download/4792>

- Space Studies Board. (2007). *Earth science and applications from space: national imperatives for the next decade and beyond*. National Academies Press. Retrieved from <http://www.nap.edu/catalog/11820/earth-science-and-applications-from-space-national-imperatives-for-the>
- Space Studies Board. (2014). *Pathways to exploration: rationales and approaches for a U.S. program of human space exploration*. Washington D.C. Retrieved from <http://www.nap.edu/catalog/18801/pathways-to-exploration-rationales-and-approaches-for-a-us-program>
- Space Studies Board. (n.d.). NAS Space Studies Board reports by year. Retrieved January 31, 2016, from http://sites.nationalacademies.org/SSB/SSB_051650
- Spence, D. E. L. (2013). Submersibles debut at Monaco Yacht Show. Retrieved April 6, 2016, from <http://shipwrecks.com/tag/seamagine-hydrospace/>
- Stachiw, J. D. (2004). Effect of ASME PVHO-1 safety standard on the design of viewports in pressure vessels. Presented at the Underwater Intervention, New Orleans, LA: MTS/IEEE. Retrieved from http://www.hydroports.com/documents/New_Orleans_Meeting-Feb_2004.pdf
- Stanley, K. (2016). Roatan Institute of Deepsea Exploration: Mission. Retrieved April 6, 2016, from <http://www.stanleysubmarines.com/about/mission/>
- Staudenmeir, J. M. (1985). *Technology's storytellers: rewaving the human fabric*. Cambridge, Mass.: MIT Press.
- Stein, J. K., & Good, G. A. (1986). Government funding of scientific instrumentation: a review of U.S. policy debates since World War II. *Science, Technology, & Human Values*, 11(3), 34–46.
- Stokes, D. E. (1997). *Pasteur's Quadrant*. Washington D.C.: Brookings Institution Press.
- Stommel, H. (1963). Varieties of oceanographic experience. *Science*, 139(3555), 572–576.
- Strauss, A., & Corbin, J. M. (1998). *Basics of qualitative research: techniques and procedures for developing grounded theory*. SAGE Publications.
- Substation Curacao. (2016). Substation Curacao. Retrieved July 14, 2016, from <http://www.substation-curacao.com/>
- Takayama, L., & Ju, W. (2008). Beyond dirty, dangerous and dull: What everyday people think robots should do. In *HRI 2008 - Proceedings of the 3rd ACM/IEEE*

- International Conference on Human-Robot Interaction: Living with Robots* (pp. 25–32). <https://doi.org/10.1145/1349822.1349827>
- Talkington, H. (1976). *Manned and remotely operated submersible systems: a comparison* (No. AD-AO28 018) (p. 33). San Diego CA: Naval Undersea Center.
- Task Force on Science Policy. (1986). *A history of science policy in the United States, 1940 - 1985* (No. Science Policy Study Background Report No. 1) (p. 132). Committee on Science and Technology House of Representatives Ninety-Ninth Congress Second Session. Retrieved from <https://ia801407.us.archive.org/20/items/historyofscience00unit/historyofscience00unit.pdf>
- TEDx Talks. (2013). *Living in an underwater sea lab*. Retrieved from <https://www.youtube.com/watch?v=WmSY4GECQ4I>
- Teich, A. H. (1994). Priority setting and economic payoffs in basic reserach: an American perspective. *Higher Education*, 28(1), 95–107.
- Terry, R. D. (1966). *The deep submersible* (2nd ed.). Western Periodicals.
- The Engineer. (2012, May 13). Graham Hawkes, founder and chief engineer of Hawkes Ocean Technologies. Retrieved from <https://www.theengineer.co.uk/issues/14-may-2012/graham-hawkes-founder-and-chief-engineer-of-hawkes-ocean-technologies/>
- The Turing Institute. (1996, July 31). History of stereo photography. Retrieved May 23, 2016, from http://www.arts.rpi.edu/~ruiz/stereo_history/text/historystereog.html
- ThinkTech Hawaii. (2014). *Falkor at Loihi Seamount with Ken Rubin and Brian Glazer*. Retrieved from https://www.youtube.com/watch?v=8goc7kG7_po
- Thompson, G. N., Estabrooks, C. A., & Degner, L. F. (2006). Clarifying the concepts in knowledge transfer: a literature review. *Journal of Advanced Nursing*, 53(6), 691–701. <https://doi.org/10.1111/j.1365-2648.2006.03775.x>
- Thomsen, A., Nieboer, N., & van der Flier, K. (2015). Obsolescence – the underlying processes. Presented at the European Network for Housing Research, Lisbon, Spain.
- Thomsen, A., & van der Flier, K. (2011). Understanding obsolescence: a conceptual model for buildings. *Building Research & Information*, 39(4), 352–362. <https://doi.org/10.1080/09613218.2011.576328>

- Thomsen, A., Van der Flier, K., & Nieboer, N. (2015). Analysing obsolescence, an elaborated model for residential buildings. *Structural Survey, forthcoming*.
- Thwink.org. (n.d.). Definition of sustainability. Retrieved July 3, 2016, from <http://www.thwink.org/sustain/glossary/Sustainability.htm>
- Toye, S. (2000). *Ocean sciences at the National Science Foundation: an administrative history*. National Academies Press (US). Retrieved from <http://www.ncbi.nlm.nih.gov/books/NBK208803/>
- Travis, J. (1993). Deep-sea debate: its ALVIN against JASON. *Science, New Series*, 259(5101), 1534–1536.
- Trembanis, A. C., Forrest, A. L., Miller, D. C., Lim, D. S. S., Gernhardt, M. L., & Todd, W. L. (2012). Multiplatform ocean exploration: insights from the NEEMO space analog mission. *Marine Technology Society Journal*, 46(4), 7–19. <https://doi.org/10.4031/MTSJ.46.4.2>
- U-Boat Worx. (n.d.). Support vessels - U-Boat Worx. Retrieved October 10, 2016, from http://www.uboworx.com/Support_Vessels.shtml?lan=ENG
- UH Marine Operations. (2013, February 14). Lu‘ukai ROV. Retrieved from <http://www.soest.hawaii.edu/UMC/cms/h6000-rov/>
- UNCW SBTDC. (2007). *Aquarius Reef Base summit: strategic planning retreat report* (Local program manager records No. UNCW Small Business Technology Development Center). Islamorada, FL: UNCW, Southeastern Region 601 South College Road Wilmington, NC 29403-5977.
- Undersea Hunter. (n.d.-a). DeepSee submersible. Retrieved July 25, 2016, from <http://www.underseahunter.com/b187/introduction.html#.V5YIAY7WKAs>
- Undersea Hunter. (n.d.-b). Submarine DeepSee Cocos Island. Retrieved July 25, 2016, from <http://www.underseahunter.com/b187/introduction.html#.V5YFEY7WKAs>
- Uninspected Vessels (2015). Retrieved from <https://www.law.cornell.edu/cfr/text/46/chapter-I/subchapter-C>
- UNOLS. (1982). *UNOLS submersible science study*. UNOLS. Retrieved from https://www.unols.org/sites/default/files/Submersible_Science_Study_1982searchable_lo_res.pdf
- UNOLS. (1990). *Submersible science study for the 1990's*. Retrieved from https://www.unols.org/sites/default/files/199011des_searchable_lo_res.pdf

- UNOLS. (2009a, March). Research vessel safety standards - 9th edition. Retrieved from [https://www.unols.org/sites/default/files/2009RVSS_web2012updates\(1\).pdf](https://www.unols.org/sites/default/files/2009RVSS_web2012updates(1).pdf)
- UNOLS. (2009b, March). Unols safety standards for human occupied vehicles. UNOLS. Retrieved from <https://www.unols.org/document/unols-safety-standards-human-occupied-vehicles-2009>
- UNOLS. (2013). *UNOLS charter*. Retrieved from <https://www.unols.org/what-unols/unols-charter>
- UNOLS. (2015a). *UNOLS fleet improvement plan*. Retrieved from https://www.unols.org/sites/default/files/UNOLS%20Fleet%20Improvement%20Plan_12_01_2015_.pdf
- UNOLS. (2015b, July). Research vessel safety standards (RVSS) tenth edition. University National Oceanographic Laboratory System. Retrieved from <https://www.unols.org/document/research-vessel-safety-standards-rvss-tenth-edition-july-2015>
- UNOLS. (2016). UNOLS fleet improvement plan. Retrieved June 8, 2016, from <https://www.unols.org/documents/fleet-improvement-plans>
- U.S. Coast Guard. (1993, July 20). Guidance for Certification of Passenger Carrying Submersibles: Navigation and Vessel Inspection Circular No. 5-93. U.S. Coast Guard. Retrieved from <https://www.uscg.mil/hq/cg5/nvic/pdf/1993/n5-93.pdf>
- U.S. Coast Guard. (2016, March). Requirements for uninspected passenger vessels. Retrieved from https://www.uscg.mil/pvs/docs/UPV_GUIDEBOOK_under100GT_CGD11_rev2016.pdf
- U.S. Congress, Office of Technology Assessment. (1991). *Federally funded research: decisions for a decade*. Washington, DC: U.S. Government Printing Office.
- U.S. Department of Defense. (2016, July 3). Defense acquisition guidebook, Chapter 4. Retrieved from <https://acc.dau.mil/CommunityBrowser.aspx?id=638374>
- U.S. Human Spaceflight Plans Committee. (2009). *Seeking a human spaceflight program worthy of a great nation* (p. 157). NASA. Retrieved from http://www.nasa.gov/offices/hsf/meetings/10_22_pressconference.html
- Usability Body of Knowledge. (n.d.). Cognitive task analysis. Retrieved September 8, 2016, from <http://www.usabilitybok.org/cognitive-task-analysis>

- van Hoek, S., & Link, M. C. (1993). *From sky to sea: a story of Edwin A. Link*. Best Publishing Company.
- Vance, T. C., & Doel, R. E. (2010). Graphical methods and cold war scientific practice: the Stommel diagram's intriguing journey from the physical to the biological environmental sciences. *Historical Studies in the Natural Sciences*, 40(1), 1–47. <https://doi.org/10.1525/hsns.2010.40.1.1>
- Various. (2012). Argo design papers. Retrieved July 3, 2016, from http://www.argo.ucsd.edu/Argo_design_papers.html
- Vaughan, D. (1997). *The Challenger launch decision: risky technology, culture, and deviance at NASA* (1 edition). Chicago: University of Chicago Press.
- Video Ray. (2016). Video Ray Brochure. Retrieved April 6, 2016, from http://www.videoray.com/CB_Online/VideoRay_CBOnline.pdf
- Video Ray, E. E., Outland, B. M., SeaBotix, D. R., & Shark Marine Technologies, J. H. (2013, February). Underwater Intervention 2013.
- Vyborny, L., & Davis, D. (2004). *Dark waters: an insider's account of the NR-1, the cold war's undercover nuclear sub* (First Paperback Printing). New York: New American Library.
- Wagner, R. J., Randall, R. E., & Albaugh, E. K. (2000, December 1). Subsea production technology. Retrieved September 8, 2016, from <http://www.offshore-mag.com/articles/print/volume-60/issue-12/news/subsea-production-technology-work-rov-contractors-trying-to-evade-cycle-of-more-power-heavier-umbilicals-with-depths.html>
- Walsh, D. (1990). Thirty thousand feed and thirty years later: some thoughts on the deepest presence concept. *Marine Technology Society Journal*, 24(2), 7–8.
- Walsh, D. (2014, April 1). Diving deeper than any human ever dove. *Scientific American*. Retrieved from <http://www.scientificamerican.com/article/diving-deeper-than-any-human-ever-dove/>
- Walsh, D. (2016, September 21). Historical Quote.
- Ward, C. (2015, April 8). If the human eye was a camera, how much would it cost? Retrieved May 28, 2016, from <http://www.premiumbeat.com/blog/if-the-human-eye-was-a-camera-how-much-would-it-cost/>

- Water Encyclopedia. (n.d.). Submarines and submersibles. Retrieved October 26, 2016, from <http://www.waterencyclopedia.com/St-Ts/Submarines-and-Submersibles.html>
- Watkins, R. J. D. (2004). *An ocean blueprint for the 21st century* (p. 676). Washington, D.C: U.S. Commission on Ocean Policy. Retrieved from <http://www.oceancommission.gov/>
- Weber, B. (2013, April 3). Barbara Piasecka Johnson, maid who married multimillionaire, dies at 76. *The New York Times*. Retrieved from <http://www.nytimes.com/2013/04/04/nyregion/barbara-piasecka-johnson-maid-who-married-multimillionaire-dies-at-76.html>
- Weinberg, A. M. (1962). Criteria for scientific choice. *Minerva*, *I*(2), 158–171.
- Weitz, A. (2016). The photographic eye, how our eyes see vs. how our cameras see. Retrieved May 28, 2016, from <http://www.bhphotovideo.com/c/find/newsLetter/The-Photographic-Eye.jsp>
- Whitehead, S. (2009, October 3). The normalization of deviance. Retrieved September 14, 2016, from <http://theemtpot.com/2009/10/03/the-normalization-of-deviance/>
- Wicklund, R. I. (2012). *Eyes in the Sea*. Mariner Publishing. Retrieved from http://www.goodreads.com/work/best_book/18928394-eyes-in-the-sea-adventures-of-an-undersea-pioneer
- Williams, K., Rooper, C. N., & Towler, R. (2010). Use of stereo camera systems for assessment of rockfish abundance in untrawlable areas and for recording pollock behavior during midwater trawls. *Fishery Bulletin*, *108*(3), 352–362.
- Winner, C. (2014). Rebuilding Alvin: Jefferson Grau. *Oceanus Magazine*, *51*(4). Retrieved from <http://www.whoi.edu/oceanus/feature/alvin-viewport>
- Wong, A. (2014, February 10). Human-manned subs are being phased out — but at what cost for Hawaii? *Civil Beat News*. Retrieved from <http://www.civilbeat.org/2014/02/human-manned-subs-are-being-phased-out-but-at-what-cost-for-hawaii/>
- Woods Hole Oceanographic Institution. (2002). The discovery of hydrothermal vents. Retrieved July 24, 2016, from http://www.divediscover.whoi.edu/ventcd/vent_discovery/scientificrevolution/print/majordisc_life_p.html
- Woods Hole Oceanographic Institution. (2015a). History of ALVIN. Retrieved April 15, 2016, from <https://www.whoi.edu/page.do?pid=10737>

- Woods Hole Oceanographic Institution. (2015b, March 10). Research Submersible Alvin Completes Depth Certification to 4500 Meters. Retrieved January 13, 2016, from <http://www.whoi.edu/news-release/alvin-4500m>
- Woods Hole Oceanographic Institution. (2015c, September 24). Marine archaeologists excavate greek antikythera shipwreck. Retrieved January 19, 2016, from <http://www.whoi.edu/news-release/antikythera-shipwreck-excavation>
- Woods Hole Oceanographic Institution. (2016a). Human Occupied Vehicle ALVIN. Retrieved August 21, 2016, from <http://www.whoi.edu/main/hov-alvin>
- Woods Hole Oceanographic Institution. (2016b). JASON fact sheet. WHOI. Retrieved from <http://www.whoi.edu/fileserver.do?id=55543&pt=10&p=38332>
- Woods Hole Oceanographic Institution. (2016c). ROV JASON/MEDEA. Retrieved August 15, 2016, from <http://www.whoi.edu/ndsFVehicles/Jason/>
- Woods Hole Oceanographic Institution. (2016d). WHOI: JASON and towed vehicle operations summary. Retrieved May 26, 2016, from <http://www.whoi.edu/main/jason/operations-summary>
- Woods Hole Oceanographic Institution. (2016e, March 4). Alvin dive log & metadata. Retrieved March 3, 2016, from <http://www.whoi.edu/page.do?pid=10735>
- Woods Hole Oceanographic Institution. (n.d.). AUV SENTRY. Retrieved October 28, 2016, from <https://www.whoi.edu/main/sentry>
- Workman, W. T., & Maison, J. (1998). The use of pressure vessels for human occupancy in clinical hyperbaric medicine. *National Board of Boiler and Pressure Vessel Inspectors BULLETIN, 67th General Meeting 1998*. Retrieved from <http://www.nationalboard.org/>
- Wunsch, C. (2016). MIT EAPS directory Carl Wunsch. Retrieved from <https://eapsweb.mit.edu/people/wunsch>
- Wyanski, D. (2003, August 17). NOAA Ocean Explorer: investigating the Charleston Bump: mission summary. Retrieved August 18, 2016, from <http://oceanexplorer.noaa.gov/explorations/03bump/logs/summary/summary.html>
- Wynn, R. B., Huvenne, V. A. I., Le Bas, T. P., Murton, B. J., Connelly, D. P., Bett, B. J., Hunt, J. E. (2014). Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience. *Marine Geology*, 352, 451–468. <https://doi.org/10.1016/j.margeo.2014.03.012>

- Wynn, R. B., & Linley, E. (2013). *Global inventory of AUV and glider technology available for routine marine surveying* (Marine Renewable Energy No. Appendix 1). NERC. Retrieved from <http://www.nerc.ac.uk/innovation/activities/infrastructure/offshore/catalogue-of-auvs/>
- Xinhua. (2012, July 16). Submersible Jiaolong may dive in South China Sea in 2013. Retrieved April 6, 2016, from http://www.china.org.cn/china/2012-07/16/content_25924379.htm
- Yoder, J. A. (2002). NSF 03-014, Division of Ocean Sciences - Fall 2002 Newsletter. Retrieved from http://www.nsf.gov/pubs/2003/nsf03014/nsf03014_3.htm
- Yoklavich, M. M., Laidig, T., Watters, D., & Love, M. (2013). *Understanding the capabilities of new technologies and methods to survey west coast groundfishes: results from a visual survey conducted in 2011 using the dual deepworker manned submersible at footprint and piggy banks off southern california*. NOAA SWFSC. Retrieved from <https://swfsc.noaa.gov/publications/CR/2013/2013Yoklavich.pdf>
- Yoklavich, M. M., & O'Connell, V. (2008). Twenty years of research on demersal communities using the delta submersible in the northeast pacific. In J. Reynolds & H. G. Greene (Eds.), *Marine Habitat Mapping Technology for Alaska* (pp. 143–156). Alaska Sea Grant, University of Alaska Fairbanks. Retrieved from <http://www.alaskaseagrant.org/bookstore/pubs/AK-SG-08-03.html>
- Yoklavich, M. M., Reynolds, J. R., & Rosen, D. (2015). *A comparative assessment of underwater visual survey tools: Results of a workshop and user questionnaire* (NOAA Technical Memorandum No. NOAA-TM-NMFS-SWFSC-547) (p. 47). San Diego CA: NOAA SW Fisheries Science Center. Retrieved from <https://swfsc.noaa.gov/publications/TM/SWFSC/NOAA-TM-NMFS-SWFSC-547.pdf>
- Youngbluth, M. J. (1993). *National Undersea Research Program: a summary of research activities 1989-1990*. NOAA Office of Undersea Research.

BIOGRAPHY

Karen Marie Kohanowich received her Bachelor of Science in Geology from Vanderbilt University in 1982, a Master of Science in Air Ocean Sciences from the U.S. Naval Postgraduate School in 1995, and a Master of Science in Environmental Science and Policy from Johns Hopkins University in 2001. She has been a marine research and undersea technology director and manager at NOAA's Office of Ocean Exploration and Research and NOAA's Undersea Research Program since 2005. She has served as NOAA program manager for the *Aquarius* undersea habitat and Hawaii's Undersea Research Laboratory, chaired NOAA's AUV Working Group, and co-chaired the National Ocean Partnership Program (NOPP) federal working group and an interagency task force on ocean exploration and research.

Karen began her career as a U.S. Navy Diving and Salvage Officer, serving onboard USN and Canadian diving ships in the Western Pacific, Caribbean, and North Atlantic. She completed her Navy service as Navy Meteorology and Oceanography Officer, specializing in ocean policy, retiring from the service in 2005. She has been a NAUI SCUBA instructor, Navy parachutist, and pilot of the *Pisces IV* submersible. Karen was MTS's first Vice President for Government Affairs (2005-2010), and is a member of the Society of Woman Geographers and the Women Diver's Hall of Fame. She began the PhD program at George Mason University in 2010, and was awarded her doctorate in Environmental Science and Public Policy in 2016.