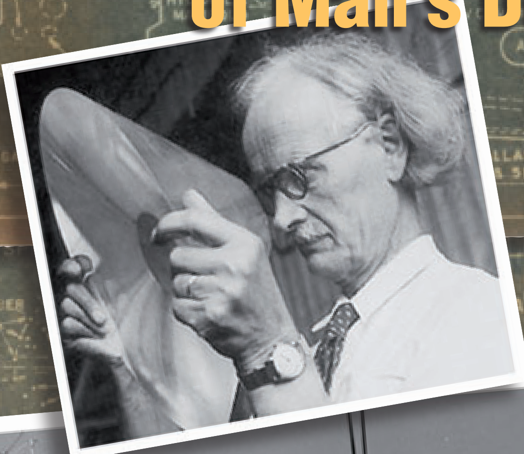
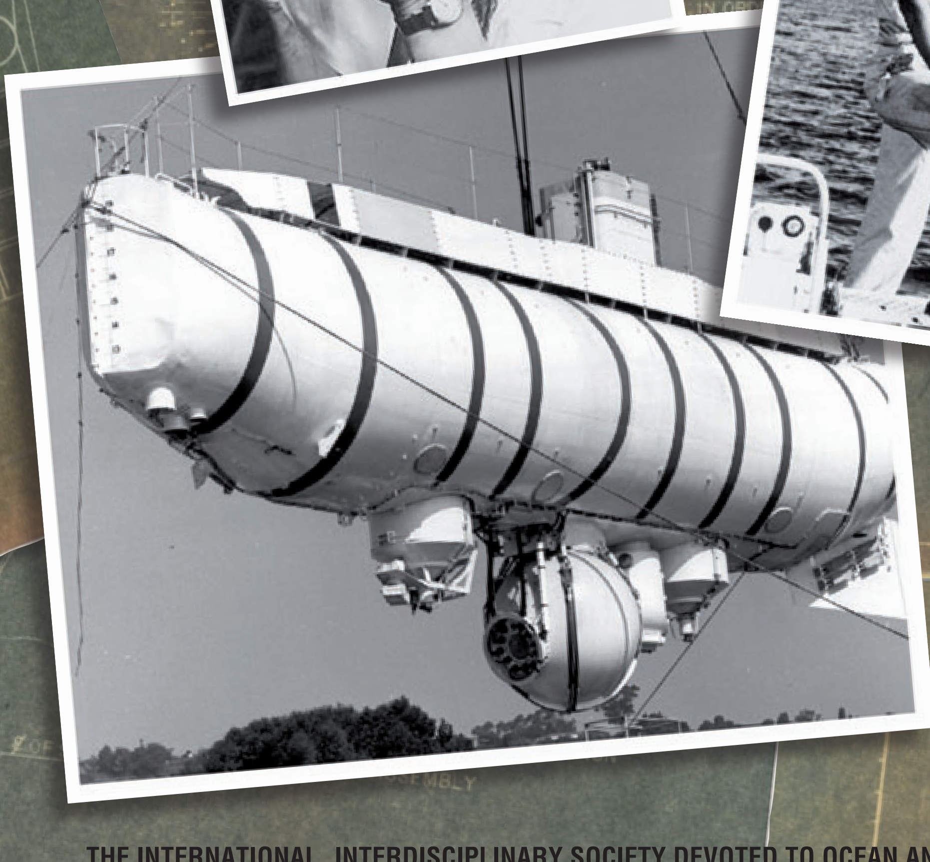
Marine Technology Society
JOURNAL

Into the Trench:
Celebrating the Golden Anniversary of Man's Deepest Dive





THE INTERNATIONAL, INTERDISCIPLINARY SOCIETY DEVOTED TO OCEAN AND MARINE ENGINEERING, SCIENCE, AND POLICY
VOLUME 43, NUMBER 5, WINTER 2009

Front Cover: Clockwise from top left: Inventor of the bathyscaph Swiss Professor Auguste Piccard examines one of the two acrylic plastic windows used to see outside the personnel sphere; *Trieste* Top Guns: Lt. Larry Shumaker, AOIC, Lt. Don Walsh, OIC and pilot on the Deep Dive, Dr. Andreas Rechnitzer, Project Nekton Director and *Trieste* Chief Scientist, and Jacques Piccard, son of Auguste and scientific observer on the Deep Dive; The bathyscaph *Trieste* as received at Sub Base-Point Loma, San Diego, California. (All photos: U.S. Navy) *Trieste II* blueprint background courtesy of Sheldon Rubin, SeaBotix, formerly with *Trieste II*.

Back Cover: Clockwise from top left: Plaque given to crew of *Trieste* commemorating the "Conquest of Inner Space, 35,800-feet, Challenger Deep, January 23, 1960" (photo: Andrea Rechnitzer Fry); Returning to Honolulu following the Deep Dive, wearing a Hawaiian lei, is *Trieste* Program Director Dr. Andreas Rechnitzer, shaking hands with RADM W.E. Ferrall USN, COMSUBPAC. Behind Rechnitzer, and also wearing leis, are *Trieste* AOIC Lt. Larry Shumaker and, to his right, *Trieste* OIC Lt. Don Walsh, pilot of the bathyscaph on the Deep Dive (photo: U.S. Navy); Sixth grade student Justin Linvill studies the operation of his model bathyscaph to learn the physics that brought *Trieste* back from the deepest ocean trench (photo: Kevin Hardy).

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Into the Trench: Celebrating the Golden Anniversary of Man's Deepest Dive

Guest Editors: Kevin Hardy and Brock J. Rosenthal

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The Marine Technology Society is a not-for-profit, international professional society. Established in 1963, the Society's mission is to promote the exchange of information in ocean and marine engineering, technology, science, and policy.

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Contributors can obtain an information and style sheet by contacting the managing editor. Submissions that are relevant to the concerns of the Society are welcome. All papers are subjected to a stringent review procedure directed by the editor and the editorial board. The *Journal* focuses on technical material that may not otherwise be available, and thus technical papers and notes that have not been published previously are given priority. General commentaries are also accepted and are subject to review and approval by the editorial board.

Message from the *MTS Journal* Editor

Justin Manley
***MTS Journal* Editor**
Liquid Robotics

Many events deserve to be celebrated. This special issue is a celebration of our community's accomplishments in the deep ocean. Science, technology and the spirit of adventure have motivated great achievements. I am most appreciative to Kevin Hardy and Brock Rosenthal for their efforts as guest editors. I hope you enjoy the papers, commentaries, technical notes, and historical reviews as much as I did.

For myself there is another moment worth celebrating, or at least acknowledging. This issue marks my last as Editor of the *Marine Technology Society Journal*. Over the 3 years I have served in this role, we have seen many changes. I believe these have strengthened the publication and the value of membership in our society. Just as this issue looks back over decades of achievement, I would like to take a moment to review the recent history of the *Journal*.

Since 2006, we have created a regular focus on the state of technology with bi-annual special issues. We created new concepts including our "best of conferences" issue and an issue dedicated to the work of our student members. To accommodate these new ideas, and the many excellent general papers we receive, we have expanded our publication to six issues each year. Fifty percent more material for our readers at no additional cost—that is change I believe in.

Another major development has been our move to a new digital platform. While digital versions of the *Journal* were available many years ago, we have substantially improved this service. We are making our archives available and slowly digitizing our way back to the earliest editions of the publication. Combined with improved search capabilities and readability, the new digital format has been positively received by our readers. The new format has also been a major attraction to institutional subscribers. We have seen many new organizations signing on to receive the *Journal*. This both strengthens the finances of our society and brings our flagship publication to more readers.

I have been honored to lead the *Journal* through these changes, but I have not done it alone. Throughout my tenure, I have been supported by exceptional guest editors and my colleagues on the editorial board (of which I will remain a member). It would not be possible to remark upon this experience without offering the most profound thanks to Amy Morgante. As our managing editor, she is the behind-the-scenes glue that holds this publication together. To steal a notion from the nautical realm, we call the *Journal* our flagship publication; if I am the captain, Amy is the executive officer. Those of you with seagoing experience know how valuable a good executive officer is to the ship. For those unfamiliar, all I can say is the *Journal* could not be what it is without her. Amy, thank you for steering me clear of the rocks, helping me weather the occasional storm, and making headway to the next destination.

I leave the *Journal* well positioned for continued success and I look forward to supporting the next editor. I prefer not to pull back the curtain and will leave it to my successor to introduce himself and his ideas. Suffice it to say, I have every confidence this publication is in great hands and I look forward to many more years of exceptional reading.

Live Like You Mean It

Kevin Hardy
Guest Editor
DeepSea Power & Light

What says that better than the lives of the ocean trench explorers of *Trieste*? Our *Journal* team asked before we started, "What can be written about such an historic event that hasn't already been done in the past 50 years?"

Great books covered the topic, "Seven Miles Down" (Jacques Piccard and Robert Dietz), "Earth, Sky and Sea" and "In Balloon and Bathyscaphe" (Auguste Piccard), "Half Mile Down" (William Beebe), "The World Beneath the Sea" (Otis Barton), and "Two Thousand Fathoms Down" (Georges Houot and Pierre Willm). MTS produced a *Journal* issue on the occasion of the 35th anniversary, reflected on in this issue by Jack Jaeger.

Many of the *Trieste* pioneers belonged to MTS during their careers, and a lot still do. So it was understood we could not pass by this golden anniversary without reflecting once again on what transpired under blue skies and black water in the western Pacific and taking account of what came to pass because of it. Surely, the bow wave of those days in the deep continues to roll forward through time.

The collective authors in this issue examined the "why" and "how" of *Trieste*. They considered "what *Trieste* unleashed." They went back in time to important relevant events that preceded *Trieste* and looked ahead to ways *Trieste* still influences the future. In all, this collection of notable authors covers a century and the globe.

In this issue, you will find very interesting, unpublished work from the time when bathyscaphs ruled the deep sea. Other stories detail manned vehicles, unmanned free vehicles, remotely operated vehicles, and autonomous underwater vehicles that dwell in the dark halls of the hadal depths, forbidden to terrestrial air breathers.

We are delighted to publish the work of two middle school science teachers who developed a new and innovative hands-on project to teach concepts of buoyancy based on bathyscaphs. Perhaps some pre-teen students will discover they have a knack for ocean science and engineering and pursue a career that could well extend into the latter half of this 21st century. We suggest that MTS include such projects in future issues of the *Journal*.

Finally, many thanks to my good friend and co-guest editor, Brock Rosenthal, for his continued collaboration; Amy Morgante, the outstanding *MTS Journal* managing editor; and Justin Manley, the youthful and energetic *MTS Journal* editor. I point to the center of my galaxy for 30 years, Michelle. She's the first to see the glint in my eye as I ponder a big project and asks "What are you up to now?" Our offspring, Jason and Kristin, vigorous young adults, flourish in a world enriched by the contributions of themselves and many. Give more than you take, and we all live in a better place.

I gratefully acknowledge the contributions of Loralee McAuliffe for her artwork and graphics skills, Sheldon Rubin for the *Trieste II* blueprints that appear on the cover, and Anne Cressey and Carolyn Rainey from the Scripps Institution of Oceanography. This editor's sincere thanks are extended to Mark Olsson, Scripps graduate, protégé of Professor John Issacs, researcher of the Challenger Deep, innovator and entrepreneur, for his insights, encouragement, and patronage of this academic enterprise.

It has been a privilege to work on this *Journal* commemorating the 50th anniversary of the deepest dive ever made by man. I hope you enjoy it.

Co-Guest editors Brock Rosenthal and Kevin Hardy.

INTRODUCTION

How Deep Is Deep?

AUTHOR
Brock J. Rosenthal
Guest Editor
Ocean Innovations

As a marine technology professional and history buff, I am happy to say that this special *MTS Journal* issue combines two of my favorite interests. Thus, when I learned from Kevin Hardy what he had in mind to commemorate the anniversary of the Deepest Dive, I did not hesitate to jump in when he asked if I would help.

In order to explore the deep ocean, one has to know where to find it. Measuring the depths, or hydrographic surveying, is speculated by some to be the world's second oldest profession. Before crossing a river, people in ancient times undoubtedly used a stick to probe the waters to determine depth. And thousands of years ago, the Egyptians were known to navigate their cargo vessels through the Nile using papyrus charts on the basis of depth soundings taken by measuring pole.

It is interesting to note that despite this early start in hydrography, throughout most of history, mankind had no idea of what depths the oceans contained—in a very literal sense, they were unfathomable. Soundings were taken to find shallows where vessels might get grounded. There was no reason to plumb the depths until the 1870s when routes for transoceanic telegraph cables were contemplated. At this same time, the first voyages specifically for oceanographic research were conducted.

The classic method for measuring depths was with a lead line, which consisted of a length of rope with a weight, or plummet, at the end. When the line went slack and stopped running out, the length of rope in the water was measured as it was pulled back in. This technique worked fairly well in shallow waters. At deeper depths, the weight of the rope in the water would exceed that of the plummet, making it difficult to determine when the bottom was reached. In addition, the currents working on long lengths of line would cause it to continue to pay out after the weight reached the bottom. Accurate measurements were further complicated by the longer times needed to deploy and recover the lead line. Since there was no way to keep the vessel stationary in deep water, the ship's movement would have to be factored in as well.

Using a lead line for sounding was the state of the art for hundreds of years until the Victorian age when the development of iron wire rope and steam-driven winches changed the game. Designing these so-called sounding machines attracted some of the leading intellects of the era. Their inventions were used until the early 20th century when acoustic methods were developed.

The Challenger Expedition of 1872–1877 was one of the first to report on the depths of deep ocean trenches. The British survey ship *Challenger II* surveyed the Marianas Trench near Guam in 1951 and identified the deepest known point in the ocean at 35,800 feet. This was named the Challenger Deep.

Our *Journal* issue picks up the story from here. We are very fortunate to have as contributors to this issue some of the pioneers of exploring and researching the deepest reaches of the ocean. I hope you enjoy reading this issue as much as we did putting it together.

In the Beginning… A Personal View

AUTHOR
Don Walsh[1]
Bathyscaph Trieste Officer-in-Charge, 1959-1962
International Maritime Inc.

I have been fortunate to be active in the world's deep submergence community since its very beginnings a half-century ago. However, I will admit in advance that my recollections may differ from those of others. In some ways, it is difficult for a participant in historical events to avoid errors of omission and fact. What I offer here is how I saw my years with the Navy's bathyscaph program. Hopefully, I can add a little bit to the existing record of lessons learned and progress made so long ago.

This history began in January 1958 when the Navy's Office of Naval Research (ONR) purchased the *Bathyscaph Trieste* from its inventor, Professor Auguste Piccard and his son, Jacques. By that summer, it had been shipped from Naples to San Diego to begin its new life with the U.S. Navy.

In addition to *Trieste* and its supporting equipment, ONR hired Jacques Piccard as a consultant to train our Navy team to operate and maintain it. Jacques brought with him his chief mechanic, Giuseppe Buono.

I became aware of the Navy's *Trieste* program that summer. I was a lieutenant serving in submarines at San Diego and assigned temporary duty with the staff of Submarine Flotilla One commanded by Captain Ralph Styles USN.

It was a summer afternoon when a Dr. Andreas Rechnitzer came to my office on board the submarine tender *Nereus*. He was from the nearby Naval Electronics Laboratory (NEL) and was the *Trieste* program manager there. He asked if he could brief Commodore Styles about the newly acquired bathyscaph which was one of only two manned submersibles in the world.

Since SUBFLOT ONE was the primary submarine force command on the West Coast, "all things underwater" were of interest to the commodore and his staff. So Commodore Styles invited Andy to do the briefing at lunch on board *Nereus*. He also invited Jacques Piccard and me to join them.

The briefing went very well. Andy's presentation about this strange new device was energetic and lucid. Ever the entrepreneur, he arranged for a barge carrying the disassembled *Trieste* to be temporarily brought alongside *Nereus*. The submersible had just arrived from Italy and was being moved down the harbor to NEL that day. As we looked over the side of the tender at the collection of metal components, I thought it all looked like an explosion in a boiler factory.

At the end of the visit, Commodore Styles asked how he might help. The answer was immediate! Andy hoped to get two qualified submarine officers and a few enlisted personnel assigned to his project. While scientists at the laboratory would determine the scientific projects, the military team would operate and maintain *Trieste*. In his view, submariners would be as close as the Navy could get to a job description for "bathyscaph pilots."

I was ordered to send a message to all the submarines on the West Coast asking for volunteers. Remarkably, there was only one. Good news for me—this was my chance to get away from behind my desk. I volunteered and was selected for the program. Regrettably, I was not present for *Trieste*'s first U.S. Navy dive in December 1958.

A month later, I reported to NEL and shortly thereafter was designated as *Trieste*'s Officer-in-Charge (O-in-C). The project was in the early stages of setting up its operating homeport at the waterfront. It was a very busy time as a complete support infrastructure was put into place.

Andy had recruited a few permanent civilian staff for his team. They joined Jacques Piccard and Giuseppe Buono and began to learn about the "care and feeding" of this strange new scientific platform.

The first Navy person in our group was Senior Chief Petty Officer E. John Michel. An inventive and brilliant machinist, he had been recruited by Andy just before I joined NEL. I then got submarine officer Lieutenant Larry Shumaker to be assigned as the Assistant Officer-in-Charge. By late spring of 1959, we had added another chief petty officer and a first class boatswain's mate.

As one of only two deep diving manned submersibles in the world

[1]The Marine Technology Society additionally acknowledges Don Walsh for serving as this Journal's Editor from 1976 to 1980.

(the other was the French Navy's FNRS-3 bathyscaph), our "school of the bathyscaph" was more of an apprenticeship than formal learning. At times, it seemed that I spent more time in overalls than in my Navy uniform, but Larry and I were used to this as that is how we qualified in submarines to earn our gold dolphins.

In March, I had my first dive. It was to a depth of about 4,000 feet, but I was very impressed! I had little knowledge of ocean depths beyond where a submarine could safely operate. My last submarine had a maximum operating depth of 300 feet. So as long as there was a comfortable amount of water under the keel at that depth, then that was all I needed to know about depths. Yet only 10 months later, I would be diving in *Trieste* to a depth of nearly 7 miles!

I did not know about the proposed deep dive project when I reported to NEL. Andy had not mentioned it in his briefing to the commodore. It turned out that there were good reasons for this. While the Piccards and ONR representatives had discussed this when the *Trieste* was purchased, the Navy's top policy levels were not aware of it. Curiously, we did have the ONR funding to do the necessary modifications of the bathyscaph.

It was very fortunate that the oceans' deepest spot, Challenger Deep, was only about 200 miles from the Island of Guam, because there was a major Navy presence there. It would be relatively easy to establish our operating base at the Naval Ship Repair Facility waterfront.

Once organized on site, we would begin a series of progressively deeper test dives to work our way down to the bottom of the Marianas Trench. If we could get set up at Guam by late summer of 1959, then we should be able to do the deepest dive by January 1960.

Early 1959, our project was named "Project Nekton" after the free swimming creatures in the sea. It was a generic name that barely fit the underpowered *Trieste*. NEL geologist Dr. Robert Dietz had suggested the name. Earlier he had been stationed at the London ONR office and had been instrumental in the purchase negotiations with the Piccards.

Originally, *Trieste* had a depth rating of about 20,000 feet. The Piccards claimed it could safely make the dive to the planned depth of 36,000 feet. Nevertheless, it was decided to get a new sphere from the Krupp Works in Germany. They were the only supplier who could produce it on time and within our budget.

Also the float (balloon) had to be enlarged to provide the buoyancy needed for greater depths. This work was done, based on our design requirements, at the Navy's Ship Repair Facility in San Diego.

Meanwhile, back at NEL, the *Trieste* team was busy working to develop new on-board equipment, sensors, and samplers. It was slow going; there were no "off-the-shelf" suppliers. Our small team had to design and build everything using the NEL shops or local businesses that could build from our specifications.

On the operational side, I worked with Andy and Larry to prepare a proposal to get Navy Department approval for Project Nekton. We developed an operating plan and got it approved by the laboratory's top management. When it was forwarded to Washington, I went back there to help push things along.

To my surprise, I was quickly passed up through the offices of commanders, captains, and admirals at ONR and the Office of the Chief of Naval Operations. No one wanted to make the final decision. Ultimately, I, a lieutenant, ended up in front of Admiral Arleigh Burke, Chief of Naval Operations.

Admiral Burke asked me who would be making the dive. I replied that I, as the Navy commander of *Trieste*, and Dr. Rechnitzer, our chief scientist, would be on board. Furthermore, I told him that Lt. Shumaker would be in charge of topside activities. Burke then said, "I want you to tell Shumaker that if the *Trieste* does not come back, then you, Walsh, are the lucky one because I will have Shumaker's balls."

Regrettably, Andy did not make the dive because Jacques Piccard invoked a clause in his contract with ONR that gave him the right to make any dives that were "different or unusual." So Admiral Burke mandated that Jacques and I would dive, even though I had said I would step aside in favor of Andy. He was a CDR in the Naval Reserve and the Navy could have ordered him to active duty. Then we would still have had a naval officer on board. However, the Navy did not agree to that. Very sad, as Andy deserved to be there.

After I had briefed Admiral Burke about Project Nekton, he reluctantly agreed to let us proceed. However, he stipulated that there would be no Navy publicity in advance of successful completion of the deepest dive. The "no publicity" mandate was fine with us; media attention would interfere with our tight timetable for getting out to Guam. The important thing for us was having the highest level approval for going to the oceans' greatest depth.

By summer 1959, all of this work converged at NEL's waterfront. *Trieste* was reassembled for testing and a harbor test submergence, followed by an 800 foot offshore dive. Everything was satisfactory, and on October 5th, *Trieste* was sent by ship to Guam. Then the project team flew out there to set up our operating base in Apra Harbor.

By late October, the bathyscaph was reassembled and our test diving program began. By the end of the year, we had done eight test dives. The deepest was in November when Andy and Jacques Piccard dove to 18,150 feet to set a new world's depth record. The previous record was held by the French FNRS-3 with a 1954 dive to 12,300 feet.

Up to this point, our dives had been relatively trouble-free, but on this one, we ran into a big problem. The Krupp sphere was made of three pieces; instead of a mechanical fastening, they were glued together with epoxy cement. After surfacing from the dive, the glued joint failed with a great bang. At the time, the cause of the noise was not evident, but once back in harbor, we found evidence that water had seeped into the sphere along the glued joint. We needed to dry-dock *Trieste* and figure out if we could fix the problem. Also we decided not to bother our masters at NEL with this particular situation. Most certainly this would have been the end of Project Nekton.

John Michel figured out a brilliant although unorthodox fix using local materials. He built a series of metal bands that would mechanically hold the sphere sections together after putting automotive gasket compound and rubber strips along the two joints' external surfaces. Using a forklift holding a piece of timber as a "battering ram," he "bumped" the sphere sections until they were out of alignment by only a few thousands of an inch. Considering that the sphere thickness was between 5 and 7 inches, we were confident that we had a good and safe fix. Even at this point, we did not tell NEL what had happened.

In December, our final dives were to test the sphere fix and to do pilot training dives in Apra Harbor. While Jacques Piccard had gone back to San Diego for Christmas, the rest of the team stayed at Guam. We needed that time to get our equipment ready for January dives to the Nero Deep and Challenger Deep.

On the 8th of January, the Navy tug *Wandank* (ATA-204) and the destroyer escort *Lewis* (DE-535) left Apra Harbor for the Nero Deep. *Wandank* towed *Trieste* at a stately 5 knots while *Lewis* acted as our "command ship" for most of our group.

We reached the dive site on the 9th, and with well-practiced moves, the bathyscaph was quickly rigged for a dive. With Jacques and myself aboard, we submerged. The bottom was sighted at 23,000 feet, but we did not land. We wanted to keep this final test dive as brief as possible to quickly get back to Guam to prepare for the final dive.

On January 20, our little convoy again left Guam for the more distant dive site of the Challenger Deep. *Lewis* went ahead of the slow moving *Wandank* so we could do our depth soundings to find the "exact" location of the deepest part of the site.

Lewis did not have a depth sounder capable of measuring such great depths. So Andy arranged to use 1-pound blocks of TNT and stopwatches to time the explosions and their return echoes. Watches were started when the block exploded and then stopped when the return echo was heard on the ship's fathometer hydrophone. So 12 seconds was deeper than 10 seconds and so on. A few days later when *Trieste* arrived on site, Andy had figured out that the "target zone" was about a mile wide and 7 miles long.

Trieste was quickly disconnected from its towing line, and team members went aboard to prepare for the dive. The first order of business was to inspect for any towing damage. Many of the external equipment items were very fragile. Even at a towing speed of 5 knots, something could have been ripped off en route to the dive site. We found a few items missing but none were mission critical.

The sea state on site was six to seven, so we needed to get started as soon as possible to avoid any additional damage. The dive started at about 0800 h with Jacques and myself on board. It was the 23rd of January, 1960.

Initially, our trim was good, but then we had a problem getting through the thermocline as *Trieste* was only slightly negatively buoyant. We valved off a little gas to get heavy, and finally, we were on our way at a good rate of descent.

The dive proceeded smoothly until about 31,000 feet when a great bang shook the submersible. We looked at each other and our instruments. All seemed well, so we proceeded with the dive. We touched down smoothly after near 5 hours. Then another surprise, the depth gauge read 37,800 feet! Had we found an even deeper spot? Later, we found out that the depth gauge had been calibrated in Switzerland using distilled water. Correcting for the density difference between that water and seawater, our actual depth was about 2,000 feet less.

Once on the bottom I found out what the "big bang" was. It was a cracked window at the back of the entrance tube that led down from topside to the hatch on the sphere. This tube was flooded during the dive and had a curved acrylic window at the back. This let us look through the port in the hatch to the rear of the bathyscaph to check the aft ballast tub and the external lights.

Sea pressure acting equally on the inside and outside faces of the large window had caused the acrylic to creep against its steel frame. There was not enough slack room in the frame to accommodate this movement, and the stored up stress resulted in the bang as the window cracked.

The problem was not our immediate safety. However, we might not be able to let ourselves out of the sphere when back on the surface. If not, we would remain in the sphere until we got back to Guam and could dry-dock *Trieste*. This might be 5 to 7 days. It was not an attractive prospect…

After 20 min on the bottom, we made a quick three-and-a-half hour trip back to the surface. Once there, we used compressed air to carefully blow the water out of the entrance tube. The cracked window held and we quickly left the sphere, shut the hatch, and went topside.

Once on the surface, the sea state had increased to about 8 and we could not see any sign of *Wandank* or *Lewis*. It was a lonely feeling after our 9-hour dive. Before leaving Guam, I had gotten an aviator's emergency transmitter and advised Navy and Air Force units about our operational plans. As a result, there were aircrafts in the area when we surfaced. They quickly spotted us and vectored the ships to our location.

Why did we only spend 20 min at the bottom? There were three reasons: length of day, sea state, and bottom sediment.

Although we were in the tropics, it was wintertime. The days were shorter and the sea state was pretty rough for our operation. Therefore, we wanted as much daylight as possible for dropping the tow before the dive and to hook up the tow afterwards. The 1-inch towing wire had to be hand connected to *Trieste* with some of our team members hanging over the front of the vehicle. The other end of the wire was attached to a large towing ship. The possibility of injuring someone would be greatly increased in poor light.

The third reason was the character of the bottom sediment where we landed. It was a "diatomaceous ooze," very fine and light colored. As we landed, a cloud of sediment was stirred. This happened with all of our dives and usually after a few minutes it would drift away. Not this time. The cloud remained for the entire time on the bottom and showed no signs of moving away. It was like looking in a bowl of milk. So there were no photographs or direct observations of the sea floor other than just before landing.

With some difficulty, the tow was hooked up while there was some daylight left. Most of us left the area on board *Lewis*. We had to hurry back to port. Once the Navy Department knew we had been successful, Andy, Jacques, Larry, and I were ordered back to Washington to give briefing reports to various officials. A Navy transport aircraft was sent to Guam to fetch us.

Our trip to DC was via San Diego so we could report to our dedicated supporters at NEL. These were the people who really helped make this project a success. It was a grand homecoming with those most closely associated with Project Nekton.

At Guam, we never had more than 14 civilian and military personnel on our team at any given time. There were long working days with virtually no weekends off. But we got the job done because we had a great group of colleagues with a shared sense of mission. Now we had done what we said we would do and we did it on schedule. That feeling of success on behalf of the whole team and those others who believed in us was something very special.

An interesting special event happened while we were in Washington. The second morning there, a black official car picked us up at the hotel. We expected here would be another day of official briefings. Instead, we were driven to the White House where President Eisenhower presented the four of us with awards. As a *quid pro quo*, we gave him one of the American flags we took on the dive.

Another memorable occasion was when we called on Admiral Burke. To say the least, he was delighted that we had actually done it. He also seemed especially relieved that a junior civil service oceanographer and two Navy lieutenants had actually carried off this "first." We gave him one of the flags…

After the Washington events, ONR consultant Jacques left the *Trieste* program. However, Giuseppe stayed with us. Andy, Larry, and I returned to Guam for Project Nekton II. We planned to make more dives up to the beginning of the typhoon season then pack up the project and come home to San Diego.

For some reason never revealed to me, the Navy decided *Trieste* could not dive deeper than 20,000 feet. Perhaps it was because they did not like our "field fix" for the sphere. However, Larry and Andy did make a dive to that depth as part of our second series at Guam.

Upon returning to NEL, we began on a comprehensive upgrade project for *Trieste*. This work was based on "lessons learned" during the very arduous diving programs at Guam. We had many improvements that we wanted to make so *Trieste* could be an even more effective deep research platform.

The work took several months, and we developed or added several "firsts" for submersibles. These included the following:

- The first submersible manipulator, built by General Mills.
- The first CTFM sonar, which we procured from Straza. As I recall, Larry Shumaker took the government check for $20,000 and personally gave it to John Straza.
- High pressure housings for underwater cameras and lights. For quality insurance, we built our own precision high pressure test facility using a sawed-off 12-inch gun barrel from a battleship. Larry found it at a Navy ammunition depot in Idaho.
- Underwater connectors and penetrators capable of maximum ocean depths. These were developed by companies based on our specifications. Some of them became big names in that business.
- The design of the ROV *Tortuga*, one of the very first ROVs; it was designed to "fly off" from the *Trieste*. At that time, NEL was the leading developer of ROV technology in the United States.
- A variety of *in situ* samplers and sensors for on board collecting of physical samples and data while submerged.
- One of the first deep ocean color television camera systems.
- Refinement of the design, manufacture, and use of pressure compensated motors, battery pods, and external electrical systems.
- Development of underwater light systems that could operate effectively at high pressures.

There were many more developments too numerous to list here. Suffice to say that even today I can see our faint "fingerprints" on undersea vehicles all over the world. I make no claim that our group was the best or most innovative in undersea technology. As *Trieste* was one of only two manned submersibles in the world, if we needed stuff we had to develop it ourselves. Literally, necessity was the mother of invention. That is the burden of pioneers.

In addition to the development of hardware, our small group at NEL also helped develop new capabilities in underwater operations for others:

- Andy, Larry, and I developed the baseline design for a *Trieste* replacement. By late 1961, we realized that there were improvements that simply could not be made to the original and 8-year-old bathyscaph. *Trieste II* would have more of everything although its depth rating would be limited to 20,000 feet. We were not with the program when it was delivered to NEL, but as built, it embraced most of what we had proposed. Built by the Naval Shipyard at Mare Island, California, it was christened at the NEL waterfront in early 1964.
- The three of us also developed a conceptual design for a small submersible to supplement *Trieste*'s capabilities. The bathyscaph was far too fragile to do day-to-day operations off San Diego. We proposed to ONR that the Navy procure a 6,000 foot submersible that would be operated by the *Trieste* group. We called it *Sea Pup.* I took the proposal back to ONR and they liked it very much. Too much… Instead of NEL, the project went to Woods Hole Oceanographic Institution and a greatly changed *Sea Pup* became *Alvin.* I still have a copy of the original proposal in my "personal archive." Certainly, I do not claim we "invented' *Alvin*. A great team at WHOI made it into the world's most productive manned research vehicle. However, our *Trieste* team was most certainly present at the beginning.
- Our *Trieste* group was also host to several individuals and organizations interested in developing manned submersibles. Two naval reserve submarine officers, Bill Rainnie and Art Markel, did their annual active training duty with us. Bill was to run the *Alvin* Program at WHOI and Art was in charge of the Reynolds *Aluminaut* submersible for that company.
- During our time with the NEL project, Andy, Larry, and I spent a lot of time giving lectures, speeches, and talks all over the United States to help spread the "gospel" on the importance of deep ocean exploration. At the time, we had easy access to all types of media since our deepest dive was a "hot prospect." We used this access to the maximum extent possible to "advance the cause" of undersea vehicles.

Trieste resumed diving operations off San Diego in the late spring of 1961. The bathyscaph was now a proven platform, and our operations would support oceanographic research.

In mid-1961, there came one mission that I had to turn down. In July, Astronaut Gus Grissom's capsule sank after his splashdown in the Atlantic. NASA asked the Navy if *Trieste* could locate it and assist in the recovery.

While the water depth was no problem, we simply had no way to get the bathyscaph to the dive site. It was too far from any land support base. A proper mother ship was needed for the *Trieste*, and this never happened during its 5-year career with the U.S. Navy.

Now it was also time for some personnel changes. Gradually, the old team was getting dispersed. Later that year, Andy left for a very good position with North American Rockwell. NEL's Art Nelson took over as project manager.

Then in early 1962, Larry returned to submarine duty. His replacement was another submarine officer, Lieutenant George Martin, who became Navy submersible pilot #3.

In the spring of 1962, my relief as O-in-C *Trieste* reported to NEL. Lieutenant Commander Don Keach was a submarine officer who had gotten a brief postgraduate course in oceanography from the University of Washington. Don, submersible pilot #4, commanded *Trieste* until its retirement at NEL after the *Thresher (SSN-563)* wreck investigation in 1963.

By my estimation, over 200 manned submersibles were developed worldwide from the early 1960s onward. And it is with some pride that I can see faint traces of *Trieste* in most of them. Yes, we set a perhaps unbeatable world record, but more importantly, we showed the way into the oceans' greatest depths.

Two more bathyscaphs, both called *Trieste II*, would continue to serve the Navy until mid-1984 when the last one was retired. Remarkably, they operated these pioneering manned submersibles for a total of 26 years. However, the stories of those later years are for others to tell…

While I was with the *Trieste* program for slightly over three and a half years, it seemed much longer. We did so much in that short time… Returning to submarine duty seemed quite tame after all the excitement of deep ocean exploration. I am happy that I was part of the beginning.

REMINISCENCE

U.S. Navy Involvement With DSV *Trieste*

AUTHOR

Charles B. Bishop
CAPT USN Ret.

In 1957 Jacques Piccard was operating *Trieste* based in Naples, Italy. His support was quite limited, consisting of free aviation gas from an Italian company and towboat support from the Italian Navy. *Trieste* carried the company's logo on her sail and flew the Italian flag. He had been informed that further Italian Navy support would not be available. When word of this came from ONR London, RADM Rawson Bennett, Chief of Naval Research, decided to investigate its potential for naval research.

At that time I worked for CNR in the Undersea Warfare Branch and had a trip to Scotland planned to make an evaluation ride in HMS *Explorer*, one of two British submarines with hydrogen-peroxide power plants. My orders were changed to visit Naples first and evaluate the *Trieste*.

On arrival at the Naples train station, Jacques Piccard met me and took me directly to an appointment with the Italian Navy Vice Admiral who was the local area commander.

After a three-way discussion in French, Italian, and some English, the Admiral agreed to provide towboat support for a U.S. Navy evaluation.

Trieste was located in the harbor on Capri Island, but the maintenance base was at the shipyard in Castellemare di Stabia, at the south of the Bay of Naples. There I learned that the principal technical support came from one Italian mechanic with a teenage assistant. We then proceeded to Capri and inspected the DSV in harbor. The north winds blew strong for 3 days, keeping *Trieste* in harbor and preventing me from making a test dive before I had to leave for Scotland. After considerable discussion with Piccard on *Trieste*'s diving experiences, I left with a positive impression on his ability to use *Trieste* as a research platform.

My recommendation to CNR was to support *Trieste* test dives with scientists from U.S. Navy-supported research laboratories. At a later meeting of laboratory directors at the National Academy of Sciences, Jacques Piccard was interviewed and his support was recommended.

There was a civilian scientist at ONR London who was a strong supporter, and my relief as Head, Undersea Warfare Branch in 1958, CAPT C.B. Momsen, Jr. USN, carried the load from there.

My memory on the particulars of who was involved with the decision to upgrade the sphere and buoyancy tanks for deeper depth is foggy, but I do recall some success in getting *Trieste* supported in the three budget years that I was in OP-713 OPNAV's Undersea Warfare Branch for Submarines, 1960–1963. That included getting her assigned to the *Thresher* search when I was co-director of the Technical Search Group in 1963.

Funding for advanced science and technology projects has always been sketchy, even for *Trieste*. I was given a photo of her at sea in a good wave, signed by Don Keach and George Martin, and addressed to "*Trieste*'s Best Friend". That's when I was OP-713 with my hand on the throttle for submarine R&D money, and *Trieste* needed some urgent funds for a special project. It's tough for a submariner to leave the boats, but it is important for officers with operational experience to move up the chain and help our Navy request and wisely allocate research appropriations.

FIGURE 1

REMINISCENCE

Meanwhile, Back on the Surface: Further Notes on the Sounding of Trenches

AUTHOR

Robert L. Fisher
Geosciences Research Division,
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In the early 1950s there remained a number of still-young scientifically trained civilians, recently discharged from the U.S. Navy, who found the small but established (or gestating) U.S. oceanographic institutions to be exciting, fecund, and rewarding intellectually and career-wise. Broad sponsorship from the enlightened Office of Naval Research (ONR) provided use of converted small but fully seagoing vessels. *Ad hoc* teams applied or invented techniques with deck hardware, surplus World War II explosives, and laboratory electronic rigs to investigate the oceans in regions and environments key to the Navy's potential missions but also to examine several crustal structures and tectonic processes fascinating to human curiosity, sometimes deemed "basic research." One war-born example known to all is the observational explosion made possible by SCUBA; many of us did become saltwater dermatologists in those icy, pre-wetsuit days. For some, it was not enough.

By 1952, as an established graduate student at Scripps, I had become focused on observing and interpreting the geology and geophysical setting of the trenches, truly the trademark of the Pacific, and present to some degree elsewhere. With ONR's sustaining interest providing shiptime, with the Navy Electronic Laboratory (NEL) nearby, and Roger Revelle's warm encouragement, I was able to persuade—or accompany on their cruises—a hard-nosed *caudrilla* of superb seagoing geologists—seismologists, oceanographic engineers—electronic "older brothers" to be with me on the converted 147-foot seagoing tugs *Horizon* and *Spencer F. Baird*. Persons that MTS members in particular might recall include Max Silverman, Russell Raitt, Alan Jones, Bill Menard, Harris Stewart, George Shor; each a true "sea man" in the Elizabethan sense. That interval—1950 through 1963—indeed was an explorers' "Golden Age" at SIO, also at Lamont, Woods Hole, Cambridge; exploration driven by science in the naval interest, but adventure and discovery every day.

Scripps early 1950s research ships initially were equipped with deep-water echo-sounders evolving from the WWII "flashing red light rotary scale," dicey at best, and later, 2,000-fathom "five second" sweeps, printing on scales of 0–2,000 and 2,000–4,000 fathoms. By 1953, Lamont Geological Observatory's Bernard Luskin and coworkers applied Wirephoto technology to develop a "precision depth recorder" (PDR) that eliminated timing uncertainties within the sounder (Luskin et al., 1953). Line-source frequency variation (59–62 cycles) did distort very markedly the deepest sounding values.

Program electronic specialists modified the PDR system (1-s keying rate, 400 fathoms, i.e., 1 s to sweep across a 12-inch-wide sensitized recording roll and depths based on a nominal 4,800 feet/s "sounding velocity") to permit "single ping"/"listen" for echo-train at, say, a 12- to 15-s interval. In effect, the "virtual" recording scale at, for example, 4,400–4,800 bottom became about 12 feet wide, with only the outgoing ping(s) and any returns echoing from that 400-fathom depth range being recorded on the paper. With timing precision, clear 1960s–1970s PDR records could be read to ± 1 fathom. A ping returning from an extensive flat bottom would produce a discrete notation; with a trench a mushier, varying echo-train—returns from multiple, commonly rough reflecting surfaces within the insonified "cone"—could make spatial, hence geological, interpretation maddening. The still-omnipresent problem in hadal geological mapping: getting enough sharply bounded pulse energy into the ocean to yield a detectable and decipherable echo after its 15- to 21-km journey.[1]

By mid-1959, our own efforts had delineated extent and sinuosity of axis, recognized sedimentary ponding and

[1]In the years prior to 1965 even U.S. research ships recorded depth soundings in fathoms, using a nominal sounding velocity of 4800 feet/s. By the 1970s nearly everyone worldwide had accepted the metric scale, nominal sounding velocity of 1500 m/s (about 4910 feet/s). For nearly five decades, depth values (or the contoured bathymetric charts prepared from them) as reported in popular accounts as well as scientific papers have employed "corrected meter notation", the values adjusted to the on-site, or regional, best-known velocity of sound in those waters.

precipitous flanks, dredged some small rocks, and established the correct maximum depth (and locale) for the Middle America Trench, the Tonga Trench, the Peru-Chile Trench, the Ramapo Deep in Japan, and the Cedros Deep, a senile trench off Sebastian Vizcaino Bay. As for geophysics, with our two ships off western Guatemala in late 1954 doing seismic refraction, we observed and confirmed the tectonic process later called "subduction," a first. In Tonga Trench just before Christmas 1952, we had discovered the world's second deepest locality (and deepest in the Southern Hemisphere), Horizon Deep, ponded seafloor at 10,800 ± 5 m.

At Tonga, the measurements required "bomb sounding," employing half-pound TNT demolition blocks as the sound source, the echo-sounder's transducer amplifier as an ear, and a paper-tape/ink-needle Brush oscillograph, at high-speed setting, to graphically log the shot instant, the ensuing travel time, and the complex wiggly returning echo-train. The quieted ship moved at two to four knots, crisscrossing the trench axis and up the lower flanks. Lighted-fuse TNT blocks were tossed off the fantail at 2-min intervals, ideally to explode 35–40 s later. I published a critique of the technique and topographic interpretation (Fisher, 1954). None aboard could sleep during this operation (Figure 1).

But by mid-1959, we had not reached Challenger Deep, the Holy Grail since HMS *Challenger*'s 1951 observations (Carruthers and Lawford, 1952; Gaskell et al., 1953), or even the Philippine Trench off Mindanao, commonly held to contain the greatest depth even at the close of WWII (Hess and Buell, Jr, 1950). However, in June 1959, SIO's R/V *Stranger*, a 134-feet wooden-hull yacht, built in Seattle in 1938, was to be sent to Bangkok for a several-year biological study to inventory the Gulf of Thailand. That program's leader, Anton Bruun, then in near-retirement at Scripps, was a world-renowned hadal biologist, earlier on the 1929–1930 Danish DANA Expedition, subsequently leader of Denmark's 1950–1952 world-circling *Galathea* Expedition to sample trench fauna.

FIGURE 1

Maxwell Silverman, an engineer with Scripps Institution of Oceanography, heaves a half-pound explosive TNT demolition block with a lit fuse overboard during the 1953 trench exploration on R/V *Spencer F. Baird*. The small charge provided a short acoustic burst that allowed researchers to distinguish reflections from multiple targets, such as trench walls and the trench floor. The technique is referred to as "bomb sounding." (Photo used with permission of Scripps Institution of Oceanography Archives, UC San Diego Libraries).

I had heard from my NEL contacts at Point Loma that our Navy had acquired the Piccard bathyscaph *Trieste* with the intention of reaching the Pacific seafloor at the so-called "Inner Space" record depth to match *Sputnik*'s late 1957 "Outer Space" accomplishment. I realized that *Stranger*'s summer of 1959 delivery track could be modified to let me reconnoiter Challenger Deep and perhaps make a base map to focus NEL's investigation and, secondarily, to scout the Philippine Trench. Anton Bruun heartily agreed: I recruited a shooter, found the necessary surplus demolition blocks in Hawaii to stow aboard *Stranger* and the shooter and I joined the vessel for the Agana to Manila traverse (Figure 2).

FIGURE 2

Dr. Robert L. Fisher, Chief Scientist, 1958, off Easter Island. (Photo used with permission of Scripps Institution of Oceanography Archives, UC San Diego Libraries).

Shooter Bob Winsett, certainly the key player on this operation, was a longtime scientific illustrator at SIO. Some years earlier he had spent several months on a construction crew in Nome and had learned to prepare explosive charges. We entered the deep region at about 142°50'E. I directed ship's track by intercom with the bridge, called the shooting, and recorded and monitored the returns on the several laboratory instruments. We recognized that the southern part of the Marianas Trench trended nearly East–West, so I had the bridge run more or less north-northwest/south-southwest courses at three knots, with navigation from island-based Loran. Steep mid-depth to lowermost trench flanks provided multiple echoes on the PDR, deeper than 10,500 m only the half-pound blocks offered decipherable detail except for short stretches of crisp echoes from narrow axial ponds. Following preliminary track adjustment, correlation of oscillograph echo-trains and "correction" of sounding values, *Stranger*'s August 1959 traverse revealed two, maybe three, small elongated depressions between 142°35'E and 142°05'E, the largest centered at about 142°12'E and each floored at more than 10,800 m (Figure 3).

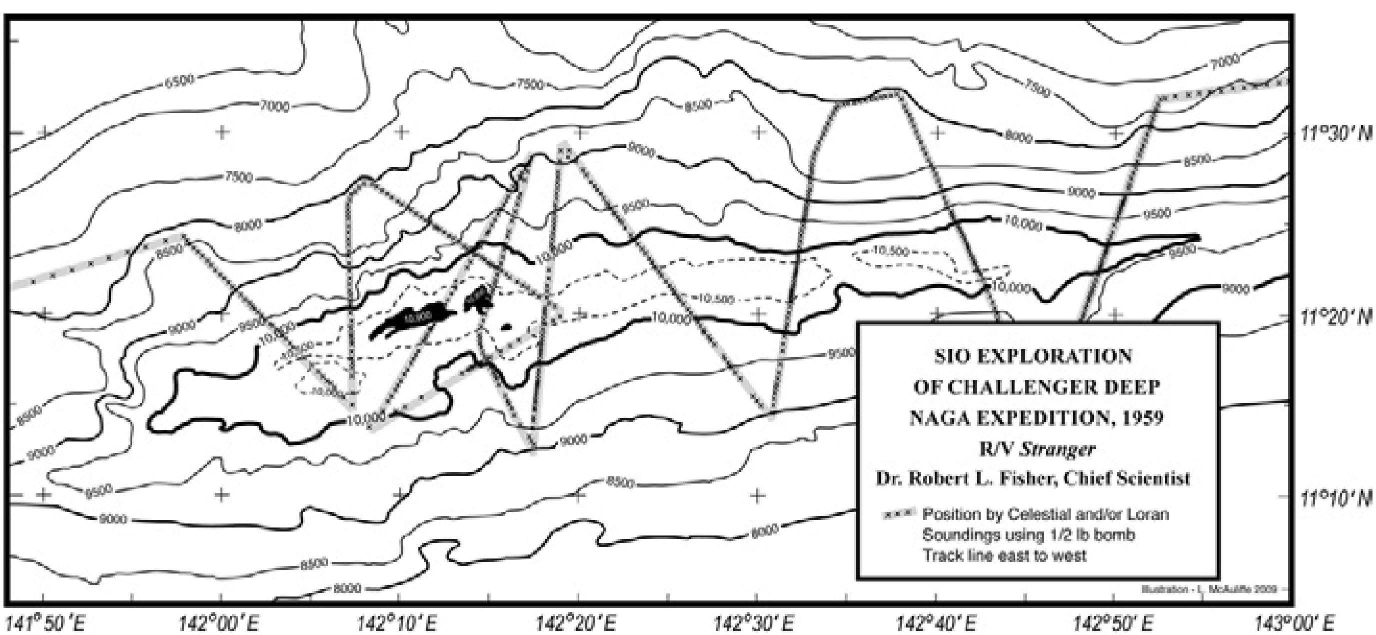
Throughout the hours that explosives were being used, the ship's messboy remained enthralled, almost hidden just forward of the fantail, fixated on Winsett's performance. We repeatedly inventoried the ready box since that crewman twice attempted to purchase two demolition blocks from the shooter. Our extreme caution perhaps was well justified; not many years thereafter, *Stranger*'s messboy became a co-founder of La Jolla's "MacMeda Destruction Company," a coterie of perpetually adolescent societal anomalists celebrated in author Tom Wolfe's 1968 collection, *The Pump House Gang*.

On return to La Jolla and further plot adjustment interpretation, I gave a copy of *Stranger*'s results to Bill Menard to pass to Bob Dietz, his former colleague, still at NEL. From then until the following January, I heard nothing about the project from anyone, civilian or Navy. However, in late January, I was at an advisory board meeting of perhaps three dozen academic and agency scientists and Navy sponsors in Washington, DC. At mid-morning, an officer came briskly to the podium and read aloud a press bulletin: the Navy's bathyscaph *Trieste* had reached—and returned from—the seafloor at world's greatest depth, 6,300 fathoms. The headline was "The U.S. Navy has conquered 'Inner Space!'" We all cheered, most sincerely, Don Walsh and Jacques Piccard's magnificent achievement and noted their great courage and good luck. Reading on, the spokesman repeated *Trieste*'s preliminary record depth, 6,300 fathoms, considerably deeper that anything I had found close nearby on ponded sediment, mine being specifically 10,915 ± 10 m by PDR/bomb sounding (e.g., Fisher and Hess, 1963).

Several in that audience knew very well my longtime trench obsession;

FIGURE 3

Map showing ship track of R/V *Stranger* as it surveyed the Mariana Trench before the *Trieste*'s deepest dive. (Illustration by Loralee McAuliffe, 2009, based on plots by R. L. Fisher).



hence, I was asked to respond, i.e., to "toast," with tabled Sparkletts water, probably. This I did, warmly congratulating *all* the NEL participants, but wondering slightly about the maximum depth *Trieste* has logged. Several in the uniformed audience hissed, but the chair asked the Navy's spokesman to query Guam by radio to secure confirmation of their measurement.

Sitting with me that day were University of Miami chemist Fritz Koczy and John Lyman, government agency physical oceanographer. Immediately, and then over lunch, we three continued to compare the numbers reported, mine from echo-train interpretation, *Trieste*'s by recording pressure. By mid-afternoon, the spokesman returned, very confident, with Guam's confirmation; he cited the exact same value, 6,300 fathoms, actually just re-reading the bulletin he had presented that morning. Once more I congratulated the entire NEL operation. But Fritz doodled and mused about the ratio: "that's about the difference of fresh and salt water." Early in February, John Lyman took his annual 2-week reserve assignment to check out the Navy Weapons Plant's re-calibration and re-calculate *Trieste*'s measurement. By March 10, ONR's Art Maxwell distributed a notice "correcting" *Trieste*'s observation to 10,913 ± 5 m. Very reassuring, physics is.

Fittingly, perhaps, in earliest March Jacques Piccard, an acquaintance since 1955, was returning from Guam to Switzerland and came through La Jolla, visiting my work area. I showed him *Stranger*'s plots and told him of the Washington, DC, incident. Jacques was amused. "But Bob," he laughed, "we'd calibrated the depth gauge in Lac Le'man!"[2]

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[2]Lac Le′man, the freshwater Lake Geneva.

In the Trenches… Topside Remembrances by the Chief of the Boat, DSV *Trieste*

AUTHOR
John Michel
Master Chief, USN

Guest Editor's note: The dive prior to the Deep Dive was made by Andy Rechnitzer and Jacques Piccard to test the Krupp sphere to 18,500 feet, a new world record depth. Not bad for a test dive. Surface water temperature was 84°F, while deep it was 34°F, a 50°F thermal range. On the return from the bottom, it is thought the masses of the three pieces were different enough that the thermal expansion of the three pieces caused a lateral shear force that caused the epoxy joint to fail with a loud "bang!", recalled Andy Rechnitzer, Project Director, Project Nekton. After recovery and examination of the bathyscaph, it was found the mid-section was about 1/8-inch offset from one end. Something had to be done with whatever was available to the crew in Guam. Failure would end the attempt at the deepest dive. Here, in his own words, John Michel, Chief of the Boat and Master Machinist, describes what they did to get the sphere back in alignment. Keep in mind, the dive following these repairs was to the bottom of the Mariana Trench. A second story from the chief is a first-person account of the morning of the *Trieste* dive to the Mariana Trench. Who cannot hope they'll make the same decision when faced with similar circumstances as Andy Rechnitzer, who gambled his career to give his men the few extra minutes they needed to get underway for the bottom of the Mariana Trench.

Kevin Hardy

Part 1: Repair of the Krupp Sphere

As to the "repair" of the Krupp sphere, almost without fail, the narrative as stated by numerous sources, although close, does not rate a cigar. Plan 1 was to remove the windows in the door and front view port, replace these with aluminum ones that I machined at the Ship Repair Facility (SRF), put a spindle through with nuts, washers, and a 60-ton hollow bore jack in line like a shish-kebob, then apply pressure and hopefully realign the sphere seats, since the faying surfaces are somewhat conical. Sounds good, but not conical enough for success.

Oh yes, I did the machining of the window substitutes because, although a world-renowned physicist, August Piccard was not an engineer. He chose the thickness and diameters for the Plexiglas ports, resulting in an included angle of 86°, 44′. The machinists at SRF were scratching their collective heads as to how to bring this angle about, so I took over that chore. Were one of the window diameters chosen with the included angle being 90°, machining would have been much simpler to accomplish. Of course, Plan 2 was now needed (Figure 1).

FIGURE 1

Master Machinist John Michel machines a window seat plug prior to realigning and banding the Krupp Sphere after a deep dive of 18,500-feet caused separation and misalignment. (Photo U.S. Navy, courtesy of John Michel).

The steel alloy of the Krupp sphere is basically the same as US 4340, a high strength alloy that when heat treated is super hard and strong. Jacques, although a sharp individual and versed in several disciplines, is also not an engineer. He would have had a fit or a heart attack if he could have seen what my alternative plan was. To this end, I had Andy take the team, less Denny Jensen, up to COMNAVMAR hill. I asked Denny to remove from the sphere's interior anything that could not survive a magnitude 7 quake, which he promptly did (only two items).

From day 1 in Guam, we had two Filipino SRF workers assigned to see to expediting whatever we required. Their names were Salvation and Conception, to the best of my memory. I asked Salvation to get a large forklift, the kind used for heavy lifting (two large front tires), rig it with the forks pushed together and a 12 × 12 inches mounted on them in the manner of a battering ram. Meanwhile I examined the front section of the sphere to locate the most out-of-place spot and marked it with a pen marker. This was some 3 mm out of position. Once Salvation returned, I had him practice lurching the ram and then had him line up with my X mark. When we were both confidant with him hitting and me with the pump on the jack, we had a go at it. After some repositioning and three or four hits, the sphere section was in almost perfect alignment once again (Figure 2).

Now, much has been made of the fact that I used Permatex to seal the joint. The only reason it was used was to keep sea water from leaching

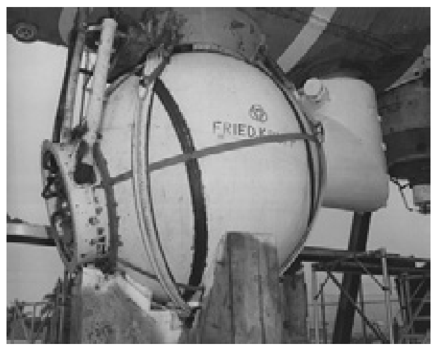
FIGURE 2

The machined aluminum plugs are placed in the window seats, and a 60-ton hydraulic hollow-ram jack is placed on a spindle through the sphere axis. No photos were taken of the nudging exercise employing the forklift described by the author. (Photo U.S. Navy, courtesy of John Michel).

under the paint and corroding the metal of the sphere. No pressure seal was intended. My next chore was to draw up a banding system to effect a mechanical method for holding the sphere sections together. This was promptly fabricated by the troops at SRF and then installed by Gieuseppe Buono (Figure 3).

FIGURE 3

The Krupp Sphere reseated, Permatex and rubber seal applied, the new bands in place, and the hydraulic ram and spindle removed. (Photo U.S. Navy, courtesy of John Michel).



Part 2: The Morning of the Deepest Dive, Andy Waits to Phone In

After expending several tons of mixed explosives in an effort to get back to the deepest spot we had found, Don Walsh and I made our way to the main deck of the Destroyer Escort (DE) *Lewis* and prepared to board the motor whaleboat for a ride to the Underwater Demolition Team raft trailing from the bathyscaph (Figure 4). The sea was very lumpy and our volunteer crew in the boat was having a hard time trying to come alongside to pick us up. At times it looked like they were going to go over the gunnel and come aboard, then they dropped down as far as the exposed bilge keel. We

FIGURE 4

DE 535 USS *Lewis*. *Trieste*'s team lived aboard her at sea during the world's record dive, 240 nautical miles SW of Guam. (Photo U.S. Navy, courtesy of John Michel).

could not just straddle the rail or climb outboard as the boat might crush our legs. It was going to be up and over in a carefully timed jump. The boat crew had spread out about 20 kapok life jackets so we could make a more or less soft landing. I jumped first. Timing was not too good. I fell the full vertical distance that the boat traversed and hit my right shin on a seat edge. My shin was bleeding nicely as I arranged some kapocs on the motor cowling. Don was not looking very happy so I told him to jump when I cued him and I would steer him to a soft spot. He jumped on cue and because his vertical position was off, I hit him with kapocs in hand and he landed on the motor cowl. Unhurt. I managed to get back on board where I was met by Andy Rechnitzer who escorted me to the sick bay to have my leg bandaged.

At this time, Larry Shumaker had taken a position on deck and had our UQC transducer in the water. Andy and I were now in search of a cup of coffee and were making like tourists with not much to do but wait. After some time had passed, the ship's radioman found us and said he had a message for Dr. Rechnitzer and handed it to him. Andy read it, had no visible reaction, then handed it to me.

The message read:

FROM C.O. AND DIRECTOR U.S. NAVY ELECTRONICS LABORATORY to DIRECTOR U.S. NAVY PROJECT NEKTON. CANCEL DIVING. COME HOME.

Andy was nonplussed but I was fit to be tied. Andy said "Let's find some more coffee," and we made our way back to the mess. After a short time, we walked to the stern. We discussed the project and other things. Then he said "Let's go to the radio room, I have to check in." We found the radioman and he said "Radioman, send a message." That message read:

FROM DIRECTOR PROJECT NEKTON to C.O. AND DIRECTOR U.S. NAVY ELECTRONICS LABORATORY. "TRIESTE" NOW PASSING 20,000 FEET.

(Figures 5, 6, and 7).

FIGURE 5

On station for the deep dive at the Challenger Deep, 35,800-feet down, January 23, 1960. A bit rough, the raft is the only safe way to make an approach to the bathyscaph at sea. Note the rubber raft near the bottom center of the photograph. The tug Wandank stands by at the top of photo. (Photo U.S. Navy, courtesy of John Michel).

FIGURE 6

Personnel at Guam for project "Nekton" (not appearing Jacques Piccard). The back of the original photograph was signed by the crew. (Photos U.S. Navy, courtesy of John Michel).

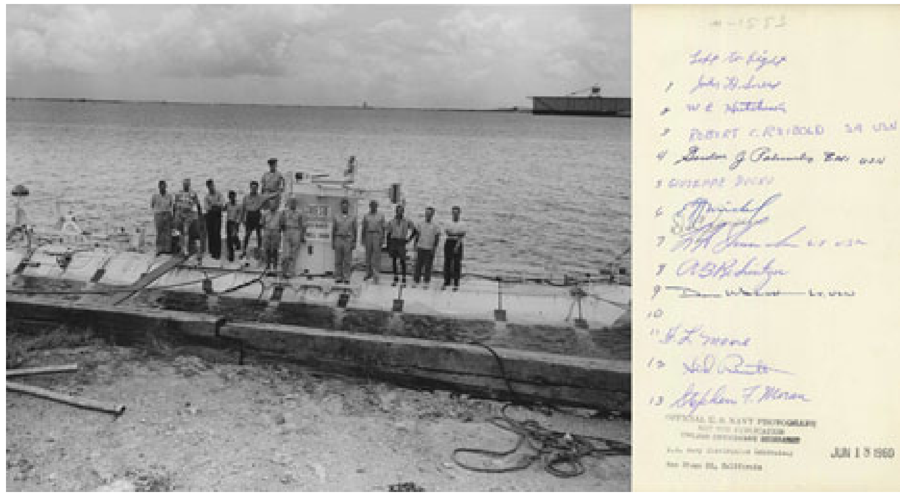
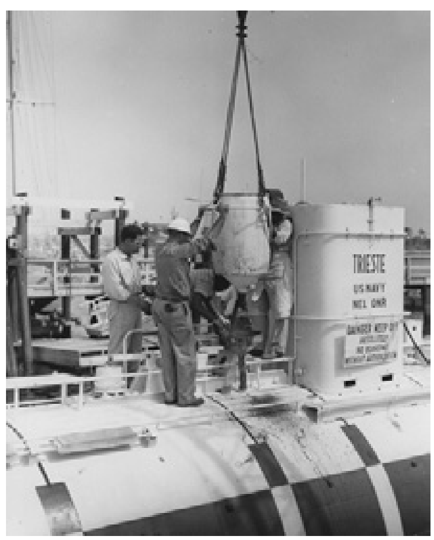


FIGURE 7

Ballasting *Trieste* at NEL, San Diego, CA. Both *Trieste* tubs each held 8 tons of magnetic iron shot with low magnetic permeability, approximately 1/8-inch diameter. (Photo U.S. Navy, courtesy of John Michel).



Trieste I Deepest Manned Dive Passes 35th Anniversary

Guest Editor's note:
Andy Rechnitzer, the brilliant and sometimes flamboyant *Trieste* Program Manager and Science Advisor, was known as a terrific friend and engaging professional to many around the world in the ocean community. He would have sincerely enjoyed being a part of this issue, and we sincerely could not imagine this issue without him. Thanks to Amos Bussmann, Compass Publications, we are able to include a report by this important pioneer. I will always remember the firm grip of Andy's Viking handshake. Herewith, Andy reflects on the deepest dive at an earlier anniversary, and what it meant to those who made it.

Kevin Hardy

(Reprinted with permission from *Sea Technology*, June 1995, pp. 59–60, www.sea-technology.com).

By Dr. Andreas B. "Andy" Rechnitzer, Viking Oceanographics, El Cajon, California.

A salutatory change in deep-sea research began when the Office of Naval Research (ONR) purchased the bathyscaph *Trieste* for the U.S. scientific community in 1958. ONR sponsored, along with the Bureau of Ships, the 1959–1960 phases of Project Nekton, a scientific deep-sea exploration project that included the deepest dive possible—35,800 feet.

Project Nekton was conceived and implemented by a team of civilians and military personnel seeking to descend to the deepest known depth in the world ocean—the Marianas Trench—a world record was achieved that cannot be broken. January 23, 1995, was the 35th anniversary of that event.

To commemorate the event, the San Diego Section of the Marine Technology Society hosted a luncheon for 135 at the Torrey Pines Inn on March 18, 1995. The special meeting theme, "Genesis and Maturation of Deep Submergence," brought the attendees from the beginning to the promising future for deep submergence. Dr. Andreas Rechnitzer, master of ceremonies and meeting initiator, introduced Dr. Don Walsh, Larry Shumaker, Capt. Charlie Bishop, John Michel, and Stephen Moran (all members of the deepest dive team) (Figure 1).

RAdm. Brad Mooney, Dr. Eugene LaFond, Glen Liddiard, and other attendees who had served with or conducted research using *Trieste* and *Trieste II* were also introduced.

FIGURE 1

Author Rechnitzer models commemorative T-shirt and cap for onlooker Bob Wernli (who also chairs the upcoming Oceans95 MTS/IEEE Conference). Design is by David Rechnitzer.

VAdm. James Webber, Naval Undersea Museum, announced that *Trieste II* is now on display at the Keyport, Washington museum. *Trieste* is on exhibit at the Navy Museum, Washington, DC, Navy Yard.

Evaluation Dives

Rechnitzer covered the initial ONR-sponsored 1957 evaluation dives in the Mediterranean prior to purchasing the *Trieste* and explained events leading to its transfer to San Diego. He also reviewed the historic deepest dive to 35,800 feet 35 years ago. Robert Fisher provided historical information on his Marianas Trench survey, which established the deepest known spot in the world ocean and explained that a correction for the onboard manometer that provided a "new," but wrong, depth of 37,800 feet. The instrument had been calibrated in Swiss freshwater, which gave an erroneous reading that was unfortunately used by the press (Figure 2).

Walsh, Kevin Hardy, Dr. Sylvia Earle, and Mooney described the current world fleet of manned submersibles and plans for future advancements. It was a 5-h marathon meeting full of facts about the success of deep submergence in the U.S. and the legacy of *Trieste* that is being carried on by American manufacturers, commercial operators, and government agencies throughout the world.

Deep submergence facilities are now considered to be a vital component

FIGURE 2

Special guests at the MTS celebration include Drs. Walter Munk (left), Sylvia Earle, and *Trieste* record co-holder Don Walsh.

of the University-National Oceanographic Laboratory System facilities inventory and the U.S. Navy fleet. Thus, the original ONR sponsorship of deep submergence served as the primary catalyst for U.S. achievements in manned exploration of the deep ocean. Academic projects using these unique facilities have contributed to many U.S. "firsts" and revolutionary scientific discoveries that have changed the course of oceanographic research.

The U.S. Navy operates no less than six manned submersibles from San Diego facilities. Cdr. Patrick Baccei, officer in charge of the U.S. Navy Deep Submergence Unit, gave an overview of vehicle developments and their impressive operations, both domestic and foreign.

Evolving New Technology

Attendant to pragmatic search and recovery, plus scientific achievements, there has evolved a new technology field, "ocean engineering," and a spectrum of underwater work systems—manned and unmanned. Many of the fundamental concepts demonstrated in *Trieste*'s technology have been adopted and modified to provide an industrial base that serves a significant portion of the underwater business worldwide. Deep submergence has also significantly influenced basic and applied scientific research, engineering developments, international law, government, industry, and academia. It has given a good return on investment.

Following this historic achievement, there has evolved a continuing and highly varied series of scientific and technology firsts. First it was a burgeoning U.S. growth in manned submersibles. The availability of deep water scientific vehicles contributed to the successful recovery of the H-bomb off Palomares, Spain. Beginning in the mid-1970s, ROV technology, a derivative of U.S. Navy manned submersible technology, was extensively advanced by the civil sector to meet the needs of the offshore oil and gas industry for underwater systems. There is an emerging autonomous undersea vehicle technology. It is gratifying for the deepest dive team to note that today the legacy of the *Trieste* is evident throughout the world in the form of advanced vehicles and other developments (Figure 3).

FIGURE 3

Bathyscaph *Trieste* Program Manager and Science Advisor Andy Rechnitzer on the deck of *Trieste* in San Diego, CA discussing operational plans with Giuseppe Buono.

REMINISCENCE

Swim Call!

AUTHOR

W. James Kear[1]
CAPT, USN Ret. and
former Commanding Officer,
USS *Mobile Bay*

Did you have the opportunity as a child, or maybe even as an adult, to take a dive into that idyllic swimming hole or river as Opie did in Mayberry? If nothing else, maybe you thought how neat it would be immersing your body in clear, pristine, and unchlorinated waters enjoying the exhilaration being in water where your toes do not touch bottom.

Let's take that dream or childhood experience a quantum leap forward. It was summer of 2002 and the 350+ men and women serving aboard the Guided Missile Cruiser, USS *Mobile Bay* (CG 53), had departed their homeport of San Diego, CA, en route to the Arabian Gulf. It was an uncertain time for the U.S. military. 9/11 had shaken the very core of our nation several months earlier and, not knowing the full intention of the Iraqi leadership, soldiers, sailors, and airmen alike were preparing for whatever they were called upon to do. Hence, the crew of *Mobile Bay* deployed that summer "battle ready" in one of the U.S. Navy's most sophisticated warships.

The crew was confident and ready but not without some question as the ship steamed westward toward the Arabian Gulf as part of the Lincoln Battle Group. For a portion of the journey, the ship was independently steaming to a brief port call in Guam. The South Pacific seas that summer were magical and almost "lake-like" with a smooth glassy surface and barely a swell day after day.

Not far from Guam, the Navigator exclaimed, "Captain, we'll be sailing very close to the deepest part of the Marianas Trench [11″21′ North latitude and 142″12′ East longitude]." We would arrive the next day around midnight. "Hmmmm" I thought, "Here is an opportunity for a little stress release for the crew!" As Captain, I directed my navigator to lay a course for that very spot to arrive several hours earlier the next day. I had an ulterior motive—swim call.

The word was promulgated that evening to the crew; we would be steaming for the deepest part of the Marianas Trench and would arrive by late afternoon for swim call complete with a BBQ, Beach Boys music over the topside speakers, and beach attire. The ship was abuzz with anticipation.

The next afternoon we arrived. As in the days before, the ocean was perfect—smooth as glass and so crystal clear you could hope to see the bottom. Water temperature was a balmy 84°. "Swim call! Swim call!" bellowed the boatswain's mate of the watch from the 1-MC speakers.

The BBQ grills were primed and ready for burgers, hotdogs, and chicken. The crew donned their beach attire and swim suits and the Beach Boys music set the tone. There was no lack of smiles that day among this crew.

"Fifteen at a time!" declared the ship's Master-at-Arms from the fantail, who was charged with keeping a running head count to ensure everyone was accounted for from the time they

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jumped off the fantail to the moment they ascended the rope ladder onto the deck.

But, he did it! He was immensely proud and his shipmates were immensely proud of him.

No one was hesitant to share this special experience; after all, it was only a little over 36,000 feet deep.

One particular sailor specifically comes to mind. During the swim call, which lasted over two hours, one young engineer stood on the fantail watching shipmate after shipmate jump into the azure blue waters beneath. He was not a strong swimmer and was afraid of the water, yet his heart and imagination yearned for this once-in-a-lifetime memory. Near the end of the swim call, he quietly disappeared from the deck. Ten minutes later, he emerged—in his swim trunks. His shipmates let out a huge cheer in approval. Hesitantly yet wantonly, he stood at the ship's edge—it was a long way down; over 20 feet he thought, even from the fantail. But to the enthusiastic cheers and encouragement of his shipmates, he turned, smiled calmly and made the leap! The crew went nuts with joy! He hit the water with little form and as he surfaced he turned his body immediately to the hull only to scurry back up the rope ladder.

As the BBQ and swim call came to a close, the ship engaged its engines and continued its journey into the evening toward Guam. They had created a very special memory together. Not related to the high-tech nature of their billion dollar warship or the training that would eventually serve them well at the outset of Iraqi Freedom launching dozens of Tomahawks during the infamous night of "shock and awe," but a very special and shared memory known only to sailors who go down to the sea in ships.

PAPER

From Beebe and Barton to Piccard and *Trieste*

AUTHOR

Will Forman[1]
Submersible Designer, Builder, and Pilot, San Diego, CA

Beebe and Barton: Bathysphere and Benthoscope

On June 3, 1930, two Americans in a very small steel sphere dangled in the ocean at the end of a cable below a barge near Bermuda, British West Indies. The men, William Beebe (1877–1962) and Otis Barton (1899–1992), initiated manned deep-sea exploration on that day. It was the beginning of the modern era of humans entering the deep abyss in a pressure resistant hull.

Once the two tall men and all of their equipment were inside the 4-foot, 6-inch diameter sphere, named the *Bathysphere*, a crane hoisted the 400-lb hatch onto 10 bolts sticking out from the hull around the entry hole. Next, the deck crew tightened nuts onto the bolts, first finger tight and then ever tighter by hitting a long wrench on its handle with a huge sledge hammer, which nearly deafened the occupants. After a dive, the process was reversed to get the people out.

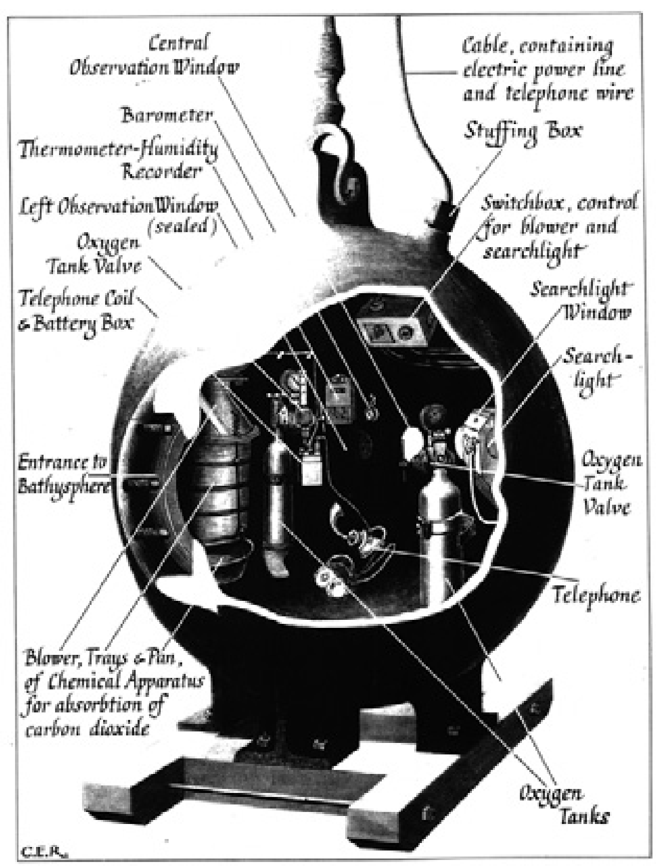
Beebe, at 53, had written 17 scientific books, been curator of Ornithology for the New York Zoological Society (NYZS) for 31 years, and was at that time director of the Department of Tropical Research for NYZS. Barton was half of Beebe's age, an engineering graduate of Columbia University in New York, and had just finished a "hop around the world playing at being explorer" on a sizable inheritance from his grandfather's estate that also funded the diving sphere they were using.

Three viewport housings were located at the front of the sphere opposite to the hatch on the equatorial line. Inside of each housing was an 8-inch diameter, 3-inch-thick viewport of fused quartz made watertight by paper gaskets. The axis of the three viewports converged a few feet in front of the sphere so that cameras, lights, and viewing were all aimed at the same area of view (Figure 1).

A special 7/8-inch cable terminated into a pad eye on the top of the sphere. The electrical and communication wires, which attached to the hoisting cable, entered the hull through stuffing glands. The glands were fitted with a threaded tube and tightening nut to se-

FIGURE 1

Cutaway of the bathysphere as viewed from the personnel access hatch. It was the first use of a pressure sphere for manned observation of the deep sea.



[1]For this article, the author drew upon the original research done for his book, Forman, Will, 1999, The History of American Deep Submersible Operations, Best Publishing Company, Flagstaff, AZ, 312 pp., in addition to other sources, including first person interviews.

cure the wires from being squeezed into the cabin by sea pressure. The 110-V electrical cable powered a 250-W flood light. Communication wires served for the telephone to the surface.

Oxygen was metered from two storage tanks with another tank as standby. Each tank contained enough oxygen for two men for 2 h. Carbon dioxide was scrubbed by trays of soda lime and moisture was scrubbed by calcium chloride. A Japanese hand-held palm leaf that had to be continually fanned manually "kept air in circulation."

The 5,000-lb Bathysphere was tethered by a cable 3,500-foot long, made by Roebling and good for 29 tons in tension. Barton estimated the crush depth of the sphere at 4,500 feet.

Unmanned tests of the Bathysphere were conducted which proved the sphere watertight but resulted in the conductor cable getting tangled around the hoisting cable.

Manned observations in the deep sea rewarded the researchers with views of live marine life, which taught more than dead samples available previously by trawl. The concentration and excitement was so much that Beebe sat on a monkey wrench for over an hour without realizing it, leaving him with a sore tailbone long afterwards. Of the two men, Beebe seems to have been the calmer. Barton relates: "We were descending. Pieces of seaweed and small fish moved upward before our window. It was at this time I had my first fright. A stream of water was coming in under the door, wetting my shorts. Dr. Beebe, I called, 'There's a leak! Shall I tell John to pull us up?' Dr. Beebe glanced at the door and studied it for a moment. 'No, I think not,' he said. 'Don't frighten them at the surface.'"

The deepest dive of the first season was to 1,428 feet. Most of the many other dives were in shallower water where contour dives were practiced. These were accomplished by putting the barge into a desired location and letting it drift with the sphere below. If an obstruction appeared or the bottom came up, the researchers would call up to the winch operator to raise them out of danger.

In 1932, dives were resumed, beginning with an unmanned test of the Bathysphere to 3,000 feet.

Upon recovery, the sphere seemed too heavy. When a 4-inch diameter plug in the hatch was removed, water pressure that had built up inside the sphere from leakage at depth shot across the deck and dented a steel winch. A second 3,000-foot test gave the same result, but the sphere returned dry on the third try and manned dives commenced. The last dive of the season was broadcast over NBC from Beebe and Barton's new record depth of 2,200 feet.

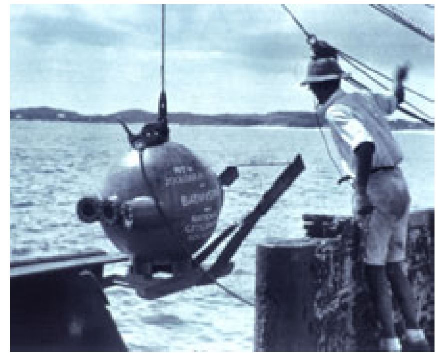
Thanks to the publicity received from the press and radio, several U.S. companies furnished some newer equipment for the project. The Air Reduction Co. provided new oxygen tanks and an electric blower to replace the palm leaf fan. General Electric provided new quartz windows while Bell Telephone provided an improved telephone system.

The 1934 dives began in the Bahamas in August. A 3-h dive to 2,510 feet was the longest in the series, while the biggest fish seen occurred on dive No. 32 when a 20-foot-long unidentified specimen swam by their viewports. The deepest dive, to 3,028 feet, was made until only a few turns of the hoisting cable were left on the winch drum and rough surface weather required the dive to be terminated (Figure 2).

The Bathysphere was then retired to the aquarium at Coney Island, New York.

FIGURE 2

As the deck boss signals the boom and winch operators, the bathysphere is lowered into the sea off Bermuda. The power and communications cables will be married to the wire rope lifting line as the sphere is lowered.



Following his adventures with William Beebe, Otis Barton tried various endeavors. Some involved filming undersea or jungle life, another a new diving suit he invented. Then, when WW 11 began, he joined the Navy. After his Navy discharge, he had a new diving sphere fabricated which was quite similar to the Bathysphere which Beebe had designed. Made of a stronger chrome-nickel steel, the inside diameter was the same as that of the Bathysphere (54 inches), but a half inch thicker (1 3/4 inches). Barton calculated the crush depth at 10,000 feet. Named the Benthoscope, it weighed 7,000 lb in air and had only two viewports. One was centered amidships on the equatorial line of the sphere and the other, smaller one, was angled downward and located below the first. Like those on the Bathysphere, the quartz viewports were 3-inch thick and sealed with paper gaskets. The new hatch was concave in shape, which reduced its weight to 150 lb. External lights consisted of a 1,500-W spotlight and a small high intensity photography light. Six thousand feet of electrical, phone line and hoisting cable connected the sphere to the topside winches. The Benthoscope cost $16,000 compared with the $12,000 cost of the earlier Bathysphere (Figure 3).

FIGURE 3

Otis Barton's Benthoscope is deployed off Southern California, 1949.

After an unmanned test of the sphere at 6,000 feet, near Santa Cruz Island off Southern California, Barton made the first manned dive in August 1949. On his fourth dive, he went to 4,500 feet. In October, contour dives were made from Catalina Island to the south of Santa Cruz Island until winter weather caused the operations to be ended.

There followed a 5-year sabbatical from the oceans while Barton was in Africa. Upon his return to the United States in 1954, Barton headed for the San Clemente Basin, off the coast of Southern California with the Benthoscope. Still photos were taken for Life Magazine at 3,100 feet. After the lights malfunctioned, the dive series was terminated. The Benthoscope was last seen on exhibit in the old Marineland of the Pacific in Los Angeles. It's location today is uncertain.

William Beebe continued his work in the natural sciences, writing many books and papers. His last article in *National Geographic* in 1958 at age 81 years was as sharp, clear, and instructional as his several contributions to that magazine were in the 1930s. He died a few years later.

Beebe and Barton's undersea research by direct observation was the first of its kind in the United States. Their work also represented some of the earliest submarine research to be sponsored by nonmilitary funding and a forerunner of many more oceanographic programs to follow.

While the Bathysphere and Benthoscope cannot be described as deep submersibles, their inclusion is necessary for both historical background as well as for the appreciation of the work of the giants that lead the way for others.

Piccard and the Invention of the Bathyscaph

The Swiss-designed but mostly Italian-funded *Trieste* was an important bridge between the early U.S. submersibles and the American-built deep submersibles that followed its purchase and operation by the U.S. Navy. The catalytic affect of the Navy *Trieste* program was a major factor in the initiation of deep submergence technology in the United States.

The designer and builder of the *Trieste* was Auguste Piccard (1884–1962). His extensive knowledge as a physicist contributed to practical engineering and established many of the basic design standards still in use today over 70 years after he introduced them. As a university student, Piccard dreamed of oceanographic expeditions in submersibles. Before he ever went below the sea, the same concepts led to his stratosphere ballooning. About a year after the Beebe/Barton dives began, Piccard set a balloon altitude record over Switzerland.

Professor Auguste Piccard began work on his first bathyscaph in 1938, but the Second World War forced him to set that project aside. Shortly after that war, Robert H. Davis wrote in his definitive text, *Deep Diving and Submarine Operations*, "The 'bathyscaph' designed by Professor Piccard, the Swiss scientist, with which he hoped to attain the remarkable depth of 14,000 feet or more, did not rely on a submarine cable for controlling its ascent and descent, but on an intricate system of ballasting. As is well known, the attempt by this intrepid professor had to be abandoned, but it is understood that another will be made. It would, therefore, be premature to attempt to describe it here as a practicable diving proposition" (Davis, 1951, p. 218).

After WWII, Piccard requested and received funding for a bathyscaph from the same Belgian group (F.N.R.S.) that funded his balloon explorations. Named the *FNRS-2*, since the balloon project was the first FNRS, it operated with a system similar to those used on balloons, with gasoline for buoyancy and iron shot for ballast. Piccard chose an oil heavier than water in which to submerge the motors. The rotating shaft stuck up through the oil into the surrounding sea water vertically and, consequently, did not require a shaft seal. Gravity kept the oil in place, in or out of the water (Figure 4).

The spherical steel hull had an internal diameter of two meters (6 feet, 6 3/4 inches) with a nominal wall thickness of 9 cm (3.54 inches). The steel castings of the hull were made into two hemispheres clamped together at the equator with a hatch containing a viewport at one pole and a viewport only in the opposite pole. The sphere was positioned so that the viewport opposite the hatch was facing forward and downward.

After extensive testing, Piccard chose a 90° conical-segment-shaped view-

FIGURE 4

Piccard's bathyscaph *FRNS-2*, modified by the French Navy and rechristened *FNRS III*, on display at Toulon. Photo by: Yves Tennevin, 2008, used with permission.

port with a 10-cm (3.94 inches) internal diameter and a 15-cm (5.91 inches) thickness. Piccard's pressure tests indicated that the viewports would not fail at less than 7.4 miles deep.

The tests of the *FNRS-2* during the winter of 1948 off Dakar, Senegal, Africa, were pioneering in nature since they tested the validity and watertight integrity of Piccard's designs, both manned in shallow water and unmanned at 4,620 feet. The French Navy witnessed the *FNRS-2* tests and were greatly impressed. In response, the funding group at FNRS sold the *FNRS-2* to them so they could cannibalize it and build the *FNRS-3* to their specifications. Piccard was kept on as an advisor, but the amateurs in the French Navy thought they knew more than he did so he was pretty much ignored and lost interest.

In early 1952, the Italian city of *Trieste* offered Auguste Piccard funding and industrial support to build his own bathyscaph. He accepted. With some Swiss donations and the help of his son, Jacques, he began building the bathyscaph *Trieste*. Most of the basic design was already completed and tested based on the experience with the FNRSs, but some minor yet significant improvements were needed. The new sphere was identical to the one on *FNRS-2* except that, instead of being cast, it was forged and machined at the Terni plant in Italy. This made it much stronger. The volume of the new float was increased to 3,742 cubic feet, but the battery, buoyancy, and ballast control systems would be the same as in the *FNRS-2*. Where *FNRS-2* had to be entered prior to launching, the *Trieste* could be towed to the dive site and entered in the open sea by means of a watertight entry tube extended from the top of the float to the sphere below.

Compartmentalization of the float into 12 segments provided integrity if one more of the compartments became damaged. The fore and aft sections of the float tapered toward the ends for streamlining. Corrugations in the bulkheads between sections provided for expansion/contraction due to temperature and pressure changes. Two ballast tubs containing nine tons of releasable iron shot were provided for variable ballasting. One ballast tub was forward of the cabin and one was just aft.

Two motors with propellers were located on top and at the forward part of the float for propulsion and maneuvering. During diving, the entrance tunnel, running vertically from on top of the float down to the sphere, was flooded with sea water. While at the surface, it was blown dry to permit access to and from the sphere. The polar axis of the spherical cabin, which intersects the two viewports, was tilted 18° with the horizontal to provide a downward and forward viewing angle. Overall length of the submersible, was 49 feet, 6 inches.

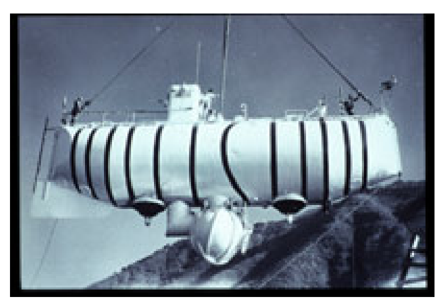
In 1953, the first dives with *Trieste* began with Auguste Piccard and his son Jacques Piccard, making most of the dives together. The maximum dive depth for the year was made to 10,390 feet. It was Auguste's last dive a few months before his 70th birthday. A few shallow dives were made in 1954, but none were made in 1955 due to a lack of funding. A few dives were made in 1956 with some modest funding from Swiss and Italian sources.

Trieste Comes to America

Many people associated with oceanography, science, and the Office of Naval Research (ONR) were aware of the *Trieste* and its capabilities. The London office of ONR brought the *Trieste* to the special attention of ONR in Washington, DC. Interested parties in the National Academy of Science got the Secretary of the Navy to lean on the head of ONR to "do something about the *Trieste*." Thus, in 1957, almost all of the 26 *Trieste* dives in Europe were made with U.S. scientists or ONR representatives evaluating the bathyscaph operations. As a result, *Trieste* was purchased by ONR from the Piccards for $200,000, and shipped to the Naval Electronic Laboratory (NEL) San Diego, California, in August 1958 (Figure 5).

FIGURE 5

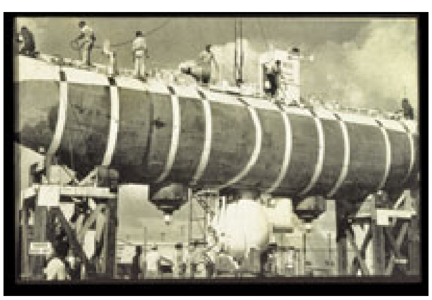
The bathyscaph *Trieste* as delivered to the U.S. Navy circa 1958–1959.



Soon after the purchase, plans for Project Nekton started. Nekton was the name given to all of the preparations and modifications necessary to reach the bottom of the Challenger Trench at over 35,000 feet of depth in the Pacific. Dr. Andreas "Andy" Rechnitzer (Scripps, 1955) was selected as Project Director for Project Nekton. Lt. Don Walsh USN volunteered and became the officer in charge with Lt. Larry Shumaker as executive officer and as scientific advisor. Giuseppe Buono came with Jacques Piccard, as an all-round chief of the boat and master of all its idiosyncrasies. A heavier and stronger sphere was needed as well as a larger float to buoy up the heavier sphere. The Krupp Werkes in Germany committed to a delivery time of 6 months at a price of $65,000 for a three-piece sphere with 3.5-inch-thick walls in the non-reinforced areas. The three-piece design was comprised of a midsection and two end caps to form a sphere. The three pieces were machined to a near perfect fit. A thin coat of epoxy glue, acting in compression, bonded the pieces together (Figure 6).

FIGURE 6

The bathyscaph *Trieste* undergoing modifications for the deep dive.



After the Krupp sphere was installed and the float lengthened an extra 8 feet, the vessel was shipped to Guam, reassembled and dive tested to 18,150 feet in November 1959, with Rechnitzer and Piccard as crew. While on the way back to the surface, the epoxy joint popped with a loud noise. Even with the glue cracked, the external sea pressure sustained a tight fit in the joints both at depth and at the surface. The best explanation for the epoxy bond breaking was that the larger central hull had undergone a change in dimension—due to pressure and/or temperature affect—that was different from the smaller end pieces.

Large screw jacks were obtained from a Navy yard in Japan, and the parts were moved back into near perfect alignment. The joint, after reseating, was then given an additional external seal, and extra retainer rings and straps were added and placed around the sphere to prevent reoccurrence. Without calling official attention to the field repairs, Don Walsh test dived the modified *Trieste* to the bottom of the Nero Trench at 23,000 feet on January 8, 1960—fortunately, with no further leaks or noises (also see *Trieste* Master Chief John Michel's recollection of this event in this Journal).

On January 23, the modified *Trieste* was towed 220 miles from Guam to a dive site directly over the deepest spot in the Marianas Trench for the 65th dive of its career (Figure 7).

The *Trieste* flooded down and ejected gasoline until it submerged.

FIGURE 7

The modified bathyscaph *Trieste* on the surface before descending to the floor of the Marianas Trench, January 23, 1960.

A brief stop on the first thermocline at 300 feet was made while descending, as they hit the denser, colder water. More gasoline was ejected to make the boat heavier, and the dive continued. Additional thermoclines stopped them momentarily at 425 and 530 feet. After 600 feet, the craft attained a constant rate of descent at about 3 feet/s. They observed luminescence at 2,200 and 20,000 feet. At 26,000 feet, the rate of descent was reduced to 2 feet/s, and at 30,000 feet to 1 feet/s. Walsh, in the *Trieste*, and Shumaker, at the surface, made phone calls to one another at 5,600, 10,000, and 13,000 feet. In the sphere at 26,000 feet, Walsh and Jacques Piccard could hear the conversations between the tugboat and the Navy destroyer at the surface.

At 32,500 feet, they heard a dull crack-like sound coming from somewhere in the bathyscaph. They stopped and looked about them to see what the problem was, but finding nothing wrong they continued downwards. At 1256 h, the bottom sounder indicated that the bottom was 300 feet away. Ten minutes later, at 1306 h, they landed on the bottom reporting a flat fish. A few minutes later, a shrimp swam by. Walsh called to the surface, "This is *Trieste* on the bottom, Challenger Deep. Six three zero zero fathoms, over." They heard him topside, weak but clear. He repeated the message adding, "We will surface at 1700 h." Later, Walsh looked through the aft viewport located in the hatch and noticed that the viewing window in the access trunk was cracked, explaining the noise they had heard on the way down. The thin acrylic window was not normally subject to stress, since the access trunk was filled with water prior to leaving the surface and was not subject to pressurization. The window would be needed in place at the surface, so that the bathyscaph crew could blow the trunk free of water and go up the trunk to the surface.

After 20 min of observations and note taking, they decided to leave the bottom and head for the surface. The ascent was without incidence. Their vertical velocity increased as they ascended due to the gasoline expanding as the water pressure decreased. The less buoyant, warmer waters at the thermoclines were barely discernible. Bioluminescence was noted at 3,300 and 2,000 feet. They surfaced at 1656 h and blew the access trunk very slowly and carefully. The acrylic window held. Fifteen minutes after surfacing, they exited into daylight after a dive that lasted a total of 8 h and 35 min.

The crew were each given a special award and handshake by President Eisenhower for their part in taking a manmade vehicle to the deepest part of the ocean at 35,800 feet and safely returning for the first time in history (Figure 8).

FIGURE 8

President Dwight Eisenhower (left) shakes hands with Lt. Don Walsh. To Walsh's right is Jacques Piccard. Behind Walsh in the foreground is Lt. Larry Shumaker, and Dr. Andreas Rechnitzer to Shumaker's right in a light suit.

After a brief home stay, the American crew returned to Guam planning to revisit the Challenger Deep two more times, but they were enjoined by the Navy and limited to depths of 20,000 feet or less. On the seventh dive of their return, the last mercury vapor light burned out ending the Marianas dives.

On April 10, 1963, the *U.S.S. Thresher* was lost at sea with 129 men aboard during a routine sea test after a shipyard overhaul. The sinking of U.S.S. 593 occurred 260 miles off the coast of New England in 8,400 feet of water. Results of the official inquiry would indicate that the cause of the disaster was due to a rupture in the seawater piping; jetting water wiped away power and control cables in its path as if they were cobwebs.

The only submersible in the United States capable of exploring the ocean at 8400 feet was the bathyscaph *Trieste*, in San Diego, one small canal and one large ocean away.

Trieste was immediately ordered to Boston by the Navy. It had been over 3 years since the Challenger dive. Don Walsh had been relieved by Don Keach, who was now the officer in charge of *Trieste*. It was a frustrating time for Keach when he got the call. The old *Trieste* float was full of holes, plugged with wooden pegs to prevent the gasoline from leaking out. A recent overhaul had not included a badly needed new float. Under tow, the old float could actually stretch as much as a foot in length. On the positive side, the field-repaired Krupp sphere had been replaced with the original Terni sphere, which was still good for thousands of dives as deep as 12,000 feet.

Keach got word to deploy to Boston on April 11, 1963. *Trieste* was immediately hoisted aboard the Landing Ship Dock *U.S.S. Preserver*. After a long slow trip to Boston followed by a long tow to the dive site, the first dive was made on June 24, 1963. After months of back-breaking effort and observing endless pieces of nondescript debris in dive after dive, the wreckage itself was not discovered. However, a plastic shoe cover used for radiation protection with part of the *Thresher's* hull number visible on it was found. The *Trieste*, lacking a manipulator, could photograph it but not recover it.

Needing repairs and additional batteries, the *Trieste* was returned to Boston, where among other things, a manipulator was added. Returning to the dive area on August 18, they began their second dive series. With the approaching fall weather threatening to disrupt operations, they persisted and found a tangled mass of twisted metal and debris of all kinds. Positive identification was made when a piece of pipe was recovered with the inscription "593 Boat" on it. The trick was to maneuver the underpowered 60-foot-long blimp-like structure while looking out of one small viewport in a steel sphere hanging below it. Scooting and dodging the bathyscaph among the wreckage, they photographed everything in sight with the automatic cameras. After dive No. 10, the badly worn and damaged battery compartment finally failed, and operations were halted. Upon return to San Diego, the faithful old *Trieste* float, along with the Krupp sphere, was retired to the Naval Historic Museum at the Washington, DC, Navy Yard. The *Thresher* search was later to be continued by *Trieste II*.

Trieste II

After the last dives for the *Thresher* search in 1963, the original *Trieste* float, enlarged for the Mariana's dives, was in such bad shape that a new one was required. With a pointed bow and flat sides, the new float—sometimes called the "boat float"—had the original but refurbished Terni sphere recessed into it for a better towing combination. Larger, externally located pressure compensated lead acid batteries were substituted for the silver-zinc batteries providing eight times the power previously carried inside of the sphere. The two propulsion motors were upgraded to 5 hp with 48-inch diameter propellers. Sonar, other search systems and instrumentation were all vastly improved in preparation for undersea search, salvage, and photography. By launch date, January 17, 1964, modifications had been so major that the vessel deserved a new name: *Trieste II* (Figure 9).

FIGURE 9

Trieste II is seen shortly after her new float was completed at Mare Island in November 1963. (U.S. Navy photo no. 63526, submitted by Darryl Baker).

After the deployment and initial testing, it was found that the separation of the center of buoyancy and the center of weight was not enough for a stable craft after the ballast hoppers were emptied, so skids with lead pigs were added to the left and right of the personnel sphere. The first half dozen dives in 1964 were spent testing the new equipment and training new pilots. Oceanographic-oriented dives were then made for the scientists at the Naval Electronic Laboratory. In June, the submersible was moved to Portsmouth, Rhode Island, in preparation for the second series of "*Thresher* search" dives. During dive no. 1 at a depth of 8,400 feet, a severe short occurred in the bathyscaph's main propulsion motors, causing the external batteries to drain to zero voltage. Arcing from the shorted circuits occurred only 4 feet from the gasoline in the float, causing great concern that, at the surface, gasoline fumes might be ignited from the sparks. Fortunately, this did not happen. Photographs taken on five dives and from a camera array towed on a sled from the USNS Mizar showed the tail section of *Thresher* with stern draft numbers, stern planes, and the sail with the side numbers "593." After the last dive in the series, *Trieste II* was returned to San Diego for maintenance and overhaul. In March 1965, *Trieste II* was transferred from NEL to the Deep Submergence System Project.

The first dive of 1965 took place in May, in the San Diego area. Testing of the overhauled submersible equipment took place in the first few dives, but most of the rest of the year was spent training pilots and crews in developing search, operation, rescue vehicle, and object recovery techniques. All dives in 1965 were made in the San Diego area, mostly at 3,400–3,500 feet depths. The last dive of the year took place in August for a year's total of nineteen dives.

Most of the 1966 dives were made in La Jolla or Scripps Canyon. All dive depths were 2,000 feet or less. The dives were virtually all training dives.

The first dive of 1967 took place in La Jolla Canyon. All nine dives in 1967 were made in the San Diego–La Jolla area with four pilots qualifying. The last dive of year and for the submersible was no. 54 in March, after which it was retired from service.

Towards the end of it's operational life, the top of the submersible was modified to have a V-tail and other cosmetic features. Secretly, a third bathyscaph was being built that had that top profile. Over flights by Soviet satellites would know where our bathyscaph was, while the second bathyscaph could be somewhere else.

The DSV-1

In early 1968, there emerged from Mare Island Shipyard, a completely redesigned submersible, the DSV-1. The DSV-1 was the first to be designed and fabricated entirely in the United States. It had a blunted torpedo-shaped float containing 65,830 gallons of aviation gasoline and extended legs for setting on land, seabeds, or shipboard. The "X"-shaped stabilizer fins aft provided two points of support at the stern, facilitated sea keeping ability, and provided contact points during docking and undocking (Figure 10).

The pressure sphere was made of two hemispheres of HY-120 steel de-

FIGURE 10

The DSV-1 is shown in April 1975 at Mare Island Naval Shipyard near the completion of her overhaul at the yard. (U.S. Navy photo no. MSA 130555-4-75, submitted by Darryl Baker).

signed by Southwest Research Institute of San Antonio, Texas, with an operating depth of 20,000 feet and a safety factor of two. The first dive of the new bathyscaph was made in April 1968. More than a half dozen new pilots were qualified during the dives made in 1968. In July, a 6-h dive was made to 12,720 feet, all other dives were in the San Diego area and did not exceed 6,300 feet.

When the nuclear submarine U.S.S. Scorpion was declared "officially missing" in early June 1968, an exhaustive search of the sea bottom was immediately initiated. In the fall of 1968, 5 months after the search began, the wreck of Scorpion was located by submerged cameras, remotely operated from surface ships. The location, 400 miles SW of the Azores at 10,800 feet, indicated that the sub had sunk on May 22, a day after the last radio report.

On February 3, 1969, U.S.S. *Apache*, towing U.S.S. *White Sands* with DSV-1 on board, left the West Coast of the United States for a 14,000-mile trip to the Scorpion dive site by way of the Panama Canal and the Azores. Enroute to the Azores, launching tests of DSV-1 were conducted. During one of the tests, the tow line on DSV-1 got loose and it was adrift for 9 h. Later, 2 days of storms caused damage to the submersible so no more tests were conducted until repairs could be made. Another storm encountered en route caused additional damage to the equipment on DSV-1, including the hanger on the bathyscaph that housed "Tortuga." The first ROV, suggested by John Craven, developed at San Diego's Naval Undersea Center (NUC) and built by the San Diego firm, Hydro-Products. Repairs to all the equipment were completed by arrival time in Terceira, Azores, on May 21. Departure for the dive site was made a few days later with the onsite commander Captain Bob Gautier (pronounced "go-shay") who was the COM SUB DEV GRP ONE (Commander Submarine Development Group One) on board. The dive site was reached on June 2. Three days were spent implanting DOTs (deep ocean transponders), small devices resting on or implanted in the sea floor that give directional or homing signals. Another 5 days were spent waiting out the weather.

On July 2, during the fourth dive, *Scorpion* and its entombed crew of 99 were located during a 14-h, 17-min dive. On all five additional dives, Scorpion was located accurately and timely. During those five dives on *Scorpion* (the average length of dive was just under 15 h), many photographs were taken. At last, Tortuga was launched. While the ROV worked as intended, the flotation balls on the umbilical tether continually got snagged in the debris, preventing a survey of the torpedo tubes. The last of nine dives was made in July. The DSV-1 was returned to San Diego in October and an overhaul began in December.

Back in San Diego, the pictures were developed. In the photos, *Scorpion*'s ring stiffeners had buckled; between stiffening rings, the hull plates had caved in, and in addition, an accordion collapse was evident lengthwise of the hull. It seemed apparent that the section of hull being shown had failed in all three classic failure modes at the same time, indicating that the area photographed had passed its crush depth very rapidly.

Most of 1970 found DSV-1 in overhaul.

After the overhaul, the Navy conducted only two dives that year, one in November and one in December at 13,200 feet. Both were in the Southern California area.

The first dives in 1971 were all made in the San Diego area at depths of 4700 feet or less, for post overhaul sea trials, vehicle certification, navigational network training, and one 5-h dive to recover a Scripps instrumentation package that was lost. The next two dives were made 300 miles NNW of Kauai Island, Hawaii, to recover military instrumentation packages at 16,400 feet depths during two 10-h dives.

In April 1972, DSV-1 returned to the dive site near Hawaii for an additional instrumentation package recovery dive at 16,400 feet, lasting 9 h, 19 min. The next dives were made near San Diego at 4,575 feet in search of an F-4 aircraft crash site in mid-July, averaging 7 h per dive. Three dives were made in late September, searching for the hulk of a sunken Navy Ship at 4,700 feet.

The first dives in 1973 were made near San Diego at the F-4 plane crash site in January, February, and May at depths of 4,600 feet, averaging 5 h per dive. In July, DSV-1 was deployed to an area NW of San Francisco. At a depth of 10,699 feet, she recovered a lost and submerged, unmanned sled carrying oceanographic equipment with a replacement value estimated at $250,000. Two dives were made in the San Diego area for pilot certification. The last dive of the year was made in October for a manipulator test near San Diego. The dive duration was reduced to 4 h due to a battery meltdown. In late 1973, DSV-1 went in for major overhaul that lasted all through 1974.

After leaving the shipyard on May 4, 1975, three dives were made pierside while tethered for postoverhaul tests. The fourth and last dive of the year was made in August near San Diego.

Major new electronic systems installed during the 1974 overhaul continued to be tested in early 1976. A "10K certification dive" was made in February to 10,004 feet for 7 h near San Diego. Four dives were made to locate a lost helicopter and for pilot training near San Diego. Two dives were made to recover F-14 debris near Ensenada, Mexico. A dive was made to recover a DOT at 3,946 feet near San Diego in November. A lost Sea Stallion Helicopter from Brown Field was located during an 11 1/2-h dive. The rotor assembly was recovered in November, and on the last dive of the year in December, the tail rotor was snared and pulled loose after a 13-h dive.

The most dives per year, the deepest series of dives, and the most important scientific dives made by DSV-1 were all made in 1977. The first of these were in January to 4,000 feet near Ensenada, Mexico, to recover DOTS. They averaged 13 h per dive. The next dive series was made near Catalina Island for sea trials and pilot training in conjunction with the support ship Point Loma. A dive was made west of San Francisco in an attempt to certify DSV-1 for 20,000 feet; however, the submersible reached only 17,246 feet at the bottom of that site in the Mendocino Fracture Zone.

DSV-1, on board U.S.S. *Point Loma*, departed San Diego in May for a 16 dive series of geological investigations in the Cayman Trough, Puerto Rico Trench, Blake-Bahama Plateau, and Mid-America Trench, in conjunction with several universities and research institutions sponsored by the ONR. The ships reached the Cayman Trough operations area in mid-June. The Cayman dives were made in conjunction with Dr. Bob Ballard of Woods Hole Oceanographic Institute to investigate tectonic plate spreading and volcanism.

The first dive in the series was made on June 23 to a depth of 20,236 feet for 10 h to certify the submersible. While on the bottom, DSV-1 recovered a piece of lava the size of a softball, still crackling from contact with sea water. It was the deepest object recovered from the sea floor at the time. The Cayman Trough is unusual in having all three tectonic geological zones: subduction, spreading, and strike or slip zones. The second dive was in the same area at 19,310 feet for 16 1/2 h under water. The third dive was in the same area but was cut short to 3 1/2 h when a vertical cliff was bumped while blindly sinking to the bottom during descent. The bow planes and forward pan and tilt were damaged but repairable. Since bubbles in the water resulting from the impact might have been AVGAS used for buoyancy in the float, the dive was prudently aborted. Upon surfacing, it was determined that no damage to the float had occurred and that the dive series could continue.

Dives 4, 5, and 6 were made in August at 9,200 feet or less, with the Naval Ocean Science Center scientists as observers. The dives lasted from 14 1/2 to 20 1/2 h. Dives 7 thru 11 ran from September 20 to October 1 in the Blake-Bahama Outer Ridge. These made it possible to study the formations and structures of furrows and mud waves as well as the currents that caused them. The smaller mud waves were a yard wide and a yard deep. Others were over 30 feet wide and deeper than the height of DSV-1. Arctic currents and tsunamis may have caused the "ripples." Dives were 16,446 feet or less in depth and were of 5 to 14 h in duration. One dive had to be aborted after 5 h when bottom sand got jammed into one of the shot tub outlets, preventing its ballast dropping valve from working.

Dives 10 and 11 were made to prove Puerto Rico had rotated 90° during its geological history. Dives 12 thru 15 were made in support of scientists interested in the structure of calcium carbonate platforms, their modification by plate tectonic forces, and the nature of plate tectonic subduction in the area of Mona Canyon. Fossil coral was discovered during the dives which were made between 16,500 and 20,200 feet depths for 12–1/2 to 21–1/2 h per dive. Dive 16 was completed on October 28 for the last dive of the series. The submersible was returned to San Diego in November and the crew was awarded the Meritorious Unit Commendation for the deployment.

LCDR Les Parsons relieved Kirk Newell as OIC for the 1978 dives. The first three of four dives made during the year were made in Southern California waters for training and DOT retrieval. A major deployment was made to an area near Midway Island in late August. An Air Force navigation system with recorder had splashed down in open ocean at a depth of 16,000 feet. Upon sighting the sunken hardware, at depth, it was apparent that the one ton capsule had buried itself deep into the seabed. After a manipulator was broken trying to free the heavy object, the Chief of Naval Operations (CNO) called the project off and DSV-1 returned to San Diego. The details of the operation remain classified.

The first dives in 1979 were made between San Diego and San Clemente Island at depths of 12,700 feet or less for pilot training and certification. In June, DSV-1 and the U.S.S. *Point Loma* departed San Diego for the

Panama Canal and the Mid-Atlantic Ocean. Two dives were made on the Deep Ocean Stations 1 and 2 to pick up specimens for Woods Hole Oceanographic Institute, as DSV *Alvin* was out of commission and in overhaul.

Three dives were made on the crash site of the *Scorpion* for CNO at 11,300 to 11,700 feet depths. On one of the several long dives to see if radiation activity or its migration existed (it did not), 25 h was spent submerged. During another of the dives, the surface ship lost all power. Communications from the ship to DSV-1 were made by battery power. After surfacing, the DSV-1 was left surfaced, unmanned, for 3 days while the ship's power was restored. On a dive in the AUTEC Range in the Bahamas in October at 5,000 feet, a mobile submarine simulator was recovered in record time due to the fact that, after the launch and travel to the sea bed, DSV-1 had accidentally landed on the bottom only a few feet from the simulator. After this last dive of the year, DSV-1 was returned to San Diego for postdeployment analysis and upkeep.

The first two dives in 1980 were made in Southern California waters in February and March. The next dives were expeditionary in nature, requiring transit to an area off of the coast of Guatemala known as the Mid-America Trench. The deployment was to assist Scripps Institution of Oceanography in investigating plate tectonic dynamics within the trench. The dives took place during April at a 16,140 feet depth. Earlier in the year, a Navy-owned RUWS (remotely operated underwater work system) was lost at sea near the big island of Hawaii. DSV-1 was asked by CNO to find and recover it. In July, a dive was made in the area, but the bottom was so full of massive blocks of rock bigger than the bathyscaph—or, more to the point, bigger than RUWS—that it made SONAR nearly useless, as all targets looked alike. During the next two dives in August to 16,330 feet, the vehicle was located and recovered.

After the eighth and last dive in 1980, all future dives by DSV-1 were for training. Chief Warrant Officer Burt Tharp became the officer in charge until the submersible was decommissioned. DSV-1 was kept on line due to a letter from CNO ordering that a 20K capability be maintained until Sea Cliff could be outfitted with its new 20K titanium hull.

Four dives were made during 1981 at 5,000 feet or less, followed by a brief overhaul of the sphere in July. The six dives in 1982 were made in the "reduced operating status." They were routine dives to 4,000 feet operating from a barge stationed at San Clemente Island. In 1983, two routine dives were made, followed by the 122nd and last dive of her career. During the last dive on October 7, a malfunctioning San Clemente Island Range hydrophone was recovered. DSV-1 was deactivated on May 18, 1984, and arrived at the Naval Undersea Museum in Keyport, Washington, on August 3, 1988, where it was placed on display.

From Dr. Piccard's first vision of a balloon in reverse, to the historic Piccard/Walsh voyage to the bottom of the Marianas Trench, and finally to the numerous scientific and military missions that were to follow until the wind down of the U.S. Navy's bathyscaph program in 1984, all of those involved ran a truly first-class operation.

Reference

Davis, R. H., 1951. Deep Diving and Submarine Operations, 5th ed. London: Saint Catherine Press Ltd., 654 pp.

Tech Specs: *Trieste* and *Trieste II*: From "Manned Submersibles" by R. Frank Busby

Guest Editor's Note:

Following are four pages of tech specs of the bathyscaph *Trieste* and the later *Trieste II* (DSV-1). The pages are notable for the signatures of many of the pioneering men who dared to enter the deep water in bathyscaphs.

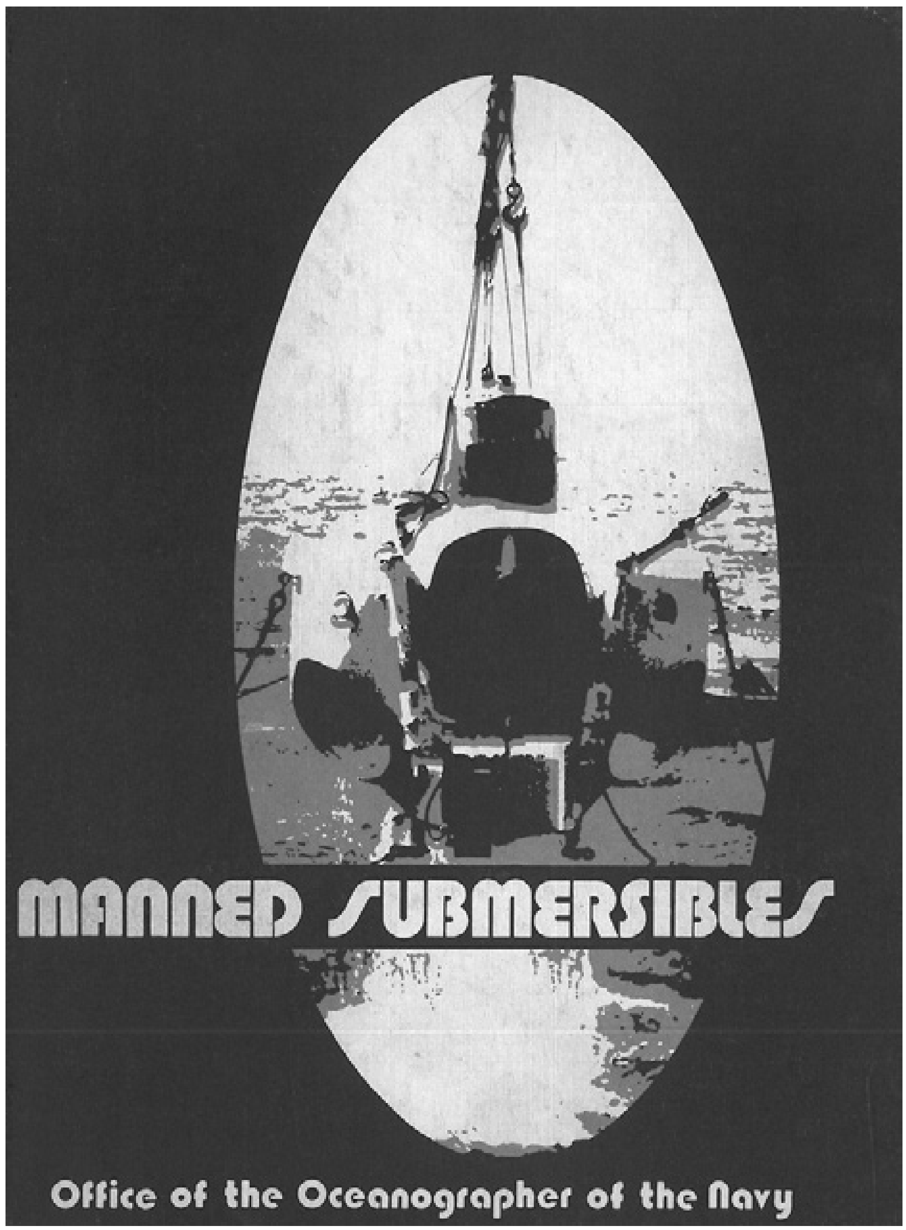
The pages are taken from "Manned Submersibles," by R. Frank Busby. Busby's textbook remains the finest single volume ever assembled on human occupied undersea vehicles. Published in 1976 by the Office of the Oceanographer of the Navy, the book is a reservoir of practical knowledge, presented with clear descriptions and relevant examples. It remains a powerful reference 35 years after its first publication. In supporting the publication and distribution of the book, Rear Admiral J. Edward Synder, then Oceanographer of the Navy, said in the Foreword, "It is the Navy's intent to encourage a wider and more productive exchange of information concerning the requirements for performing useful work in the deep ocean and information about recorded achievements in the design and operation of manned submersibles."

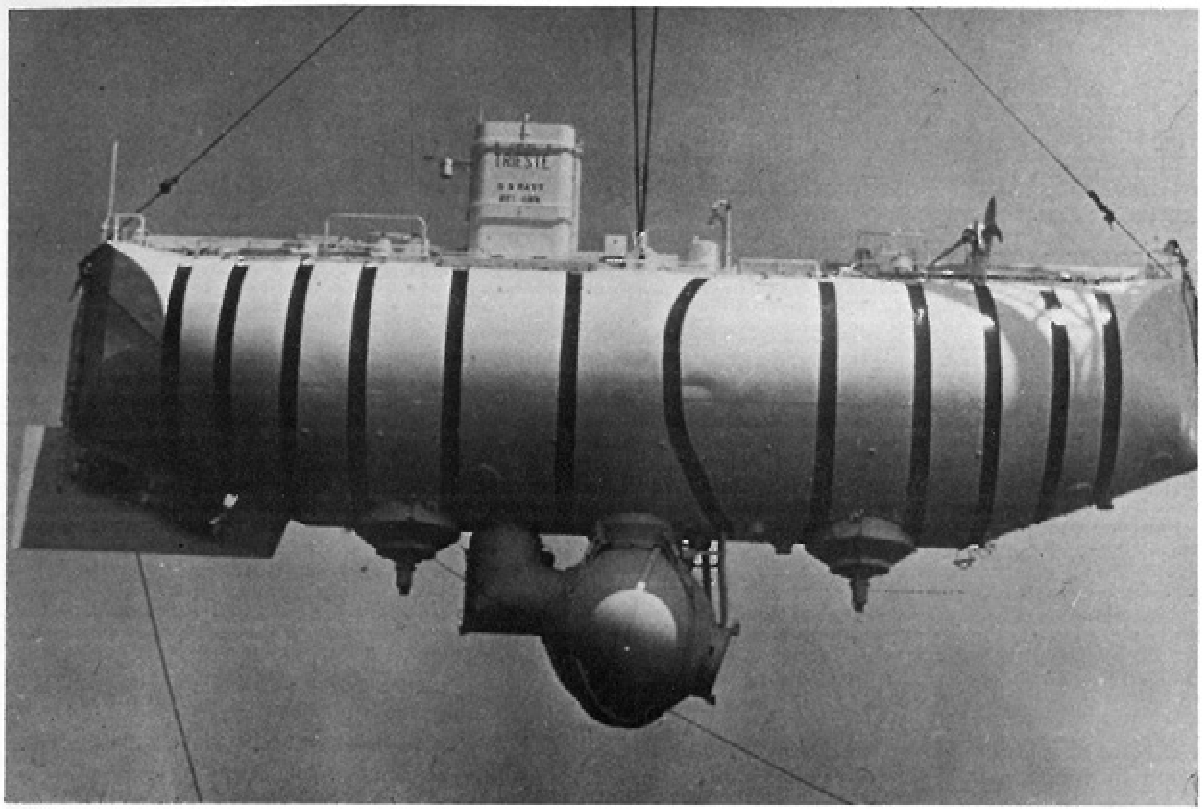
The book is no longer in print but is in the public domain. Thanks to the efforts of some hardworking volunteers at the Personal Submersibles Organization (PSUBS), this book has been converted to CD format with permission of the U.S. Navy and is available at nominal cost at http://www.psubs.org/store/media/psubs/busbycd.html.

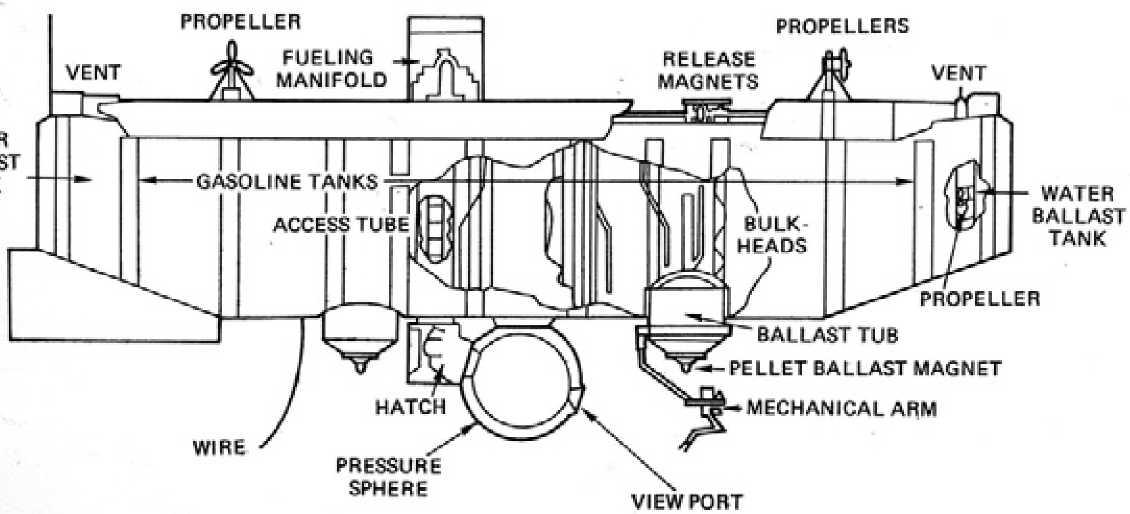
PSUBS.ORG also makes Busby's book available for free online. Visit Manned Submersibles Online at http://busby.psubs.org/ for complete access to the book.

Original copies are also occasionally available at: http://www.bookfinder.com.

Kevin Hardy



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HEADS
WATER
BALLAST
TANK
PROPELLER
BALLAST TUB
PELLET BALLAST MAGNET
HATCH
MECHANICAL ARM
WIRE
PRESSURE
SPHERE
VIEW PORT

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TRIESTE I

LENGTH:	59.5 ft
BEAM	11.5 ft
HEIGHT:	NA
DRAFT:	18 ft
WEIGHT (DRY):	NA
OPERATING DEPTH:	No known ocean limit
COLLAPSE DEPTH:	60,000 ft
LAUNCH DATE:	1953
HATCH DIAMETER:	16.9-in. ID; 22.5-in. OD
LIFE SUPPORT (MAX):	NA
TOTAL POWER:	NA
SPEED (KNOTS): CRUISE	0.5
MAX	0.5
CREW: PILOTS	1
OBSERVERS	2
PAYLOAD:	NA

PRESSURE HULL: Spherical shape of three, Ni-Cr-Mo steel forgings 6.25-in. ID and 5 to 7 in. thick.

BALLAST/BUOYANCY: Buoyancy provided by 29,000 gal of aviation gasoline. Eleven tons of steel shot ballast carried in two hoppers is released to offset compression of gasoline as vehicle goes deeper. Release controlled through an electromagnet valve. Additional shot release over amount required to offset gasoline compression initiates ascent. A small fixed percentage of gasoline may be released to offset over release of shot if necessary.

PROPULSION/CONTROL: Two, 2-hp motors used for propulsion and steering. Motors in light casings filled with Trichlorethelene and pressure-compensated.

TRIM: Some bow angles obtainable by dropping shot only from one hopper.

POWER SOURCE: Initially lead-acid batteries in the sphere, these were replaced by silver-zinc batteries.

LIFE SUPPORT: Compressed, gaseous O_2 at constant flow rate equivalent to usage of two men, passed through an eductor, draws cabin air through three Drager (LiOH) cannisters to remove CO_2.

VIEWING: Two plastic conical viewports 2-in. ID, 16-in. OD and 7 in. thick.

OPERATING/SCIENTIFIC EQUIPMENT: UQC, echo sounder, depth gage.

MANIPULATORS: None.

SAFETY FEATURES: Electromagnetic shot valves fail open upon loss of power. Each of the two hoppers held in place electromagnetically may be jettisoned if valves fail and will release automatically in event of power loss. Gasoline compartments sized such that loss of all gasoline in one compartment will not reduce buoyancy below ability of reserve shot to compensate.

SURFACE/SHORE SUPPORT: Sea-going tug for tow to and from dive site.

OWNER: U.S. Navy.

BUILDER: Auguste and Jacques Piccard.

REMARKS: The above description is from the 1953-1959 period. TRIESTE I established and still holds the world's deepest dive record: 35,800 ft in the Challenger Deep (200 miles southwest of Guam) on 23 Jan. 1960. Aboard during this dive was Jacques Piccard and LT Don Walsh, USN. The float is now on display in the Navy Yard, Wash., D.C.

Andy Rechnitzer

O-IN-C TRIESTE

'59 → '62

O in C Trieste

59-62

Stephen F. Moran

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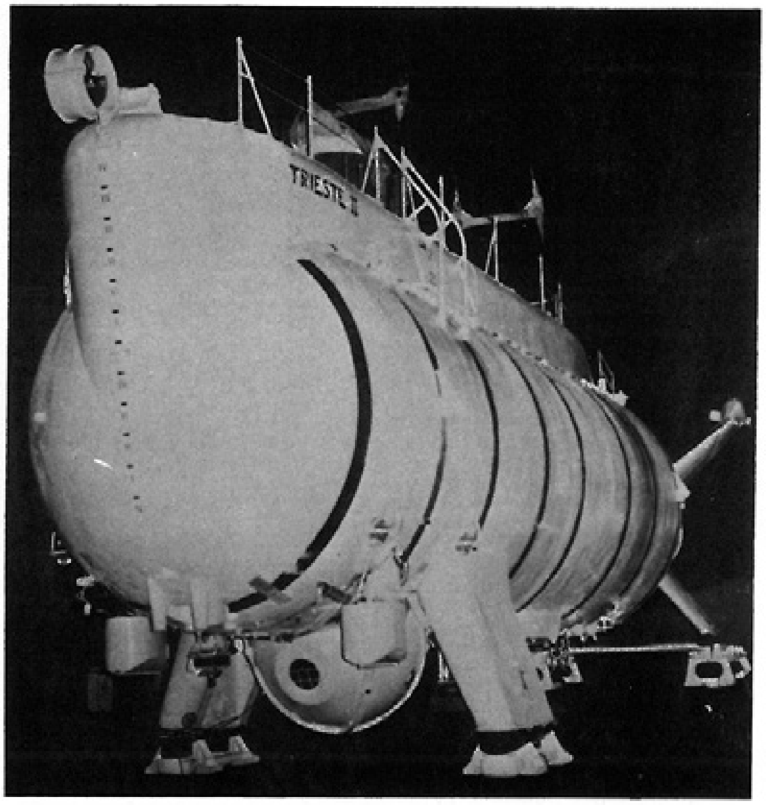
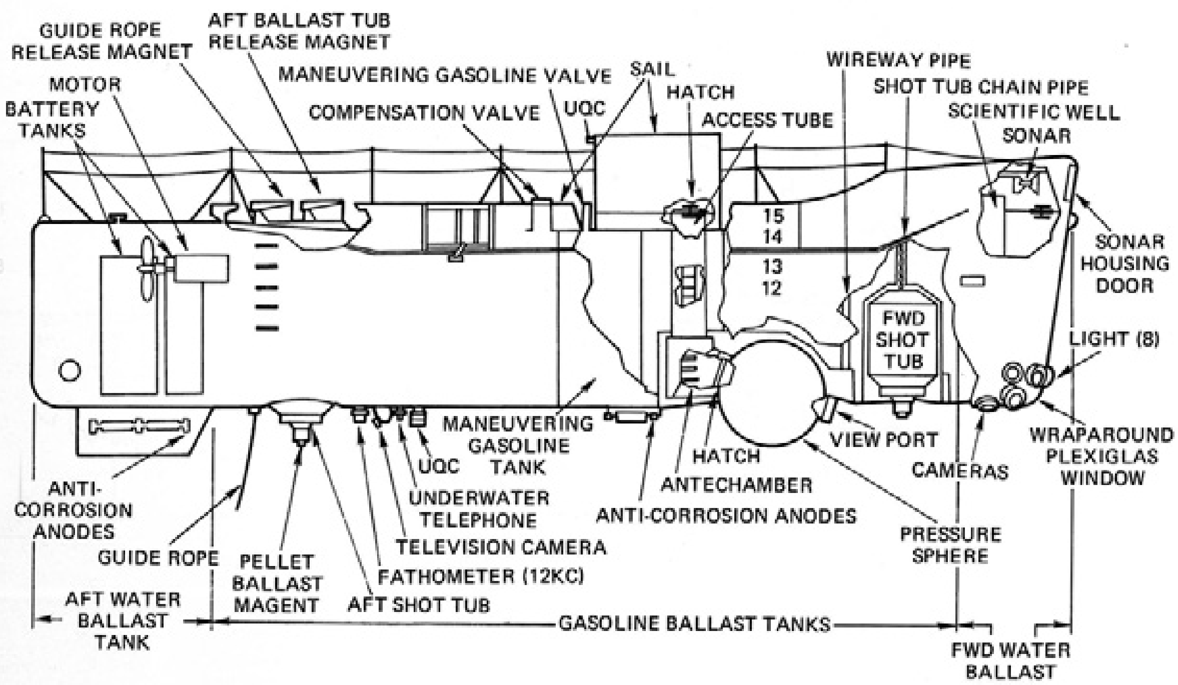

TRIESTE II


GUIDE ROPE
RELEASE MAGNET
AFT BALLAST TUB
RELEASE MAGNET
MOTOR
BATTERY
TANKS
MANEUVERING GASOLINE VALVE
COMPENSATION VALVE
UQC
SAIL
HATCH
ACCESS TUBE
WIREWAY PIPE
SHOT TUB CHAIN PIPE
SCIENTIFIC WELL
SONAR
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HOUSING
DOOR
15
14
13
12
FWD
SHOT
TUB
LIGHT (8)
WRAPAROUND
PLEXIGLAS
WINDOW
MANEUVERING
GASOLINE
TANK
UQC
VIEW PORT
HATCH
ANTECHAMBER
CAMERAS
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ANODES
UNDERWATER
TELEPHONE
ANTI-CORROSION ANODES
PRESSURE
SPHERE
TELEVISION CAMERA
GUIDE ROPE
PELLET
BALLAST
MAGENT
FATHOMETER (12KC)
AFT SHOT TUB
AFT WATER
BALLAST
TANK
GASOLINE BALLAST TANKS
FWD WATER
BALLAST
TANK

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TRIESTE II

LENGTH:	78.6 ft	HATCH DIAMETER:	19.8-in. ID
BEAM:	15.25 ft	LIFE SUPPORT (MAX):	72 man-hr
HEIGHT:	26.9 ft	TOTAL POWER:	NA
DRAFT:	21 ft	SPEED (KNOTS): CRUISE	2/12 hr
WEIGHT (DRY):	87.5 tons	MAX	NA
OPERATING DEPTH:	20,000 tons	CREW: PILOTS	2
COLLAPSE DEPTH:	>40,000 ft	OBSERVERS	1
LAUNCH DATE:	1964	PAYLOAD:	5 tons

PRESSURE HULL: Spherical shape composed of two hemispheres of HY-120 steel clamped together on an equatorial flange. ID of 84 in., 3.9 in. thick to 6 in. at viewports and penetrations.

BALLAST/BUOYANCY: Aviation gasoline (65,830 gal) is carried in a thin-walled float to provide positive buoyancy. Electromagnetically held iron shot (22 tons) provides negative buoyancy and is incrementally released to ascend or decrease the vehicle's buoyancy. Trailing ball (250 & 750 lb) on 150-ft cable.

PROPULSION/CONTROL: Three, stern-mounted, 1,750-rpm, 120-VDC, 6.5-hp (each) motors provide main propulsion. A horizontal thruster is mounted on the bow.

TRIM: Shot hoppers mounted port/starboard amidships and one aft may be differentially filled to obtain ±12° list, and +33° to −27° down bow angles at 20,000 ft.

POWER SOURCE: Externally-mounted, pressure-compensated silver-zinc batteries. Sixteen cells provide 5,000 amp-hr apiece at 24 V and 80 cells provide 952 amp-hr apiece at 120 V.

LIFE SUPPORT: Gaseous O_2, three bottles, each 72 ft^3 at 2,250 psi (two normal, one emergency). CO_2 removed by LiOH. Monitors for O_2, CO_2, cabin pressure, temperature and humidity. Air conditioning system, Hull heat exchange system. Emergency breathing off O_2 bottle.

VIEWING: Four plastic viewports. One is 16-in. OD, the remaining three are 3-in. OD.

OPERATING/SCIENTIFIC EQUIPMENT: UQC, CTFM sonar, Doppler navigator, X-Y plotter, gyrocompass, altitude/depth sonar, echo sounder, transponder interrogator system, sound velocimeter, three still cameras, one cine camera, three TV's.

MANIPULATORS: One with six degrees of freedom.

SAFETY FEATURES: Shot and several outboard equipments jettisonable. Emergency breathing of 36 man-hr. Fail-safe shot jettison. Fire extinguisher. Distress rockets. Surface lights.

SURFACE SUPPORT: Transported by floating Dry Dock towed by an ocean-going tugboat.

OWNER: U.S. Navy, Submarine Development Group One, San Francisco, Calif.

BUILDER: U.S. Navy, Mare Island Shipyard, San Francisco, Calif.

REMARKS: Operational. Studies underway to substitute aviation gasoline with Isopar F., a lower flash-point fluid. Since its first major modification in 1964, TRIESTE II has undergone numerous, significant design and operational changes. The above description is how it now (Aug. 1974) stands.

Brad Mooney

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PAPER

Human Exploration of the Deep Seas: Fifty Years and the Inspiration Continues

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ABSTRACT

The deep seas have facinated the world for centuries. The flow of new ideas has traveled through the centuries and inspired people to dive below the surface and explore the forms of life that exist in the abyss. Many early ideas led primarily to military developments, with scientific research emerging much later. Only in the past 100 years has the technological capability matched the human desire to deep dive into the oceans and discover its true mysteries. This article looks back at the history and flow of such ideas that involved submersible vehicles, how this led to the development of the *Trieste* bathyscaph, concurrent activities around the world, the efforts involved in completing the dives, and the impact this deep dive has had on the evolution of submersibles. It presents the successes, the challenges, as well as the grit and luck it sometimes took to make it happen. After fifty years, it is clear that the sea still holds many mysteries. Human-occupied underwater vehicles will remain a central element among the modern tools at the service of knowledge acquisition. The future calls us to see and discover this underwater world—not simply to be awed by its power and beauty but to learn; to comprehend the complex web of interrelations between our life on land and its impact on the seas. We stand on the shoulders of many dedicated engineers and explorers as we continue to inspire the next generation to study the many alien creatures that will teach us anew.
Keywords: Submersibles, Bathyscaph *Trieste*, submarines, Marianas Trench, ALVIN

Every breath resonated in the tight space of the submerged steel construct. They had endured 5 h of endless exertion. The air had turned musty, and heavy hours ago, everything was dark and humid. Muscles ached from being hunched over in unnatural positions and the cold seeped into all extremities. The silence, broken only by guttural strain of eight people turning the crankshaft, amplified the tension, the need for utmost self control. The labor of each breath hurts as much as the hands on the crankshaft. A lone candle was robbing precious air, but the miserable flicker offered a glimmer of hope in this claustrophobic ordeal. Will the gun powder explode? Will they ever smell fresh air and see blue sky again?

Mentally, I contrast that past with the present as I watch my guest gasp in wonder at the vertical rock formations populated by sponges, crabs, and fish. As we pass 300 m and rise back from the canyon, Mobila rays swirl and fantastic creatures glow in the mid-water column. Words developed for life on land are inadequate for this aquatic panorama. The camera shoots non-stop. We watch in silent awe. The magic of modern technology, fresh air at atmospheric pressure, transparent pressure hulls, plentiful silent electric power, the convenience of high pressure air systems, are all in stark contrast to the hard beginnings of underwater travel. The experience is right out of H.G. Wells as the submersible transports yet another guest into a world heretofore unknown.

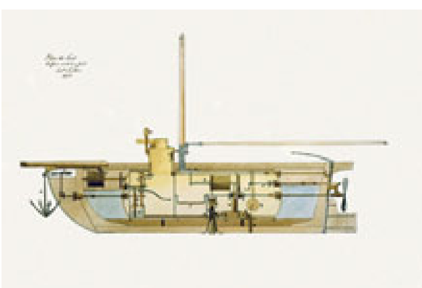
The evolution of human creativity, the history of the technological advances that have made such a ride possible, is the result of the effort and imagination of many generations of persistent engineers, sponsors, and programs; and their stories inevitably dissolve in waters of time, some things remembered more than others. With the 50th anniversary of the TRIESTE's record-breaking dive to the bottom of the Marianas Trench, at a depth of 10,916 m on January 23, 1960, it seems fitting to pay tribute to the influence this event has had on the world of submersibles and note how this singular event emerges onto the pages of history. As we look back over time perhaps, we can find hints about the convoluted road toward the future.

The Early Stages

Passing by medieval constructs of underwater vessels, the first "submarine" is the American TURTLE, built in 1772 by David Bushnell during the American Revolution. This particular submersible did not have any practical achievement; however, it is the first to have all systems needed for making a submarine: ballast and trim control, tubes for ventilation, vertical and horizontal propulsion, and demonstrates classic ingenuity paired with military motivation. Small in size and of wood construction, human powered, the sub signals a starting point in the ongoing quest for military stealth, an ageless concept. Roughly 25 years later, Robert Fulton, an American who moved to Europe to study, conceives and builds the NAUTILUS. Also a hand-powered vehicle, this four-man hull is made of copper and attempts a 70-mile voyage in the Bay of Seine. Reasonable success results in Fulton gaining Napoleon's sponsorship for use of the sub against British naval forces (Figure 1).

FIGURE 1

1800 NAUTILUS—Concept of Robert Fulton in France.



These concepts appear before 1800, well in advance of electricity, batteries, air compressors, and engines. The 19^{th} century opens with the turmoil of the American and French revolution, and the Napoleonic wars in Europe further churn up many new ideas—new social concepts, from utopia to the sustainment of aristocratic power, as well as inventions that coalesce into the industrial revolution. So it is that early in the century Robert Fulton, after being disillusioned by the vagaries of political whim, gives up on Napoleon and the NAUTILUS, and returns to the United States in 1806 to father his more successful invention, the 1835 steamship "Claremont".

With the advent of electricity, the world changes forever, but slowly. Alexander Volta formulates the first principles of electricity and batteries in 1800. It is clear by then that mechanical power can benefit the greatest human cause: quality of life. Wind and water power are old friends but are in no way portable. The idea of a secret energy, an electric form that can be stored, seems pure science fiction but dogs the minds of inventors. The genie is out of the bottle but progress is slow. Not until 1835 is a practical battery developed. Michael Faraday (in England) develops the first concepts of electric motors by 1821, but Thomas Davenport (in the United States) does not produce the first practical electric motor until 1837; and while it generates real work, it is not commercially viable. The idea of sending men underwater to recover objects, however, gains momentum in England as Augustus Siebe develops the "closed" diving helmet and suit (also 1837), and in France, Dr. Manuel Guillaumet invents a twin hose demand diving regulator (1838). More and more divers start to explore the sea.

Fully 50 years after the NAUTILUS, in 1850, Wilhelm Bauer, in northern Germany, builds the BRANDTAUCHER at the Howaldtswerke shipyards during Germany's war with Denmark. Designed as an incendiary vessel to disrupt the surface fleet, thus breaking the Danish naval blockade, it has limited success, but Bauer's second generation SEETEUFEL is built and developed in St. Petersburg in 1855 for Russia (he found no sponsors in Germany). Although it is without life support systems and human-powered by a pair of wheel cages, it does integrate a diver lockout system and presents a milestone in operational success performing a total of 133 dives. This period does not contribute to the eventual submarine development in Germany, but it provides a bridge from the early embryonic concepts into the second half of the 19^{th} century.

By the late 1850s and early 1860s, the American stage prepares for submarine innovation in military conflict on several fronts. At the start of the Civil War in 1862, a multiperson, hand-operated submarine, the ALLIGATOR, is devised by Brutus de Villeroi, a French engineer in the service of the Union Navy. (He had designed and built a small submarine in Nantes, his home town, in 1833, and had tried, unsuccessfully, to sell it to the French navy. He is also said to have been a mathematics professor at Saint-Donatien Seminary in Nantes in 1842, where a young Jules Verne was also a student.) De Villeroi moves to the U.S. in the 1850s (from Wikipedia, 2009).

After the start of the American Civil war, Horace Hunley, James McClintock, and Baxter Watson built the submarine PIONEER in 1861. It is scuttled in 1862 with the Union army taking of New Orleans. The team builds a second submarine, which sinks in Mobile Bay, Alabama. Hunley then builds a new submarine on his own for the Confederate Navy. Deployed in 1863–1864, the CSS H.L. HUNLEY, empowered by the boldness of its crew, sees numerous catastrophic test dives between Mobile, Alabama, and Charleston, South Carolina (Figure 2). One of the rare survivors, Lt. Hasker, who was the ballast control officer during the second tragedy in Charleston, will pass on the torch and recount his narrow escape 40 years later to a then

FIGURE 2

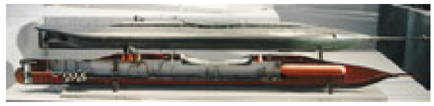
1863 HL HUNLEY—Cross section view of an eight-man hull and crankshaft.

young Simon Lake, who goes on to build some of the first U.S. Navy submarines in the 1900s (Forman, 1999). Ultimately, the HUNLEY makes history on February 17, 1864 for the first sinking of an enemy ship by a submarine (Forman, 1999). The Housatonic was a powerful Union 16-gun steam sloop. Five of its crew are killed in the sinking; the entire crew of the HUNLEY perishes.

This "success" engenders more passion and grit than technological innovation. Range and endurance are determined purely by human exertion. Life support problems mandate shallow diving and use of a snorkel; navigation is by sub-surface travel and conning tower windows. Stealth is the primary focus, diving only deep enough to avoid detection for explosive ordnance delivery. A return to safety is more hope than expectation. Travel through the deep ocean is unimaginable, and it is difficult to conceive of the terrifying visions of the abyss prevalent at that time, or the desire to seal oneself in a human construct that becomes all too often the coffin it resembles (Figure 3).

FIGURE 3

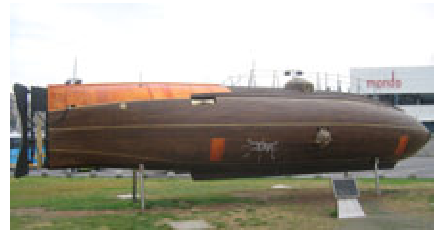
1863 PLONGEUR submarine with compressed air propulsion (Bourgeois and Brun, French Navy).



In a parallel effort in Europe, Cmdr. Bourgeois and engineer Charles Brun develop the PLONGEUR for the French Navy in 1863. The first submersible not propelled by human power, it leverages the invention of compressed air to equip the submarine with an air-powered propeller. Range is limited but the system works. By 1864, the French team of Benoît Rouquayrol and Navy Lt. Auguste Denayrouze develop the first autonomous (untethered) dive system for divers, winning the Gold Medal at the 1867 Exposition Universelle. Both developments are significant technological advances. Jules Verne, present at the Exposition, is fascinated by the potential of this technology and with electric power. In 1869, he writes his classic "20,000 Leagues under the Sea." Not only are his ideas of technology revolutionary, but just as bold and fantastic is the idea of a submarine used in civilian application. He envisions not only a submersible (an underwater vehicle of limited range which needs a support ship) but a full submarine, a self sustaining machine capable of venturing out on its own for long periods of time. Seventy-eight years later, Jacques Cousteau, also impressed by the work of Denayrouze, refers to his concept in his SCUBA invention (Figure 4).

FIGURE 4

1864 ICTINEO II—Air-independent steam engine propelled six-person submarine (Narcis Monturiol, Spain).



With a single exception, global buildup of modern armaments throughout the second half of the 19th century dictates a military application in all submarine design. The notable anomaly is the Spanish wooden submarine ICTINEO of 1859, designed and conceived by a political revolutionary with utopian visions. Narcis Monturiol is a self-taught designer in Barcelona, who dreams of an underwater boat after witnessing the hardships and an actual drowning of a clam diver near his hometown (Stewart, 2004). Monturiol has no nautical design background, and his lack of training frees him from any preconception of what is and is not possible. He developed a chemical scrubber system to remove carbon dioxide, produces oxygen, and a delivery system to achieve full life support capability. Foremost in his outside-the-box thinking, however, he incorporated 19 viewports indicative of the exploration nature of the project and develops external underwater lights combusting hydrogen and oxygen in a controlled reaction. Ultimately, he produces a second submarine (ICTENEO II, 1864), unhappy with the manual propulsion system. Although this becomes his financial demise, he creates the first mechanically driven submarine using an anaerobic propulsion system. He harnesses the steam engine technology of his time and devises a chemical reaction that generates heat and steam using peroxide compounds. This provides power as well as the oxygen needed by the crew. It is a giant leap for its time and a mostly unheralded accomplishment, compared to Halstead's INTELLIGENT WHALE design of 1870 for the U.S. Navy, which, although has a steel hull, is still hand-operated. The ICTINEO, like many designs of the era, falls far short of its planned endeavors. Monturiol firmly believes that a submarine could be put to use for the greater good of humanity, exploring the mysteries of the terrifying abyss, but finds himself isolated by his utopist sense of purpose, and the commercial venture fails. Interestingly, it would not be until 1940 that an Air Independent Propulsion (AIP) concept is tested by the German experimental V-80 submarine—Dr. Hellmuth Walter's new turbine uses hydrogen peroxide and diesel as fuel as the primary energy source to form the basis of the German Navy's new U-boot secret weapon that could go twice the speed of any conventional submarine but never made it to service.

By 1870, the pace of development accelerates briskly with the production of new military submarines. Underwater exploration is entirely suspended for nearly 60 years, until well past the end of WWI. This is when Barton and Beebe with their bathysphere appeared on the pages of history, descending into the deep ocean solely in search of knowledge. To put that moment in context, it is interesting to see how today's military submarine industry gets started.

Early Military Submarine Development

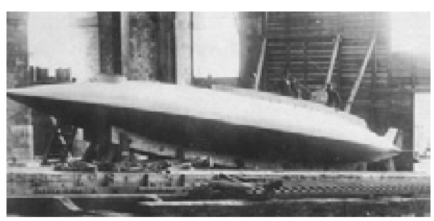
Iron becomes available in plentiful quantities in the 1860s, but it takes another 15 years before the evolution of the Bessemer process (invented in 1855) make steel readily available. In 1873, Zenobe Gramme produces the first commercial DC motor in France. In 1888, Nicola Tesla develops the first induction motor bringing AC electric power forefront. The minds of Edison, Ford, and Daimler are all working to impact the turn of the century (Figures 5 and 6).

FIGURE 5

1888 PERAL—All electric submarine (Spain).

FIGURE 6

1888 GYMNOTE—All electric submarine (France).



Move to Ireland, where John Holland's early submarines emerge with the FENIAN RAM in 1881, funded by Irish groups in the United States supporting resistance at home against the British. The design has room for three crew members. Meanwhile, in the United Kingdom (1885), a new company, Garret & Nordenfelt, builds a series of steam powered submarines for the Greek and Turkish navies. In 1887, the NORDENFELT II becomes the first submarine to fire a torpedo while submerged under water. The NORDENFELT design would later produce the W1 and W2 submarines built at the Howaldtswerke shipyards in Germany, creating a lineage of submarine construction that still exists: the Howaldtswerke-Deutsche Werft (HDW) today build modern Type 209, 212, and 214 submarines. By 1887 in France, Henri Dupuy and Gustave Zédé builds the GYMNOTE for the French Navy. This is the first fully electric submarine, capable of speeds of 4.3 knots. (It performs more than 2,000 dives and is equipped with the first naval periscope and first electric gyrocompass). Not far away, Issac Peral completes the PERAL submarine for the Spanish Navy that same year. Also all-electric, and with limited range due to the battery situation, its design achieves a speed of 10 knots, an incredible performance, respectable through WWI. Equipped with torpedoes, it contends with GYMNOTE for first "fully capable" military submarine. Unfortunately, the PERAL story is a textbook example of technological development sequestered by the vagaries of political intrigue. As a result of the stunning test data, Peral is funded by the Spanish Navy for a second generation submarine. Previous tension with the Navy led Peral to request choice of the shipyard and design team. The Navy takes offense, interpreting this as a refusal to follow orders and ends submarine development efforts (Figure 7).

FIGURE 7

1898 USS HOLLAND—First diesel electric submarine developed by the Electric Boat Co. (J. Holland, U.S. Navy).

It is John Holland who finds the solution to extend the range of the electric submarine. He combines the advantage of electric motors and electric batteries with the power of gas engines. The concept is embodied in Holland's sixth submarine, which runs submerged on electric motors, recharging the batteries with the gas engine back at surface, a system still used today with diesel. This would set the standard for the rest of the world, and nearly every country purchases a submarine from the newly established Electric Boat Company (50 years later it would become a division of General Dynamics). By the mid 1890s, all superpowers are well into the development of massive naval capabilities. Simon Lake, a generation after the Civil War and inspired by Jules Verne, develops the ARGONAUT and the PROTECTOR, competing for U.S. Navy contracts with the John Holland Co. In fact, Simon Lake's PROTECTOR launches the same year as John Holland's sixth submarine, the USS HOLLAND, eventually called the U.S. Navy's SS-1.

The ferocity of development at the turn of the century, with the emergence of commercial electricity, the development of land vehicles, and the focus of submarines for warfare, is well known. Through WWI, the flow of submarine innovation follows a steady trajectory toward naval power. Technologies in batteries, electric motors, underwater cabling, steel fabrication and forgings, high pressure valves, and controls all carry forward into a new era.

Scientific Exploration Resurfaces

Well after World War I, Otis Barton begins to design his bathysphere (1928). Together with William Beebe, a famed explorer and director of the New York Zoological Society, Barton sets out to see and record what if anything lives at the bottom of the ocean. The technology is rudimentary compared to what weapons have already been unleashed in the oceans, but the focus is knowledge acquisition, and the resulting observations documented from these voyages are pure inspiration. Other than the development of the steel pressure vessel, the biggest feature of the bathysphere is the set of three large (8.0 inch) windows (Figure 8). These are made of fused quartz, 3 in. thick, manufactured by General Electric and are, at the time, the largest pieces ever made. Both Barton and Beebe believe that sight is the most important of human senses, accounting for more than 80% of all knowledge acquisition (Stachiw, 2003). The quest for better visibility will continue to evolve through the century and become a defining element for submersible vehicles. The team is dedicated and passionate about extending knowledge of the deep ocean. Barton and Beebe set a world record on August 15, 1934 near Bermuda by descending with their bathysphere to a depth of 923 m. Beebe, who writes regularly for the National Geographic, offers the world astonishing records and drawings of glowing sea creatures. His drawings can hardly be believed, and for decades his observations are doubted to be real. Still, they open a gate, however limited, which will lead to a global endeavor within two generations.

FIGURE 8

1934 Bathysphere, William Beebe (left) and Otis Barton set a record 3,028 feet deep.

Auguste Piccard Invents

In that same time, a Swiss physicist at the Free University of Brussels, Professor Auguste Piccard, sets his sights on exploration as well, but in a quest to detect and quantify high energy cosmic particles coming from space that we now define as Nutrinos. He wanted to detect and trace these particles using *in situ* activated photographic emulsions, first with a minimum of attenuation by the atmosphere and secondly with maximum attenuation from both the atmosphere and sea water. Funded by the Belgian FNRS, *Fonds National de la Recherche Scientifique*, he designs and constructs his first stratospheric balloon, which he calls the FNRS, with which he makes 27 flights and will set the world record in altitude. On May 27, 1931, Piccard and Paul Kipfer prepare for a sunrise launch at 5:30 am from Bavaria in Germany. Following a few mishaps, the balloon departs prematurely a little before 4:00 am, with them aboard. Within 30 min they are at 15,500 m and discover a leak in the hatch. They manage to fix the seal; the temperature is cold but they manage to take measurements. By 6:30 am, they decide to return and discover that the valve manifold lines used to release hydrogen from the balloon are tangled outside with a tie-down line that was not removed during the premature liftoff. Their only option is to survive the cold and wait for nightfall to cool and lower the balloon. They land on a glacier in the Tyrol Alps after

17 h up in the gondola. They spend a chilly night by the balloon and are found by the villagers in the morning. Their record stands at 15,781 m, for which they would receive the Légion d'honneur (Piccard and Dietz, 1961).

World War II

Both FNRS and the Beebe bathysphere adventures are celebrated as achievements of human exploration in pursuit of scientific purpose. This is an early trend in the 20th century, when unlike any previous time in history, technical capabilities start to match the desire to uncover long-standing world mysteries. WWII quickly catches up to this quiet period, dragging along with it a huge thrust of human minds. It is in this tumultuous context that ideas continue to incubate. By 1940, with the Armistice declared by France, a young Jacques-Yves Cousteau takes refuge in the French Alps. He establishes a friendship with neighbor and future filmmaker Marcel Ichac, and they share a desire to publish the wonders of the world in far and remote places, which include the ocean and the high mountains. For both, it is a decision that will guide their live's endeavors. They win a first prize for an underwater film in 1943, around the time when Jacques Cousteau and Emile Gagnan develop the first SCUBA regulator.

The Second World War affects great advances in naval, air, and land technologies. Postwar scientists surge forward, seeking technological progress in all directions. In the field of submarines, the German war effort has provided new ideas for faster, quieter machines. Dr. Walter and his famous underwater turbine development find a home at Aerojet in Azusa California, where high-speed propulsion systems are developed. A young engineer named Cal Gongwer will work under Dr. Walter and provide a link 30 years later to high efficiency submersible thruster designs.

Developments (radar, navigation tools, nuclear power, rocket propulsion) leap from conception to actuality. Strategic nuclear research creates the first nuclear-powered submarine (USS NAUTILUS) in 1954, a watershed development that affects all major subsequent naval submarine developments. France, however, maintains a clear independence of thought and politics from the United States, a position that is later interpreted by the United States as a security risk with respect to nuclear technology transfer. The clear separation leads France to maintain many independent technological paths, among which is the pro-active development of new underwater systems.

During this time of frenzied submarine development, diving *sans* sub is equally empowered. As early as 1946, French Navy Lieutenant Philippe Taillier, Ensign 1st Class Jacques-Yves Cousteau, and engineer Frederic Dumas establish the *Groupe d'Études et de Recherches Sous-marines*, GERS (*Undersea Research Group*) with the aim of developing new solutions to further enable the practice of scuba diving. At the same time, a young French engineer, Dimitri Rebikoff, continues his work in photography. By 1947, he develops the first electronic flash, a watershed moment allowing the photography of extremely high-speed events never visible before. He marries photographer Ada Niggeler and by 1950 in Cannes they develop the first underwater camera with flash. Rebikoff (1953) continues to develop the first tethered remotely operated vehicle. Rebikoff and Niggeler eventually move to Ft Lauderdale, Florida, in 1959 where they establish the Institute of Marine Technology and leave a legacy of underwater filming and photography technology. The Rebikoff-Niggeler Foundation today operates a research submersible LULA on the islands of Azores, in Portugal (Jacobsen, 2009).

In Belgium after 1945, Auguste Piccard picks up his bathysphere project, which he had started before the war in 1937, and starts thinking of ways to modify it for deep ocean exploration. Invited to a formal gathering, he is introduced to King Leopold, who inquires on Piccard's latest progress. Afraid to bore the king with his cosmic results, Piccard says, "Your majesty, I am planning to build a deep-sea research submarine, a 'bathyscaph', for diving to the very bottom of the sea" (Piccard and Dietz, 1961). The king is fascinated and wants to hear all the details. The next day, Piccard returns to his lab and relates the conversation to all his assistants. Now they have to make it happen!

With the slow return to normalcy after the war, Piccard finally receives sponsorship in 1948 by the Belgian FNRS group that funded the first voyage to the stratosphere. The budget is minimal but it is an opportunity to move ahead.

The Origin of TRIESTE

Piccard sets off to study the ocean and realizes that the only way to resolve a long string of mysteries is "by going down to the depths of the sea … to clear them up" (Piccard, 1956). Piccard deeply appreciates the work of Barton and Beebe, noting that "it is no exaggeration to say that it is he (William Beebe) who opened the doors of the abyss to man" (Piccard, 1956), but finds several features of the bathysphere unattractive. These include the following:

1. Its tethered state: Surface motion of the mothership could introduce motion causing discomfort or even violent contact with the sea floor (Piccard, 1956).
2. The possibility of cable breakage caused by load-induced strain (Piccard, 1956).
3. The quartz material for the windows: It was brittle and could fracture (Piccard and Dietz, 1961).

Piccard creates his "bathyscaph," which is designated as the FNRS-2 in honor of his sponsors. He bases the design on the same concepts as the balloon. A pressure-resistant personnel sphere incorporates two windows and holds two explorers. Instead of a gas filled balloon, he devises a large float for buoyancy filled with an essentially incompressible light-weight fluid from which he suspends the personnel sphere. He chose a readily available lighter-than-water medium, gasoline. The ballasting system uses large bins of metal pellets as opposed to the sand bags used with a balloon. Electric power from batteries is now readily available. Among his most brilliant achievements, however, is his window design, of which he is personally quite proud: "These windows are perhaps the finest feature of the bathysphere" (Piccard, 1956). (Made of acrylic plastic, such windows are common today and still used on most deep submergence vehicles.) Based on a truncated cone with an included angle of 90°, Piccard's windows provide a 10 cm viewing diameter, 15 cm thick, and have an outer diameter of 40 cm. The window is inset into a finely machined metal seat. With generous lubrication, the acrylic, a plastic material, yields under compression, seating more securely as the external pressure increases. This greatly simplifies the heretofore biggest problem with windows: complex seals, gaskets and retaining rings.

Piccard goes on to design and construct a massive pressure hull. The sphere is cast in Belgium by Usines Emile Henricot, with the final sphere of 2.1 m inside diameter and a weight of 11 tons. The two ends where the window and hatch are located are reenforced with additional thickness. Final assembly is performed in Belgium at the Mercantile Marine Engineering Cie.

The French Navy offers to support the initial dives with their oceanographic ship *Elie Monnier*. Aboard is the GERS group of J.Y. Cousteau, Frederick Dumas, and Cmdr Phillippe Taillez as support divers. The untested assembly is shipped to Dakar in Senegal, West Africa, from where it is towed to Cape Verde, an arduous and slow process. The first dive is limited to a functional manned test to 25 m. In this first design, due to schedule and budget pressures, many systems are kept to a minimum. The FNRS-2 must seal the two occupants in the sphere before launching and then fill the tanks with gasoline. This meant the reverse was also required. Auguste Piccard and naturalist Theodore Monod enter the bathyscaph and the hatch is sealed. The vessel is hoisted into the water and the slow process of filling the floats with gasoline commences. It takes a long time. Eventually, the bathyscaph submerges for a dive lasting 15 min. All seems in order and the submersible ascends. The gasoline is slowly pumped out of the float, then the craft is hoisted out of the water and the hatch opened for the explorers to emerge. The total process takes 12 h.

Several days later, an unmanned test is prepared to go 1,400 m deep. FRNS-2 is equipped with an automatic ballast release set to a timer (Figure 9).

FIGURE 9

1948 FNRS-2, deployed for Auguste Piccard's first Bathyscaph test in Cape Verde.

Very early in the morning Piccard sets the timer for 16:40, allowing ample margin to permit the sub to make it down to the bottom. Once launched, the timer could not be changed. A long series of mishaps incurs one delay after another. The seas make handling difficult; the cargo vessel has several mechanical failures. At 13:00 h, the French oceanographic ship announces its sounder cannot locate a deep enough dive site. By 15:45, they find a suitable location when Piccard notices the sub is riding high on the surface. Divers need to jump in the water to add ballast. The FNRS-2 is finally released at 16:00 and disappears below the surface. Would 40 min be enough to reach the bottom? The waiting is tense and there is skepticism that this untethered mass will ever be seen again. When it surfaces, there is amazement but it is evident something went wrong. Divers go to inspect the hull and saw a few drops of water in one window. The mood remains subdued.

A squall kicked up and it was not possible to pump out the gasoline. A last resort decision was made to jettison the fuel, which meant loss of precious material and the end of all testing. Many hours later, the bathyscaph is hoisted back on deck and Piccard can open the hatch and read the depth record. FNRS-2 made it down to 1,380 m and proves successful. The expedition returns home without a manned deep dive. Media declares it a failure.

Nevertheless, FNRS2 validates Piccard's bathyscaph idea, and he negotiates the sale of the FNRS-2 to the French Navy (1950), which has plans for major improvements. Piccard is retained as technical advisor for FNRS-3 despite growing tension. The principal upgrades are for better stability, easier towing, and better access to the personnel sphere. The sphere of the FNRS-2 is re-used, but a larger 16 m float is built in Toulon, tapered on both ends for better towing. An access tunnel is devised to allow occupants to reach the sphere from the top of the float. The navy takes FNRS-3 on its first deep dive to 4,050 m on February 15, 1954 (Houot, 1955). De-commissioned by 1960 after a total of 93 dives, FNRS-3 nevertheless provides the French Navy the necessary technology to build their next deep submersible: ARCHIMÈDES.

During construction of FNRS-3, Piccard, already at odds with the French Navy, receives an offer from Italian industry associates in the city of Trieste to fund his own bathyscaph. The move is an easy one for Piccard, who will be working with his son Jacques. He duplicates the sphere design of FNRS-2 but instead of a casting, opts for a much stronger steel forging built by an engineering firm in Terni, Italy. The assembly is done at the *Navalmeccanica* yard in Castellammare di Stabia. Now the Italian Navy takes an interest, and they support testing near the island of Ponza. The first dive is performed to a depth of 1,080 m, a later dive on September 30, 1953 reaches a depth of 3,050 m. Lack of funding in 1954–1955 means that Piccard can perform maintenance and improvements only. Joint Swiss and Italian Navy funding allows for some dives in 1956, but the pace picks up the next year after Jacques Piccard meets Robert Dietz in London and the U.S. Office of Naval Research (U.S. ONR) takes an interest. American funding allows Piccard to perform a series of 26 dives in the Mediterranean in 1957 in service of U.S. Navy personnel and scientists. The results are impressive and the United States Navy purchases the TRIESTE contract in 1958 for $250,000. The bathyscaph is shipped to the Naval Electronics Labs (NEL) in San Diego, California, where the U.S. Navy sets its goal to reach full ocean depth of 11,000 m at the bottom of the Challenger Deep, in the Marianas Trench near Guam.

The World by 1959

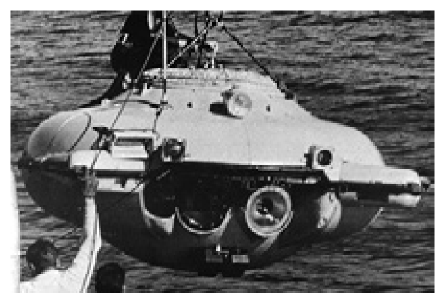
Several efforts in ocean exploration, some not commonly known, parallel around the world during the period 1952–1959. The development by the French Navy of FNRS-3 leads directly to the construction plans of ARCHIMÈDE, drawn in 1955 with the objective to reach 11,000 m. The primary improvements are for better maneuverability, easier towing, and more inside space for scientists. The funds for ARCHIMÈDE (to be constructed in Toulon with support from Belgium) are formalized in 1958. The new sphere is to have an inside diameter of 2.1 m, a thickness of 15 cm with three viewports, and will be supported by a dedicated mother ship, the Marcel le Bihan. By 1959, construction and engineering work on ARCHIMÈDE are fully engaged.

Cousteau "Soucoupe Plongeante"

Jacques Cousteau is enjoying significant success with his film work. In 1950, he is sponsored by famous brewery owner Loël Guiness to purchase his landmark research ship, Calypso. This greatly helps his filming efforts to circulate knowledge about the underwater world. Tightly associated with the GERS and having assisted the sea trials of FNRS-2, he works with engineer Jean Mollard to build his own small personal submersible, which he designates the SOUCOUPE PLONGEANTE (the Diving Saucer) (Figure 10). Cousteau launches the SP350 in 1959. Truly unique in its time, it is designed for a depth of 1,000 m but rated to a maximum depth of 350 m (Tailliez, 1964; Terry, 1966). The spherical cabin is made of steel with two viewports that use Piccard's conical frustrum acrylic window design, one for each of the occupants. The submersible is small and easily carried around the world on his ship. Cousteau now has his eyes in the ocean with his submersible and both become famous, despite SOUCOUPE's

FIGURE 10

1959—The GERS and J.Y. Cousteau launch the SP350 Diving Saucer.



relative shallow diving capability compared to TRIESTE and FNRS-3.

KUROSHIO Development in Japan

In Japan, ocean exploration moves forward as an independent effort of the country's fisheries research. Dr. Naoichi Inoue, who started as a professor at the Hakodate College of Fisheries in 1937, becomes an associate professor at the Hokkaido Imperial University Department of Fishing Science in 1950, Inoue firmly believes that, in order to study fishing grounds, in context with the surrounding environment, it is necessary to study them *in situ*, from a laboratory submerged in the sea (Busby, 1976). Inoue performs 729 dives from 1951 to 1960 with KUROSHIO I and II, both designed by Admiral Ryosaki Oaki (Terry, 1966; Busby, 1976). KUROSHIO II (38 feet long and 12 tons) has an operating depth of 200 m and uses a slack umbilical for transmitting power and communication rather than the tight line tether of KUROSHIO I. Admiral Oaki retires as head of Japan's naval research unit and works for Kawasaki Dockyards to design another tethered submersible, the UZUSHIRO. Launched in 1970, it has an operating depth of 300 m and is propelled by water jets with a tether length of 500 m. With a maximum speed of 2 knots, it has a life support of 48 h. Unfortunately, on June 17, 1974, an electrical fire leads to a fatality. Tragically, Adm. Oaki takes his own life to "accept and take full blame for the incident so that no others need to."

National interest continues and leads to the construction of several submersibles. Ultimately, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) funds and launches SHINKAI 2000 and then SHINKAI 6500 in 1989. Rated to a maximum depth of 6,500 m, it is the deepest rated submersible at its time, a title it still maintains today (Kohnen, 2005a). JAMSTEC also operates the remotely operated vehicle KAIKO, which makes a deep dive to 10,911 m to the bottom of Challenger Deep in March 1995. KAIKO was unfortunately lost at sea with a severed tether on May 29, 2003 and was never found again.

Project NEKTON

With the bathyscaph TRIESTE in San Diego, the U.S. Navy forms the Nekton Project team early in 1959. Then Lieutenant Don Walsh, USN, becomes Officer in Charge, Larry Shumaker Executive Officer, and Dr. Andreas Rechnitzer Project Nekton Project Director and Scientific Advisor. Jacques Piccard and Giuseppe Buono come to San Diego with the submersible as expert consultants. Jacques Piccard will be pilot, and the contract includes him instructing two new pilots. The TRIESTE will need significant changes to reach full ocean depth, but the U.S. Navy is paying for the development.

The two main improvements Piccard originally made on the TRIESTE from FNRS-2 were (1) the pressure sphere made from two forged hemispheres and (2) better access to the personnel sphere through a vertical entrance tunnel that led from the top of the float to the hatch. This addressed a key logistics concern that would allow the sub to be towed to location before boarding. The steel sphere consisted of two hemispheres clamped together with two viewports. At one pole was the hatch with an integrated window, at the other a window only, looking forward and slightly down. Piccard always took utmost care to protect the steel hull, considering it extremely delicate.

The modifications for Project Nekton require a new pressure hull to reach 11,000 m and a corresponding increase in the float size to carry the extra weight. The sphere is contracted out to the Krupp steel works in Germany. The company no longer had a forge capable of making hemispheres that size. It had been shipped to Yugoslavia for war reparations and laid rusting in a Yugoslav harbor because the roads were not strong enough for its further transfer (Piccard and Dietz, 1961). Hence, Krupp produces a three-part sphere with a large machined barrel shaped center equatorial ring section and two caps with mating surfaces machined on radial lines. One of the caps holds the front window, the other the hatch that also had a smaller window. All parts are bonded and mechanically strapped together. While the original Terni Sphere was 9 cm thick with re-enforcement areas around the windows of 15 cm, the new Krupp sphere is 12 cm thick with re-enforcements of 18 cm thick. The new sphere weighs 13 tons. The new float section is lengthened by 2.4 m, the two large iron pellet hoppers are kept for control ballasting with two propellers at the bow for maneuvering (Figure 11).

The Navy's nuclear submarine USS NAUTILUS reaches the milestone of crossing under the North Pole in 1958. Development of nuclear power for its fleet of submarines is of highest interest at this time. To some extent, this is a blessing to the Nekton project as the Navy has much higher strategic priorities. Some top Navy personnel are skeptical of the need for deep exploration and dubious of the cost. For the team, there is real motivation to get the job done.

FIGURE 11

1958–1959—TRIESTE original pressure hull with Terni Sphere and acrylic window.

In less than 10 months, the TRIESTE is together again. All parts are shipped to Guam, the submersible is re-assembled and a first test dive to 22 m made November 4 in Apra Harbor with Jacques Piccard and Larry Shumaker. A week later, TRIESTE performs a 1,500 m dive with Andy Rechnitzer in West of Guam. Everything works well and on November 15, 1959, Piccard and Rechnitzer dive to a new record depth of 5,530 m. Everything is flawless the entire way down. The excitement is high as TRIESTE ascends normally. At shallow depths she ascends rapidly when the crew hears two violent explosions at 15 m depth. No leaks are detected and the submersible surfaces. After a short study, the problem becomes evident. The three parts making up the personnel sphere have shifted and are now misaligned. The steel bands and epoxy bonds have yielded. The pole cap with the front window has shifted down by more than 3 mm. It is determined that the cause is the different rate of thermal expansion between the large equatorial ring section and the smaller end cap.

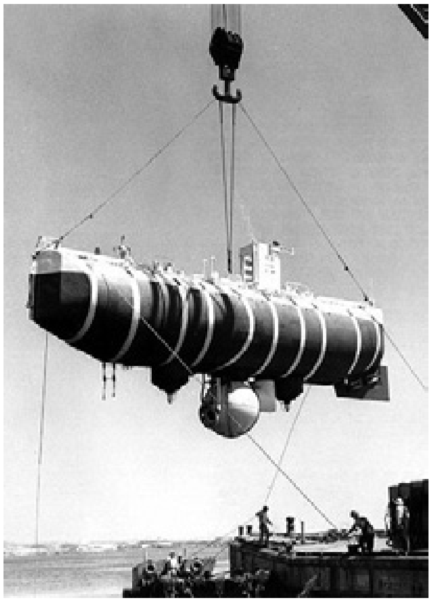
While the Command Office is informed about the event, the team searches far and wide for specialty tools to enable a repair. The general response is that it will be weeks before the tools can be gathered. Engineering chief John Michel knows exactly what he needs. While nobody can locate the right tools, he remembers exactly where and in which locker on the USS PRAIRIE is a 60 ton hydraulic jack. The USS PRAIRIE is in Japan. The jack is located and flown to Guam within a day, and the crew sets to work. The fix requires unorthodox methods, and traditional attempts fail miserably. John Michel finds the parts so big and heavy that only a combination of the powerful jack, big wood beams, and a very large and heavy forklift imparts the necessary kinetic energy, which must be synchronized with the push of the jack to slide it back into position. Given Piccard's extreme unease with any contact with the sphere, the impact of the fork lift has to be done without his presence. It takes a few attempts but it works. An additional set of six steel band rings is made to secure the parts together, and sealant is applied to the outside. The TRIESTE is ready to go again.

Since the procedures used are not those described in the navy manual and the red tape could impart undue delays, the repair is not officially reported to the Commanding Office. By December 14, TRIESTE is back in the water with a shallow harbor dive and on December 18 an ocean dive to 1,660 m west of Guam with Piccard and Don Walsh. This leads to the next big step with a test dive in the Nero Trench. Again it is Piccard and Walsh who attempt to reach the depth of 7,600 m on January 8, 1960. On the way down, two rapid explosions are heard at 6,025 m. Piccard drops ballast rapidly to stop the TRIESTE and investigate. All systems are functional, but it is the two external stanchions that imploded, which had not been drilled through to free flood the pipes. The double implosion was caused by the sympathetic implosion of the second stanchion after the first had imploded. A third implosion occurs at 6,780 m, and TRIESTE continues its dive. However, Piccard finds out he can no longer release gasoline to adjust buoyancy. At a depth of 7,000 m, the echo sounder abruptly shows the sea floor 40 m below. Piccard normally expects a warning at 150–200 m. TRIESTE is descending too fast for such close proximity, and he rapidly releases ballast from both iron bins to avoid bottom impact. TRIESTE comes to a stop and starts to rise. Unable to release gasoline, there is no way to reverse direction. The dive reaches a record of 7,025 m, but they do not reach the sea floor and get no photos of the bottom (Figure 12).

The bathyscaph surfaces successfully, and the crew prepares for the record-breaking dive two weeks later. The original Nekton plan included three deep dives to the Challenger Deep to include R. Dietz (ONR), K. Mackenzie (USNEL), A. Rechnitzer, D. Walsh, and J. Piccard. From Guam, TRIESTE is towed 220 miles (which takes four days in rough weather) to position it directly over the Challenger Deep, the deepest part of the Marianas Trench. It becomes clear that only one dive will be possible, making the choice of crew difficult. Lt. Don Walsh for the U.S. Navy and Jacques Piccard as pilot are selected, and on the morning of January 23, all dive preparations are made early.

FIGURE 12

U.S. Navy Bathyscaph *Trieste* (1958–1963) hoisted during testing by the Naval Electronics Laboratory in San Diego, California.



They board the bathyscaph with difficulty due to sea conditions and notice evident damage due to the rough four days tow. After a quick survey from the cabin they decide to proceed. At 8:23 am, the TRIESTE floods down and begins its descent. At the same time, a morning telegram arrives from the Commanding Officer of NEL in San Diego for Dr. Andreas Rechnitzer, the CO and Program Manager of the project on the ship. After a brief look, Dr. Rechnitzer inserts the note in his pocket and suggests to his engineering chief that they take a walk.

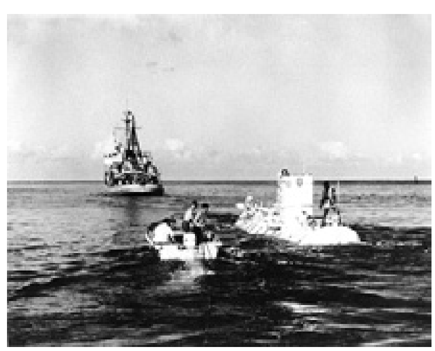
During the walk, the TRIESTE proceeds down, descending at 1 m/s, hits the first thermocline (a boundary between warm and cold water) at 100 m, and continues. With the bathyscaph a few hundred meters down, Dr. Rechnitzer reads the orders to stop all diving operations. He acknowledges with a reply that TRIESTE is already crossing 3,000 m. TRIESTE would complete this last dive. So a great feat is accomplished through a combination of solid planning, grit and determination, bold decisions to follow through, and the priceless benefit of occasional luck.

The command office had been aware of the pressure hull incident but one can believe that it had never calculated on the speed of the repair. Had the telegram come one day earlier, the paperwork for the repair tools taken an extra day or week, had weather delayed the long towing process or Dr. Rechnitzer not taken his walk, the project would have had to stand down. The Challenger Deep would have been conquered but not by the Unites States.

With no room for error, Walsh and Piccard continue their dive. They notice luminescence at several points along the descent. The ocean currents at these depths are unknown, and at 8,000 m (26,000 feet), they reduce the rate of descent to 60 cm/s, further slowing to 30 cm/s at 9,000 m (30,000 feet). Larry Shumaker manages to maintain intermittent acoustic telephone contact. At 10,000 m (32,500 feet), Walsh and Piccard hear a dull cracking sound inside the Bathyscaph. They cannot find anything wrong and continue down (Figure 13).

FIGURE 13

January 1960—Bathyscaph *Trieste* at the Marianas Trench preparing for the dive.



At 13:06 h, the TRIESTE lands on the bottom of the Challenger Deep. The crew sees a flat fish and a red shrimp, confirming sea life even at this extreme depth. Unfortunately, the water is very still and the bottom very silty. The particle cloud initiated on landing hangs like a fixed curtain and soon blocks all view. After 20 min of observation and note taking, they head back up. Don Walsh then notices that the external window in the outer exit tunnel has cracked. It allows occupants to look out the rear (hatch) window and see through the tunnel. This window is normally exposed to balanced pressure and does not affect the sphere. However, it is needed to blow the water out of the tunnel back at the surface to enable them to evacuate the sphere. The iron ballast is released further and Trieste returns to the surface after a total dive time of 8 h and 35 min. At surface, the crew is extremely careful to blow the tunnel clear of water with air pressure to avoid stress on the cracked window. The surface ship on the other hand sees TRIESTE's surface and nobody coming out. Joy is mixed with concern, not understanding the unusual 20 min delay. Finally, all is well and the project would live on. The crew flies to Washington, D.C. for commendation by President Eisenhower and returns to Guam with plans to dive at least two more times to the bottom of the trench. However, immediate orders limit dives to less than 6,000 m. TRIESTE ends its stay in Guam with 7 additional dives along the trench's vicinity.

Upon return from Guam, the TRIESTE has logged a total of 72 dives since its inception. It now undergoes a full overhaul in San Diego. The Krupp sphere is removed and replaced with the original Terni sphere from

Italy, which still has a 4,000 m rating. The TRIESTE lingers at NEL for three years when the world of submarines forever changes with the sinking of the nuclear USS 593 THRESHER.

USS THRESHER

The loss of the USS 593 Thresher during a routine sea test on April 10, 1963 changes everything. The nuclear submarine unexpectedly sinks 260 miles off the coast of New England in 2,560 m of sea water. The Cold War is raging and a lot of questions go unanswered. The TRIESTE is the only asset capable of attaining this depth and is immediately ordered to Boston. The bathyscaph is not in good condition and the transport is difficult. It is not until June 24, 10 weeks after the disaster, that the first dive is made at the fateful site. Weeks of searching fail to find the wreckage. The submersible has to return to Boston for overhaul, batteries, and the installation of a robotic arm. The rationale for a smaller, more flexible submersible could not be any clearer. On August 18, the TRIESTE returns to the wreck site. The remains of the THRESHER are found and observations made through the single viewport, with photos of everything. TRIESTE's batteries eventually fail, ending the season and the investigation. TRIESTE is returned to San Diego and retired. Two new versions of the TRIESTE are eventually built over the years: the TRIESTE II which operated from 1964 to 1968, and a more covert follow-on project also called TRIESTE II, sometimes designated DSV1 for clarity, which operated from 1968 to 1984 with a 6,098 m rating.

TRIESTE leaves a legacy of accomplishment and, due to the USS THRESHER, triggers a far-reaching set of Deep Submergence guidelines for the U.S. Navy. As a direct result of a Deep Submergence Review Group established by the Secretary of the Navy, many military and civilian experts are engaged to determine the best approach to respond to any future Thresher-like incident. Recommendations direct development in the following areas:

1. A submarine rescue system from collapse depth (which leads to the development of the Deep Submergence Rescue vehicles).
2. A deep-ocean search system with investigation and recovery capability down to 20,000 feet (which leads to ALVIN, SEA CLIFF and TURTLE).
3. A man-in-the-sea program with 600 foot operations for long duration (which leads to the construction and operation of Sea Labs 1, 2, and 3).

These criteria are far removed from the original motivations a mere 30 years earlier in Europe of extending an altitude record in a stratospheric balloon to include a deep ocean dive. It is rarely possible to extrapolate into the future with any accuracy. Certainly, the present turn of events would have been unimaginable to Auguste Piccard when he was searching for sponsorship. The future of the Replacement HOV (RHOV) for ALVIN, after 45 years of successful operation, can be planned but in no way fully imagined. If there is any lesson from FNRS-2 to TRIESTE to ALVIN and RHOV, it is that the only destiny is to move forward. With imagination, goodwill, hard work, and some luck, great things always lay in wait.

From TRIESTE to ALVIN

During the overhaul of the TRIESTE at NEL in San Diego (1961–1962), General Mills (GM) develops a new robotic manipulator for the bathyscaph. The ongoing discussions between the TRIESTE crew and Harold Froehlich from GM expand on NEL's idea for a smaller submersible, one with simpler deployment logistics. (Slow and big, the TRIESTE required four days of dive preparation, plus the towing time to the dive site and back and then seven days to return to its land cradle.) The new concept is for a vehicle small enough to be loaded on a regular ship and able to perform multiple missions on a single voyage, greatly reducing the cost of operations. The maximum depth is reduced to 2,000 m in return for better operational efficiency. GM is eager to support such a project. Don Walsh, as Officer-in-Charge of TRIESTE, presents this smaller project idea to Charles Momsen, Jr., Chief of Undersea Warfare at the Office of Naval Research (ONR) in Washington, D.C. The concept was nicknamed SEAPUP and the proposal is welcomed; not so much to support NEL's plans but because ONR had a standing request by Allen Vine at the Woods Hole Oceanographic Institution (WHOI) to provide them with a deep ocean research submersible.

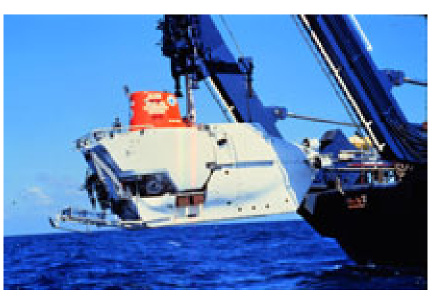
During this period, Reynolds Aluminum is pushing hard for ONR to consider an all aluminum submersible, the ALUMINAUT. Designed for a maximum depth of 4,500 m, the submersible is large, 51 feet long, and capable of holding six passengers. Louis Reynolds himself is the driving force behind this effort, a personal inspiration resulting from a visit of Simon Lake to the Reynolds factory after WWII. (Reynolds, then a recent college graduate, was captivated by the stories of 50 years of building and diving submarines related by Simon Lake.)

The U.S. Navy is still questioning the effort. In spite of the TRIESTE accomplishments, there is no clear consensus on the importance of deep ocean exploration and its cost. Charles Momsen, one of its staunch proponents, eventually secures funds for a deep submersible. (ONR had been negotiating with Reynolds for some time, had even appropriated funds for leasing the ALUMINAUT, but had not come to an agreement.) General Mills provides an aggressive bid of $500,000 to build the SEAPUP, a three-person design rated for 2,000 m. The funds are available, and the GM contract includes a guaranteed performance clause. The contract is signed, and the U.S. Navy names the submersible ALVIN, in honor of Allen Vine, the driving force behind this deep submersible capability at WHOI.

The contract with ONR is soon revised: the fabrication of three spheres is to be made of HY100 steel. Two spheres are to be pressure tested with a full array of strain gauges, a third would be tested to destruction. This takes place at Southwest Research Institute in San Antonio, Texas. The strain gauge data show that the two spheres are much stronger than the specified rating of 2,000 m. One of these is used on ALVIN (Figure 14).

FIGURE 14

1964–present, DSV ALVIN operated by the Woods Hole Oceanographic Institution.



Another sphere is installed in the test tank for destruction. At a pressure near 3,000 m of sea water, the tank fails. The remaining two spheres are clearly good. These are eventually used in the construction of two deep submersibles for the Navy's Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas. General Dynamics' Electric Boat Company builds AUTEC 1 and AUTEC 2, rated to 2,000 m and soon renamed SEA CLIFF and TURTLE. ALVIN was commissioned on June 5, 1964; SEA CLIFF and TURTLE were launched on December 11, 1968 (Figures 15 and 16).

FIGURE 15

1964–1968, TRIESTE II design modification (DSV-0).

FIGURE 16

1968–1984, TRIESTE II complete redesign (DSV-1).

The immediate net result of this activity, however, did energize many of the leading technology companies and research labs in the United States to forge full speed ahead in the development of oceanographic technology. Throughout the 1960s, everyone saw a bright future in business and technology development paralleling the national momentum NASA was experiencing in space exploration. To put the period in context, it is useful to glance at the development efforts that are happening during the period of 1960–1970.

1960: Start of an Era

By 1960, the United States is in the midst of a growing development of manned submersibles, from private, commercial, and military sources. The knowledge associated with design and construction of submersibles is sparse. Cousteau and the GERS are actively diving the SOUCOUPE PLONGEANTE. However, others have also taken notice and are intrigued by the future of sub-sea exploration. It is interesting to see where some of the companies were at the time of that first TRIESTE dive, and the paths that would lead them to get involved in deep submersible operations.

China Lake Naval Test Facility

Besides its work at the Naval Electronics Lab in San Diego, the U.S. Navy Naval Ordnance Test Station (NOTS), in China Lake, California, is proceeding with a windowless concept, the MORAY (610.m), and the DEEP JEEP (610.m), which will become the first American-built deep submersible after its initial launch 6 months before ALVIN. DEEP JEEP makes over 110 dives with Will

Forman as the test and operations pilot, diving off the coast of Spain looking for the hydrogen bomb accidentally dropped by a B-52, until ALVIN, which was completing overhaul and was not immediately available, arrives. Five years later, the AC Electronics Defense Research Lab (ACE-DRL) in Goleta, California, develops the DEEP OCEAN WORK BOAT (DOWB), another concept with a sophisticated optical viewfinder system instead of windows, rated to a maximum depth of 2,000 m.

While DEEP JEEP is in development, the Navy NOTS center is also working on the MORAY for use in anti-submarine warfare. The budget is significant, and the key characteristics of this manned underwater torpedo are high speed, positive buoyancy, and aluminum hull construction for low magnetic signature. MORAY is designed for a cruise speed of 15 knots using an outer hull construction of ring-stiffened fiberglass and syntactic foam, with two cast aluminum spheres at its center: one for sonar electronics and the other for the operators. Without windows, a TV camera provides visual navigation. Although belonging much more to the military submarine development than the civilian submersible, the project initiates a key ingredient for the future of all deep submersibles: syntactic foam. The positive buoyancy of the MORAY is crucial, and the depth rating of 610 m requires strong foam. The project engineers find that Shell Oil is using a special type of powder to cover the top of its large open oil tanks in California. This powder is made of extremely small glass spheres that float. This is soon used in conjunction with different epoxy binders to produce extremely solid foam that can resist incredible depth. MORAY makes a few spectacular runs off San Clemente Island with new silver-zinc batteries. MORAY's battery compartment blows up and the sub sinks. Quick work by divers secures a line on it before it sinks all the way to the bottom. The batteries are too expensive to replace, so only a few shallow slow operations are conducted till operations are terminated.

All three vehicles show capability, but the cost advantages of eliminating/minimizing the windows do not offset the disadvantages, and this line of design is discontinued. Interestingly enough, Will Forman, who designed and developed the DEEP JEEP at China Lake, continues on and becomes the designer of the first full acrylic hull submersible, the KUMUKAHI (1967), and the first glass hull submersible, the DEEPVIEW (1972). The success of the acrylic blazes a reliable, practical, enduring trail. Glass is extremely expensive, produces only limited success, and will not establish itself as a common solution.

Acrylic Window Material and Standards

The 1960s proves a fertile time for development of ocean engineering technology for both the Navy and science community. Motivated in large part by the accepted need for a hydrospace exploration program, all naval laboratories participate—in particular, the Naval Civil Engineering Laboratory (NCEL) in Port Hueneme, California. Jerry Stachiw, an engineering student who in 1960 is working on a graduate degree in material sciences at Pennsylvania State, will eventually specialize in pressure resistant structural components for diving systems, including glass, acrylics, and ceramics. Stachiw graduates and moves to NCEL in 1965. Building on the knowledge gained from Auguste Piccard and the continued experimentation by the crew of the first *Trieste*, the lab becomes central in the study of materials and structure for deep ocean vehicles. Stachiw's complete dedication and mastery of the behavior of acrylics greatly impact the most defining design feature on every future submersible—its windows. The internationally recognized safety standards of ASME Pressure Vessels for Human Occupancy (PVHO) are founded on 40 years of research by Jerry Stachiw, a legacy that continues to carry the industry in the 21st century (Figure 17).

FIGURE 17

Conical frustrum acrylic window, as used on the Bathyscaph *Trieste*. J. Stachiw at NCEL where the majority of acrylic certification tests were performed to establish ASME PVHO safety standards.

Westinghouse

From 1960 to 1965, Westinghouse is very active in military development with its sonar and torpedo technology. Keenly interested in the design of submersibles, Westinghouse works in close collaboration with the GERS group and Jacques Cousteau. Westinghouse had designed three vehicles rated to 610 m, 3,600 m, and 6,000 m. GERS agrees to build the 3,600 m version but while the French base their designs on one steel (Vascojet 90), Westinghouse insists on using another (HY80), which is acceptable to the U.S. Navy but which de-rates the maximum depth to 1,220 m (4,000 feet). The submersible is built in France with many components similar to the DIVING SAUCER, and is shipped to the United States. Designated DEEPSTAR 4000, it arrives in San Diego in 1965 and is certified by the U.S. Navy in 1966. Used until 1968, it performs a total of 540 dives. The 6,000 m design is never built, but a 610 m (2,000 feet) submersible, the DS2000, launches in 1969. The DS2000 dives until 1975 after which it is purchased by two of Cousteau's colleagues. The French GERS group then builds the 3,600 m design using the Vascojet 90 steel. The CYANA, launched in 1969 and rated to a depth of 3,000 m, becomes part of the research arsenal operated by IFREMER in Toulon and dives until 2003.

General Dynamics

General Dynamics, through the Electric Boat Company, develops the (Submarine Test And Research) STAR I submersible in 1961–1962 as a platform to test submarine hatch landings and later (1965) the use of fuel cells. By 1963, Dr. George Bass becomes the first civilian to purchase a research submersible, the ASHERAH, (Bass, 2006) for his nautical archaeology work in Turkey, a lifelong effort that eventually proves a theory that re-writes the commerce history of the ancient world. The submersible is used from 1964 to 1967, tested to 225 feet, and provides a total of six observation viewports. General Dynamics then constructs the STAR II and the STAR III to be used for research work and in the oil and gas fields of the Gulf of Mexico and Santa Barbara. STAR II eventually finds its way to the University of Hawaii in 1979. START III is retired in 1969.

Perry Submersibles

While General Dynamics is developing the STAR I in 1961, Perry Submersibles in Florida is manufacturing its PERRY CUBMARINE (PC3X), one of a series of submersibles: PC-2 (1962, 2-man at 600ft), PLC-4 (1967, four-man at 1350 feet), PC-5 (1968, three-man at 1,200 feet), and PC-9 (1970, three-man at 1,350 feet) developed during the 1960s. The PLC-4 is a joint effort when Perry meets up with Ed Link and they design this first diver lockout submersible. Ed Link would go on separately to develop the Johnson Sea-Link submersibles (see below). Perry continues producing his designs to serve the commercial diving industry and oil and gas fields and integrate ever increasing diver lockout capabilities. The evolution of the family of submersibles eventually leads to the famous PC-12, PC-14, PC-15, PC-16, and PC-18 series of submersibles produced throughout the 1970s. They also produce the REEF RANGER and WORK RANGER series. In 1991, the submersible division, now called Submersible Systems Technology, is sold and continued to design and manufacture both dry and wet submersibles until 2004 (Figure 18).

FIGURE 18

1967 PLC-4 Perry/Link Diver Lockout submersible on display at Harbor Branch Oceanographic Institution, Florida.

Johnson Sea Link

Ed Link developed a great idea during World War II: a flight simulator that was used to train almost every aviator in the armed forces. After selling his interests in the company, he turns to ocean exploration. In the summer of 1966, he meets with John Perry at the berth in Florida. They soon collaborate on the PLC-4 (Perry/Link 4), the first small diver lockout submersible. It has room for two crew and two divers. The sub is launched in 1967 and Link loads DEEP DIVER on his ship. In January 1968, he invites a diver/photographer from the National Geographic magazine for a dive in the Bahamas, a coverage that would make it into the January 1968 issue.

Ed Link soon thereafter meets with Seward Johnson Sr., son of James Wood Johnson, a co-founder of Johnson & Johnson. The meeting results in the design and construction of the JOHNSON SEA LINK for the Harbor Branch Oceanographic Institution. Two submersibles are built, JOHNSON SEA-LINK I and II, launched in 1971 and 1975, respectively. These submersibles provide a full acrylic pressure cabin for observers and leverage a great deal of development work in acrylic window design fostered by Jerry Stachiw at the NCEL lab during the 1960s (this includes the construction by Stachiw of the U.S. Navy NEMO, an all-acrylic hull submersible). A great deal of history comes together through the JSL I and II, particularly in the development of large acrylic windows for submersibles. The first spheres are made just like NEMO's from pentagonal curved sections bonded together that rated the submersibles to 300 m deep. California artist Bruce Beasley (1969) develops a technique that allows thick acrylic sections to be cast without any bubbles or imperfections. A single piece acrylic sphere is cast and installed on JSL I in 1980, which increases the depth rating to 610 m. Eventually, both submersibles are upgraded using full acrylic spheres with a depth rating of 915 m. The JOHNSON SEA-LINKS operate until 2009 and contribute invaluable service to the study of oceanography as well as pelagic and benthic research (Figure 19).

FIGURE 19

1971 Johnson Sea-Link, full acrylic hull research submersible with diver lockout chamber.

Lockheed Missile & Space Corp.

By 1964, after the THRESHER incident and the U.S. Navy's Deep Submergence Systems Project (DSSP), Lockheed participates in the design and construction of a submarine rescue system. The DEEPQUEST, designed during 1964–1965 and launched in 1967, has a depth rating of 2,440 m and a capacity of four occupants. The submersible is created as a technology demonstrator concept to the U.S. Navy and as a means for the company to gain experience in the field. The gamble pays off when Lockheed is awarded the contract for the design and construction of the Deep Submergence Rescue Vehicle (DSRV 1 MYSTIC, and DSRV 2 AVALON) in 1966. Both submersibles are rated to 1,525 m and allow a crew of three with space for 24 rescues. DSRV-1 launches in 1970 and DSRV-2 the following year. The last of the DSRVs is decommissioned in 2009 and replaced with a new generation PRM (Pressurized Rescue Module) System, a tethered submersible concept developed by Oceanworks International in Vancouver, Canada (Figures 20 and 21).

Grumman Aircraft Company

Aware of and eager to compete for part of the U.S. Navy's DSSP program, Grumman Aircraft seeks to position itself for a part of the U.S. Hydrospace Exploration agenda expressed by Vice President Hubert Humphrey in his "Wet NASA" promises. Grumman approaches Jacques Piccard and eventually designs and builds the BEN FRANKLIN as a floating hydrospace lab for the long-term study of oceanographic func-

FIGURE 20

De-commissioning of DSRV-1 Mystic built by Lockheed Missiles & Space Co. in 1970.

FIGURE 21

Inauguration of PRMS FALCON rescue vehicle in 2009 to replace DSRV.

tions such as salinity, temperature, density, etc. The submersible is launched in 1968. Initially focusing on the Gulf Stream, the crew of six scientists works at a depth of 610 m for a duration of six weeks (July 14 to August 13, 1969). Grumman also studies the effects on human behavior of close quarters for long periods of time, thus gaining experience to leverage its bid on the SKY LAB contract for NASA. The six crew members on this unique expedition include Jacques Piccard, team leader; Don Kazimir, Captain; Frank Busby, Oceanographer of the Navy; Erwin Aebersold, Swiss Pilot; Ken Haigh, Oceanographer of the British Royal Navy; and Chet May, NASA engineer. The Gulfstream expedition is an unqualified success, the information collected extensively. Grumman wins the contract for the Sky Lab. Much later, as Northrop Grumman, the company wins the contract for the Advanced Seal Delivery System (ASDS).

North American Rockwell

After the record-breaking dives with the bathyscaph TRIESTE, Dr. Andy Rechnitzer takes a position with the R&D Autonetics Division of North American Rockwell in 1961. He initiates a development effort for a deep ocean, offshore field work and oceanographic research submersible, BEAVER IV. The submersible has a capacity of five persons and is rated to a maximum depth of 610 m. The company produces two identical hulls; the second is sold to HYCO in Canada. This hull eventually becomes the Canadian Navy's SDL-1 diver lockout vehicle. The BEAVER IV design provides a diver lockout capability to a depth of 305 m. Launched in 1968, the submersible is christened in Long Beach, California, by Nancy Reagan, wife of then-governor Ronald Reagan. BEAVER IV is used until 1970 when it is sold by N.A. Rockwell after the Nixon administration makes it clear there will be no support for a wet-NASA.

Modern Conquest of the Deep

The TRIESTE project was not the only international effort intending to reach the trenches of Challenger Deep. The conquest of the deep ocean spawned a small family of deep submergence vehicles, five of which are still in operation today. These include the following:

Submersible	Country	Depth Rating (m)	Launch Date	Retired Date
TRIESTE I	United States	12,000	1953	1963
ARCHIMEDE	France	12,000	1961	1981
ALVIN	United States	4,500	1964	
TRIESTE II	United States	6,000	1964	1984
CYANA	France	3,000	1969	2003
TURTLE	United States	3,000	1980	1998
SEA CLIFF	United States	6,000	1985	1998
NAUTILE	France	6,000	1985	
MIR-1	Russia	6,000	1987	
MIR-2	Russia	6,000	1987	
SHINKAI	Japan	6,500	1989	
HARMONY	China	7,000	2009–2010	

Deep Ocean Work in France

The French effort to explore the deep ocean dates back to the very beginnings of the FNRS projects. After successful testing of the FNRS-3 in 1954, the French Navy undertakes the design of ARCHIMÈDE. A bathyscaph design like TRIESTE, the submersible is designed for 12,000 m, to conquer the deepest part of the ocean. Initiated in 1955 but only funded in 1958, ARCHIMÈDE is launched by the French Navy on July 28, 1961, well after the TRIESTE dive in Guam. Having searched for a deep canyon, the French Navy opts for the Kourille Trench, north of Japan, mapped by a Russian research ship at 10,500 m. The support Ship *Marcel le Bihan* arrives in Japan in 1962. The ARCHIMÈDE completes a dive to 9,200 m on July 15, 1962. Whereas the TRIESTE spent 20 min at the bottom of the Marianas Trench, the ARCHIMÈDE spends 3 h at the bottom of the Kourille. Its crew performs a series of deep dives but the deepest is 9,500 m. It is curious that although the submersible continues diving in Japan, the Mediterranean, Puerto Rico, Madeira, and the Azores, it is never deployed over the Challenger Deep. After completing a total of 139 dives (the last on July 22, 1970), the bathyscaph ARCHIMEDE is ultimately decommissioned in 1981.

France and the United States continue to lead the way with the first non-bathyscaph type submersibles rated to 6,000 m. The U.S. Navy certifies the SEA CLIFF to 6,000 m after an overhaul in 1985, which upgrades its 1968 steel sphere to titanium. France starts from the ground up and designs the NAUTILE, also using a titanium sphere rated to 6,000 m. The NAUTILE accrues more than 1,675 dives to date and remains in service, operated by the *Institut Français de Recherche pour l'Exploitation de la Mer* (IFREMER) out of Toulon (Figure 22). NAUTILE is among the first

FIGURE 22

1985–present, DSV NAUTILE operated by IFREMER, France.

submersibles to visit the wreck of the Titanic in July 1987, performing 32 dives over a 2-month period to film and recover artifacts from the site. (This spot of ocean will be frequented by the MIR-1 and MIR-2 submersibles many years later for James Cameron's feature film.) The NAUTILE is fully equipped with the latest technology for lighting, filming, navigating, and sample collecting. One of its unique features is the ROV ROBIN (ROBot d'Inspection du *Nautile*), which is integral to the submersible and has a 70 m tether range. Operated from inside the sub, it provides a safe and effective means to reach difficult places. In 2002 and 2003, NAUTILE is deployed after the sinking of the tanker *Prestige* on November 19, 2002 (with 77,000 tons of heavy fuel, 133 miles off the Spanish coast line). The wreck is found at 3850 m. NAUTILE spends 75 days on site and makes 36 dives to film the condition of the wreck and reduce its oil loss, initially from 125 tons per day to 2 tons per day (Lévêque, 2006). A return mission in 2003 allows the sealing of the wreck, the first attempt to close up an oil tanker in deep water. NAUTILE continues to operate from its new support ship, the *Pourquoi Pas?*, launched in 2007.

HYCO, a Canadian Passport to the Deep Sea

International Hydro-dynamics Co. Ltd. (HYCO) is founded in 1964 and based on North Vancouver, Canada. The venture is purely commercial, and the originating concept is the construction of a cost-effective small submersible vehicle. PISCES I is launched in 1966 and becomes the first of a family of submersibles that includes PISCES II to XI.

In the late 1960s, HYCO expands its family of work submersibles. The company designs a 2,000 m vehicle, but the pressure hulls are built by Vickers in the United Kingdom and there are pressing delays. HYCO decides to fabricate two hulls locally with different steel and de-rate the design. This produces PISCES 2 and PISCES 3, both launched in 1969. Each has a three-person capacity and a 1,000 m depth rating. Based on client requirements and availability of water depth during certification testing, PISCES 2 and 3 are certified to 732 m and 1,000 m, respectively (Figure 23).

In 1970, the company builds the Submersible Diver Lockout (SDL-1) using the spare hull from BEAVER IV. Rated to 610 m and allowing diver lockout to 305 m, the SDL-1 is

FIGURE 23

1971 PISCES V is constructed by HYCO in Vancouver, Canada, rated to 2,000 m deep. Today operated by the University of Hawaii (HURL).

launched and operated by the Canadian Armed Forces in 1971. Delivery of the Vickers pressure hulls leads to completion of PISCES IV, the first 2,000 m rated submersible. PISCES IV was ordered by the Moscow based P.P. Shirshov Institute of Oceanology. (In 1970–1971, the prospect of any East Block country buying a deep ocean submersible from the U.S. was nonexistent). Dr. Anatoly Sagalevitch spends 1971 in Canada during the construction of PISCES IV. In November 1971, a U.S. Navy commander arrives in Ottawa to meet personally with Prime Minister P.E. Trudeau and persuades him to revoke the export license previously granted by the Canadian Government. The Canadian government ends up buying PISCES IV for the Oceanographic Institute in Victoria. PISCES IV is later purchased by the University of Hawaii Undersea Research Lab in 1999 where the submersible still operates.

HYCO proceeds to build PISCES V (1973) and PISCES VI (1975), both 2,000 m rated similar to PISCES IV. During that time, the P.P. Shirshov Institute continues its efforts to purchase a deep submersible from HYCO. This leads to the eventual delivery to the USSR of PISCES VII and XI in 1975 and 1976, respectively. Both are three-person submersibles with a depth rating of 2,000 m. PISCES VII is assembled in Switzerland and tested in Italy before being shipped to Novorossiysk on a Soviet cargo ship. PISCES XI is assembled in Vancouver and delivered to Vladivostok. HYCO built three more submersibles, including AQUARIUS, a three-person sub rated to 365 m launched in 1973; LEO, a 610 m rated three-person vehicle (1976); and the last submersible, TAURUS (1976), a six-person vehicle rated to a depth of 335 m. Expertise developed at HYCO eventually spins off into several companies that turn Canada into a concentrated submersible technology center. Vancouver becomes home to four submersible companies that still exist today, including Atlantis Submarines, International Submarine Engineering, Nuytco Research, and Oceanworks International.

A Russian Deep Submergence Effort

An independent chain of connections leads to the development of a pair of celebrated deep submergence vehicles: the MIR 1 and MIR 2 submersibles. Rated to 6,000 m and operated by the P.P. Shirshov Institute of Oceanology (PPSIO) in Moscow, these become famous through James Cameron's film "Titanic." At the fore of an extraordinary effort by the PPSIO, Dr. Anatoly Sagalevitch, submersible explorer and pilot, becomes renown all over the world for his determination and dedication to submersible diving. The story started in Canada in 1971 with PISCES IV and PPSIO's eventual procurement of PISCES VII and XI. It is this Canadian effort that will eventually help launch the Russian ocean exploration effort of the 1970s. Dr. Sagalevitch readily acknowledges the important lessons learned from their early exploration work with the PISCES submersibles.

As soon as the PISCES VII and XI arrive in Russia, the subs are tested in the Black Sea. In 1977, they go on a 43 dive expedition in Lake Baikal and continue to explore the Pacific Ocean and the Red Sea. The experience is extremely valuable, and the institute starts planning deep submergence capability to 6,000 m. In the period of 1978–1979, a proposal is made by Canadian Underwater Vehicles for a 6,000 m design using a hydrazine powered gas turbine instead of batteries. The engine is tested by the Canadian manufacturer Ulvertech, a contract is signed but the project is never executed. The Institute continues to seek a foreign partner, negotiating with France, Sweden, and Switzerland from 1979–1982. By 1982, the Finnish company Rauma Repola shows interest in a nickel cadmium battery powered design and ultimately builds the MIR submersibles (Sagalevitch, 2009).

At that time, Rauma Repola developed new techniques to produce high strength, high nickel-content steel for pressure hulls. This "Maraging Steel" can be traced back to Lockheed's design of the DEEPQUEST, which used this alloy for its two pressure spheres. However, the welding between the two spheres proves to be a significant problem, and the decision is made to avoid any welding on the MIR hulls. A final contract is signed in 1985 between Rauma Repola, which includes one deep submersible and one deep remotely operated vehicle for rescue capability. The company soon determines it cannot produce a 6,000 m ROV and proposes to build a second deep submersible. On this twist of fate, the P.P. Shirshov Institute acquires two identical deep submersibles, a benefit that later proves to be enormous (Figure 24).

FIGURE 24

1987 MIR 1 and MIR 2 submersibles rated to 6,000 m operated by P.P. Shirshov Institute of Oceanology, Moscow.

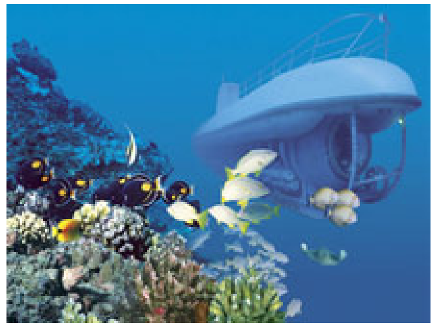
These submersibles launch in 1987 and operate from the Akademik Mstislav Keldysh mother ship, which takes the crew and subs around the world. Media exposure through the film feature "Titanic" helps the program remain operational without central government sponsorship after the breakup of the Soviet Union. The MIR submersibles find a mix of expeditions: taking paying passengers to visit the wrecks of Titanic and Bismarck, as well as the wreck of the sunken Japanese submarine I-52; transporting scientists to deep hot vents, Black Smokers, and ocean rift zones; supporting Russia remediation efforts for the sunken nuclear sub Komsomolets; various searches for deep sea treasures; and its great expedition of 2007, diving to the bottom of the North Pole. The submersibles are fully overhauled and the steel spheres re-tested for Germanischer Lloyds class certification in 2007; they continue to survive the sea conditions with excellent results.

The Golden Age

The 1960s and 1970s are often thought of as the golden age of submersibles. The developments in pressure vessel materials (steel alloys, aluminum, titanium) as well as nonmetallic (acrylics and ceramics) provide engineers a great selection of safe, well understood materials to produce better designs. New components and systems were developed to operate at high ambient pressures, batteries, external lights, scanning sonars, data and voice communications, and extremely compact computers and displays. The simultaneous formulation of safety standards for the design of manned submersibles, pressure vessels, and acrylic windows is invaluable and rests on the shoulders of many great men and women who have provided technological knowledge in the service of better, safer designs. The emergence of large tourism submersibles in the mid 1980s with the launch of ATLANTIS I by former HYCO staff forever changed the landscape of underwater touring (Figure 25). Twelve

FIGURE 25

Modern Atlantis tourism submersible.



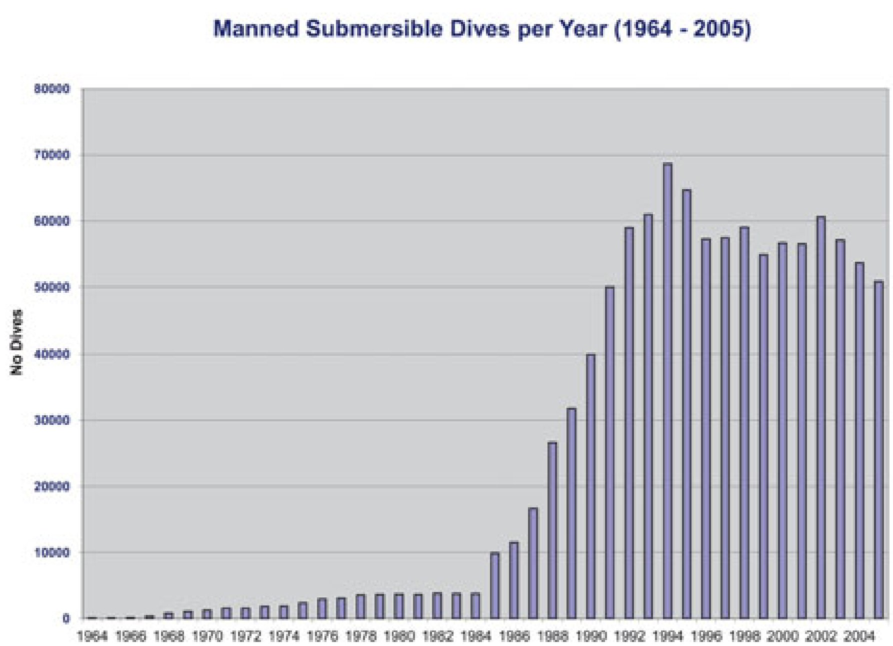
submersibles constructed between 1985 and 2004 led the way for a number of large firms in Europe, Finland in particular, to launch the production of 44+ passenger submersibles. Statistics (Kohnen, 2005b) show that the average yearly total number of submersible dives in the 1960s was in the range of 500–1000. During the 1970s, this increases to 1000–4000 dives and by the mid 1980s, to 4000–5000 dives. With the introduction of tourism submersibles, the number increases to 50,000–70,000 dives in the mid 1990s. Such an order of magnitude scale increase in diving operations combined with a perfect record of safety among professionally operated systems is a tribute to the success of modern design and the regulatory systems that have made hydrospace travel safe (Figure 26).

Inspiration for New Player

Progress is a string of inspirations from one generation to the next: DeVilleroi's inspiration flow through Jules Verne to Simon Lake to RJ Reynolds and leads to ALUMINAUT. Piccard's passion flows through the French Navy, Cousteau, Robert Dietz at ONR to the deep dive and eventually to ALVIN, SEACLIFF, TURTLE, and today's Replacement HOV project. In addition, both India and China have an increasing interest in deep ocean exploration (Kohnen, 2008). China has developed a 7,000 m rated submersible, HARMONY, undergoing sea trials, and

FIGURE 26

1964–2005 total number of submersible dives performed each year for civilian use, including research, commercial, and tourism operations.



India is interested in building a 4,000 m rated vehicle. And so the pattern continues into the future, bringing ever new players in the field (Kohnen, 2005a). In 1963, Dr. George Bass is the first civilian to commission a research submersible (Ashera) for his archaeological work in his search to rewrite history. The submersible's capability is limited. Twenty-one years later (1984), he makes his penultimate discovery. At that same time in 1984, a young Canadian engineer, Will Kohnen, vacations in Mexico and goes snorkeling for the first time. Seven years later, while working in aerospace in California, he formulates a new concept to return to this underwater world in a small personal space vehicle. A small team of engineers forms SEAmagine Hydrospace in 1995. Engaged by Dr. Bass' ongoing dream, the company delivers Hull #3 (CAROLYN) in 2000, which explores the Turkish coast with great success, overseeing excavation work and searching for new wrecks. The all-acrylic cabin offers Dr. Bass the visibility and bottom time, which he had dreamt of for 37 years.

The Future

What the sea reserves as mysteries we are left to uncover. Human occupied underwater vehicles will remain a central element in the selection of modern tools at the service of knowledge acquisition. Considering that humans learn through all five senses, but disproportionally through the visual, the future calls us to see and discover this underwater world—not simply to be awed by its power and beauty but to learn; to comprehend and understand the complex web of inter-relations between our life on land and its impact on the seas. With ever-expanding technologies of data acquisition, it is left for our minds to decipher the puzzles as we stand on the shoulders of many dedicated engineers and explorers and strive to inspire the next generation. There remains a great open door into the field of ocean exploration. Broader access to this world through an efficient and safe transport vehicle is possible for the study and observation of many alien creatures that will teach us anew. We are limited only by our ability to imagine.

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COMMENTARY

A Look Back at the *MTS Journal* of June 1990: "A Deepest Ocean Presence"

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Fifty years ago (January 23, 1960), the U.S. Navy *Trieste* descended to the deepest place in the world ocean. Twenty years ago, the June *MTS Journal* was dedicated to commemorating this historic accomplishment and attempted to predict the future.

The issue consisted of an *Overview*, wherein Don Walsh, pilot of the *Trieste,* summarized the then current technology status; Sylvia Earle suggested recent cost-effective technology developments that could enable a return to the deepest sea, whereas John Craven's presentation focused on the geopolitical significance of a deepest ocean presence.

The *Science* section included an overview by Larry Madin that accurately predicted a time when robotic technology is so transparent that human observers could not tell by any objective sense that they were not in the ocean, directly controlling their actions. Patricia Fryer outlined the needed geological research in the deepest oceans building on current discoveries. John Edmond concluded in a direct quote that "a detailed appraisal of the ROV option is the important next step" in deep-sea marine geochemistry. The biological aspects of deep ocean research prepared by Bruce Robison, Karen Wishner, and Holger Jannasch concluded that remotely operated vehicles (ROVs) hold the greatest promise for widespread use.

The *Technology* chapter overview by Norm Estabrook identified the elementary technologies necessary to establish a meaningful deep ocean presence, with each sequentially addressed by the following authors. R. E. Garvey provided details for a cylindrical composite hull, whereas J. D. Stachiw suggested ceramic housings. Ernest Blase and Richard Bis described potential power source options. Sam Kelly concluded that current technology existed for navigation and communication.

The *Design Concepts* final section provided criteria in an introduction by R. Adm. J. B. Mooney, Jr. USN (Ret), resulting in designs for two manned and two unmanned vehicles. Tapani Muukki described a concept of a manned submersible capable of 11,500 m depth. Graham Hawkes and Philip Ballou presented a radical departure from conventional manned vehicle designs with *Deep Flight Challenger*, subsequently developed but not yet making the record setting dive. James McFarlane concluded an ROV–AUV hybrid solution as autonomous underwater vehicle (AUV) technology and software were not yet developed to manage manipulative tasks. T. A. Glenn and D. R. Blidberg offered two possible configurations for a deep ocean autonomous vehicle.

The *Journal* issue of a deepest ocean presence was not limited to any one vehicle or type of approach. It concluded that each vehicle—manned, unmanned, ROV, or AUV—has its strengths and weaknesses that need to be recognized in planning for long- and short-term studies, transects, and delicate manipulative tasks.

How These Predictions of the Future Actually Occurred

The past 20 years have evidenced notable change in the capabilities for deep ocean exploration. The *MIR* submersibles delivered in 1987 can dive to a maximum depth of 6,000 m (19,685 feet). That made them two of only seven manned submersibles in the world (at that time) that could dive beyond 3,000 m (9,843 feet), the others being the U.S. submersibles *Alvin*, *Sea Cliff*, and *Deepstar 20000*, the Japanese-owned *Shinkai*, and the

French-owned *Nautile*. Up to 98% of the world's oceans are less than 6,000 m deep.

With the advent of remotely operated and autonomous vehicles over the last decade, the crewed submersible's utility has declined. The modified deep submergence vehicle (DSV) *Alvin* will be ready to make dives by the end of 2011, but enabling the vehicle for greater dive depths may not happen until *Alvin*'s next 5-year scheduled overhaul in 2015. With *Turtle* (DSV 3), October 1997, and *Sea Cliff* (DSV 4), having been retired in October 1997 and August 1998, respectively, and while according to the Naval Vessel Register the somewhat puzzling *Nemo* (DSV-5) remains in service, the fact of the existence of this vehicle is not widely attested to and details remain entirely obscure.

Other less capable U.S. manned submersibles (<1,500 m) have been similarly retired. Deep submergence rescue vehicle (DSRV) *Avalon* (DSRV 2) was decommissioned in 2000 and *Mystic* (DSRV 1) in September 30, 2008. The Submarine Rescue Diving and Recompression System—Rescue Capable System (SRDRS-RCS), depth rated to 610 m, replaced the DSRV. SRDRS consists of the Atmospheric Dive System 2000, which was delivered to the Navy in 2006. Atmospheric Dive System 2000 is a manned, one-atmosphere dive suit capable of inspecting disabled submarines and clearing debris from escape hatches. SRDRS-RCS consists of *Falcon*, a tethered, remotely operated pressurized rescue module, its launch and recovery system, and its support equipment, all of which are controlled from a Vessel of Opportunity. The final phase of the SRDRS program is the Submarine Decompression System, scheduled for delivery in late 2012. The Submarine Decompression System will allow rescued submariners to remain under pressure during the transfer from the pressurized rescue module to hyperbaric treatment chambers aboard the Vessel of Opportunity.

Despite her recent repair and upgrade, the *USS 555 Dolphin* was decommissioned in January 2007 and is now at the Maritime Museum of San Diego. NR-1 is scheduled to start the inactivation process at the end of this year.

The *Shinkai 6500* is a manned research submersible that can dive to a maximum depth of 6,500 m. It was completed in 1990 and has the greatest depth range of any manned research vehicle in the world. The vehicle is owned and run by the Japanese Agency for Marine Earth Science and Technology.

Twenty years later, Woods Hole Oceanographic Institution (WHOI's) *Nereus* dove the Mariana Trench. It is further described in the "Journey to the Challenger Deep: 50 Years Later With the *Nereus* Hybrid Remotely Operated Vehicle," included in this *Journal*.

In addition, perhaps more of a concept question, what is the reason for the current migration and transition toward more unmanned systems, and why that has happened? Likely the biggest driver has been computer processing power and bandwidth. In the 1960s, before the days of fiber-optic cables and massive computing power, it was necessary to put a man/woman on the scene. Not only for interpretation of the "view" but also to provide an "on scene" cognitive power for normal and emergency operations. Now, the bandwidth and processing power/techniques have given us a tele-presence or remote cognition allowing us to more fully appreciate the "on scene" action and information while remaining topside or remote.

This capability combined with the improved power density and power delivery systems available has made more and more decision makers to opt for the remote or autonomous solution. Added benefits derived include

a. increased human safety,
b. decreased surface support ship requirements,
c. fewer sea state restrictions,
d. improved operational cycles or time on station/site,
e. improved efficiency/cost effectiveness, and
f. decreased training requirements. (A scientist does not have to pass a physical to use an ROV/AUV. They did if they dove in a DSV.)

In conclusion, further advances in these improved capabilities (in conjunction with continuing outer space exploration technology advances) will result in future advances in the capabilities for "A Deepest Ocean Presence."

PAPER

Journey to the Challenger Deep: 50 Years Later With the *Nereus* Hybrid Remotely Operated Vehicle

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ABSTRACT

The hybrid remotely operated vehicle *Nereus*, developed by the Woods Hole Oceanographic Institution in collaboration with the Space and Naval Warfare Systems Center Pacific and Johns Hopkins University, is designed to provide a new level of access to a maximum depth of 11,000 m. *Nereus* operates in two different modes. The vehicle can operate untethered as an autonomous underwater vehicle for broad area survey, capable of exploring and mapping the seafloor with sonars, cameras, and other onboard sensors. *Nereus* can be converted at sea to become a remotely operated vehicle (ROV) to enable close-up imaging and sampling. The ROV configuration incorporates a lightweight fiber-optic tether to the surface for high-bandwidth real-time video and data telemetry to the surface to enable high-quality teleoperation, additional cameras and lights, manipulator arm, and sampling gear. *Nereus* underwent sea trials in May and June of 2009 during which it completed eight dives, including two dives to more than 10,900 m in the Challenger Deep of the Mariana Trench with a total bottom time in excess of 12 h.

Introduction

Objective and Scientific Rationale

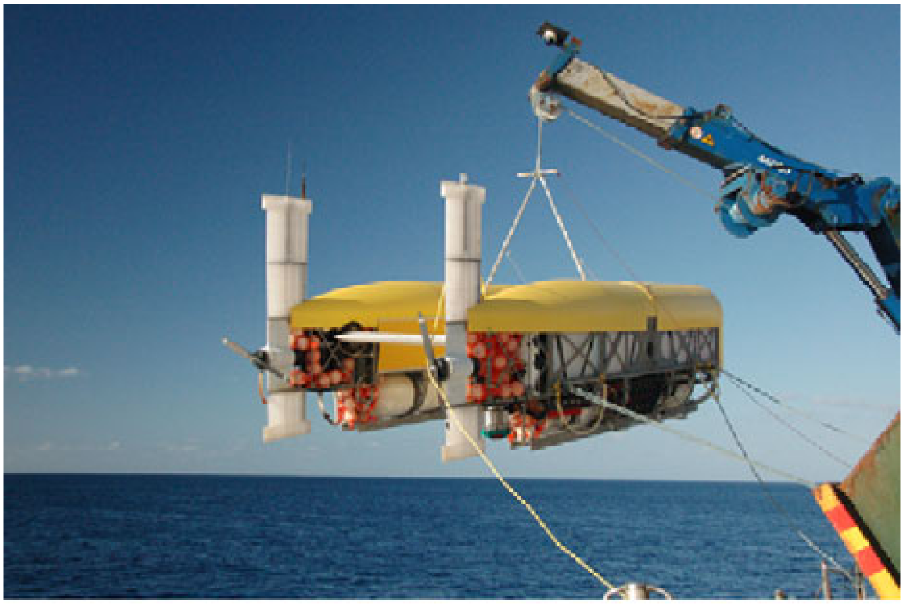
The goal of the *Nereus* hybrid remotely operated vehicle (HROV) project is to provide the U.S. oceanographic community with the first capable and cost-effective technology for regular and systematic access to the world's oceans to depths of 11,000 m. The vehicle is able to operate both untethered as a fully autonomous underwater vehicle (AUV) and also as a self-powered remotely operated vehicle (ROV) employing a small diameter optical fiber tether for real-time telemetry of data (Figure 1). *Nereus* is designed to incorporate useful features and capabilities of both ROV and AUV systems, providing both capabilities at an affordable cost. In its AUV mode, *Nereus* operates autonomously, performing sonar and camera surveys, with an acoustic link for monitoring and mission updating. In ROV mode, it is remotely controlled by an operator to perform close-up inspection, sampling, and other intervention tasks. The two modes provide for robust operation: if the fiber cable connection is lost while in the ROV mode, *Nereus* reverts to the autonomous mode, allowing for autonomous mission completion.

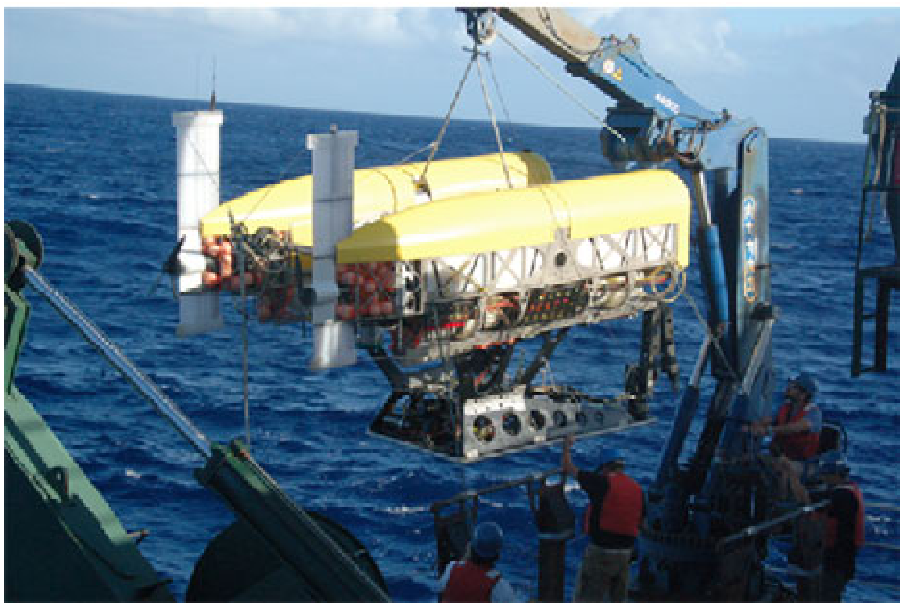
Background

A variety of studies have identified the development of an 11,000-m deep-submergence vehicle as a national priority (DESCEND, 2000; National Oceanic and Atmospheric Administration [NOAA], 2000; National Science Foundation [NSF], 1996; Shepard et al., 2002), the mandate to survey and understand the geologic and biologic complexities of deep trench systems in the newly designated Mariana Marine National Monument area (Fryer et al., 2003; Williams, 2009) and national and international imperatives regarding ocean exploration. Existing deep-submergence vehicle systems provide critical, routine access to the sea floor to a maximum depth range of 7,000 m—for example, the 4,500-m Alvin human occupied submersible (Broad, 1997), the 4,500-m autonomous benthic explorer (ABE) AUV (Yoerger et al., 2007), and the 4,000-m Tiburon ROV (Newman and Stakes, 1994). Only a few currently operational vehicles are capable of diving to between 6,000 and 7,000 m such as the 6,500-m *Jason II* ROV (Whitcomb et al., 2003) and the 7,000-m *Kaiko 7000* (Murashima et al., 2004). These and other systems have led to significant scientific discoveries over the past 50 years, including identifying and sampling mid-ocean ridge volcanic processes, hydrothermal

FIGURE 1

HROV in AUV mode (top) and ROV mode (bottom).





processes, and biological ecosystems that have revolutionized the biological sciences (NSF, 1996). The *Nereus* will extend the reach beyond 7,000 m, to the full ocean depth of 11,000 m, providing new scientific access.

Before *Nereus*, only two vehicles had reached the deepest place on Earth—the Challenger Deep of the Mariana Trench. Fifty years ago, on January 23, 1960, the human-piloted Bathyscaph *Trieste*, developed by Auguste Piccard, made one successful dive to the Challenger Deep (Piccard and Dietz, 1961), with a bottom time of 20 min. Fifteen years ago, in 1995, the remotely controlled ROV *Kaiko*, built and operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), made the first of several successful dives to the Challenger Deep (Takagawa, 1995). Neither *Trieste* nor *Kaiko* is currently operational. Moreover, the design approaches employed in these vehicles result in high operational costs—too costly to be routinely supported by U.S. oceanographic science budgets.

Use of conventional tethered ROVs such as *Jason II* for full ocean depth operation is limited by two main factors: weight of the necessary pressure vessels and the need for a power/communications tether. Typical deep-sea pressure vessels made of titanium become prohibitively heavy when built to the strength required for 11,000 m operation. The use of ceramics, with the high strength to weigh ratio, allows for reasonably sized pressure vessels to be used on *Nereus*.

Steel-reinforced cables cannot be utilized to 11,000 m because they are self-supporting in seawater only to lengths up to about 7,000 m. Alternative tension member materials for 11,000-m operations, such as Kevlar, result in large-diameter cables that require very large cable handling systems and significantly restrict maneuverability. The use of light, fiber-optic tethers offers an alternative to conventional large-diameter steel and Kevlar cables. To date, this type of tether has principally been employed in military applications; relatively, few light fiber tether systems have been employed for oceanographic research. The self-powered ROV *UROV7K* employed an expendable fiber-optic tether (Nakajoh et al., 1998). Unlike *Nereus*, this vehicle was designed to operate exclusively as a tethered ROV and did not have onboard computational resources necessary to operate autonomously. In 1999, International Submarine Engineering Limited reported the successful deployment of an AUV designed to deploy fiber-optic communication cables on the arctic sea floor (Ferguson et al., 1999). To the best of our knowledge, McFarlane was the first to report the conceptual design of an 11,000 m capable vehicle employing a small diameter (3/8 in) electro-optic tether (McFarlane, 1990).

Concept of Operations

Nereus was designed as a portable vehicle system that can be rapidly deployed from a ship of opportunity, without requiring dynamic positioning of the ship, thus enabling it to be deployed from regional class as well as ocean class ships. With two modes of operation, it can fulfill a variety of ocean exploration tasks.

AUV Mode

Like other AUVs such as the ABE (Yoeger et al., 1998), *Nereus* can operate independently in AUV mode to perform the wide area survey functions. The low bandwidth and the time delay of acoustic telemetry, however, limit real-time remote control by human operators, and consequently, AUV operations are limited to mapping survey tasks. *Nereus* carries several sensors that allow it to make maps surveys of the water column and seafloor. For the water column, *Nereus* carries a conventional CTD (Seabird SBE49), an optical backscatter sensor (Seapoint STM), and a redox potential sensor (Nakamura). For bathymetric mapping, *Nereus* carries an Imagenex 881 675-kHz scanning sonar modified by the manufacturer for 11,000-m operation. To date, we have been unable to secure a multibeam sonar that meets our depth requirements.

When operating as an AUV, *Nereus* begins with a set of preprogrammed track lines that can be run at constant depth or while following the seafloor at a prescribed height. Abstracted vehicle state and scientific sensor data are communicated to the surface in real time using the acoustic links (Singh et al., 2009). Track lines and bottom-following parameters can be updated over the acoustic link when anomalies are observed.

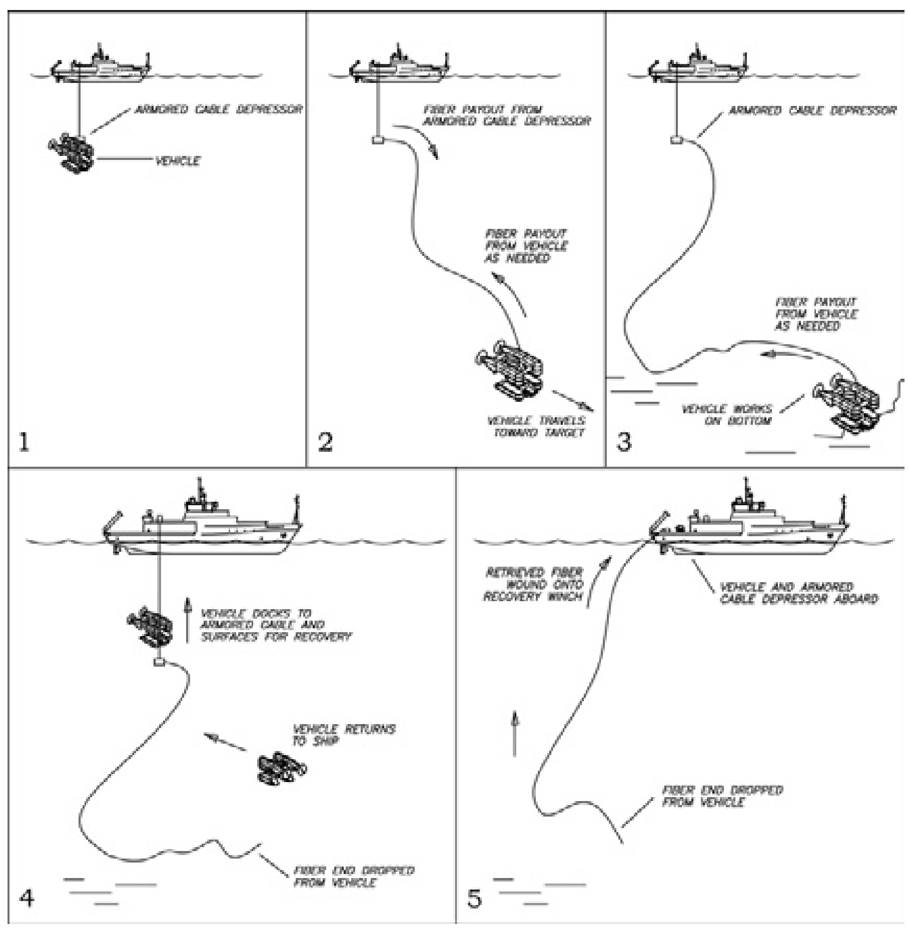
ROV Mode

In order to perform the complex sampling and manipulation tasks commonly executed by ROVs and inhabited submersibles, *Nereus* may be converted from its AUV configuration to an ROV configuration on board the ship. The ROV mode concept of operations is as follows and depicted in Figure 2:

1. Deployment: The HROV is deployed with the depressor from the support vessel using a standard oceanographic cable. This cable serves as a method both to physically launch the depressor and to enable transition to the fiber cable in a controlled environment away from surface effects. The HROV is equipped with one releasable descent weight and two releasable ascent weights.
2. Descent: Once the vehicle and the depressor have reached the desired depth, the vehicle is released from the depressor, and the vehicle begins a free fall to the seafloor. Fiber canisters contained in both the depressor and the float pack attached to the vehicle pay out fiber passively.

FIGURE 2

Nereus ROV mode concept of operations.



The canister on the float pack pays out primarily due to vehicle motion, and the canister on the depressor pays out as the depressor moves due to vessel and surface motion.

3. On bottom: Once the vehicle has reached the bottom, the descent weight is released from the vehicle. The neutrally buoyant HROV is then free to maneuver and conduct its mission.
4. Ascent: Once the HROV has completed its mission on the sea floor, the fiber-optic cable is cut at the float pack and the depressor, and the vehicle drops its ascent weight and returns autonomously to the surface.
5. Recovery: The depressor is brought on board the ship while *Nereus* ascends. Once the vehicle is on the surface, it is recovered using a shipboard crane.

System Design Overview

Vehicle Structure and Propulsion

The *Nereus* core vehicle employs twin free-flooded hulls, and it can be reconfigured at sea into ROV mode or AUV mode. The core vehicle contains the main floatation, the batteries, and the electronics common to both configurations. AUV-mode propulsion is provided by two 1-kW thrusters fixed on the aft tails and one 1-kW thruster on the articulated mid-foil. In AUV mode, there is no lateral thruster actuation. In ROV mode, propulsion is provided by two 1-kW thrusters fixed on the aft tails and the addition of one lateral 1-kW thruster and two vertical 1-kW thrusters.

Ceramic Housings and Buoyancy Spheres

Ceramic was selected for the pressure housing and buoyancy sphere material because of its high compressive strength-to-weight ratio, allowing for near-neutrally buoyant housings capable of going to these extreme depths (Figure 3). All onboard electronics, batteries, and internal sensors are housed at 1-atmosphere in novel, lightweight ceramic/titanium pressure housings developed specifically for this project (Stachiw et al., 2006). The housings consist of a ceramic section formed by CoorsTek Inc., titanium joint rings, and titanium end caps designed and manufactured at WHOI that are bonded to the ceramic with a high-strength epoxy material. The titanium elements were designed to ensure that the ceramic and titanium elements displaced compatibly during compression. These designs were evaluated using finite-element analysis then tested in the WHOI pressure test facility. Seamless spheres of 99.9% alumina ceramic, manufactured by Deep Sea Power and Light, were chosen (Stachiw and Peters, 2005; Weston et al., 2005) to serve as the primary buoyancy for the system. Additional information may be found in Bowen et al., 2008 and Stachiw et al., 2006.

FIGURE 3

Ceramic housings and spheres.

Power

Nereus is powered by a 16-kWh rechargeable, lithium ion battery system, developed for this project, contained in two additional ceramic pressure housings. Building on the design of lithium ion powered ABE (Yoerger et al., 1998) and REMUS (Allen et al., 1997) AUVs, WHOI designed a modular building block of 12 cylindrical cells. The maximum power output of the batteries is 3 kW.

Cameras and Lighting

For AUV-mode imaging, a full-motion-capable color imager based on a Uniq UC-1830CL-12B machine-vision camera used in previous deep-sea work has been employed (Howland et al., 2006). Two NTSC Insite Pacific Aurora subsea video cameras in 11,000 m housings support viewing of the work package and other utility tasks. Lighting is provided by lightweight, ambient-pressure LED arrays, custom developed by WHOI for the *Nereus* project (Howland et al., 2006).

Navigation

The *Nereus* navigation sensor suite includes the following:

Paroscientific 9000-20K-101 pressure depth sensor

SBE49 FastCAT CTD Sensor

Teledyne-RDInstruments 300 kHz Doppler sonar

IXSEA PHINS INS (inertial navigation system)

WHOI LBL transceiver

WHOI Micro-Modem (Freitag et al., 2005)

Microstrain gyro-stabilized attitude- and magnetic-heading sensor

Navigation sensor data are received by the *Nereus* control computer, where the navigation process NavEst computes vehicle state estimates. NavEst is navigation software developed by WHOI and JHU for use on deep-submergence vehicles (Kinsey and Whitcomb, 2004; Jakuba, 2007; Yoerger et al., 2007).

Communications

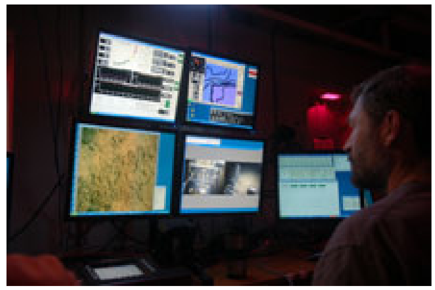
For working in the AUV mode and as backup to the fiber in ROV mode, *Nereus* employs an acoustic telemetry system. The acoustic telemetry system is designed to send data between multiple vehicles including one or more surface ships. The system employs WHOI Micro-Modems (Freitag et al., 2005). The setup for the 2009 *Nereus* sea trials involved one EDO/Straza SP23 transducer mounted on the forward starboard brow of the vehicle. The general acoustic communications architecture is reported by Eustice et al. (2007) and Webster et al. (2009), and analysis of the May–June 2009 communication performance is reported by Singh et al. (2009) and Webster et al. (2009).

Command and Control

One of the most notable features of the *Nereus* system is the ability to be accommodated on oceanographic ships of opportunity. The complete operations center may be installed in a shipboard laboratory, not requiring a dedicated van (Figure 4). Within the operations center, a network of computers performs operations of navigation, command, control, and communications. On board the vehicle, the *Nereus* mission controller performs the job of the pilot in the absence of high-bandwidth telemetry (Jakuba et al., 2007; Bowen et al., 2008). In AUV mode, the mission controller supports fully autonomous survey missions. In ROV mode, the mission controller permits normal pilot-controlled teleoperation of the vehicle and, in the event of the loss of tether telemetry, assumes control of the vehicle and autonomously completes a preprogrammed mission. During the 2009 Mariana sea trials, all ascents were executed autonomously under the guidance of the mission controller (Bowen et al., 2009 a, b).

FIGURE 4

WHOI research engineer Matthew Heintz remotely pilots *Nereus* during Dive 10. Vehicle controls and displays include manipulator master control, high-resolution imaging camera display, depressor navigation and control panel, vehicle navigation display, vehicle control panel, and utility camera displays.

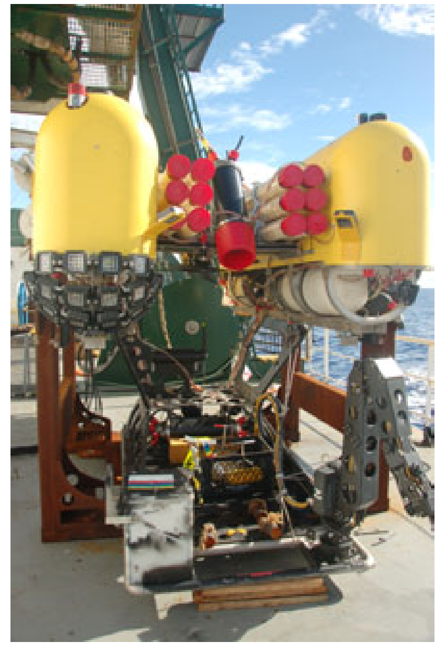


Manipulator and Work System

Nereus is designed so that it may be converted into ROV mode on board a ship within about 24 h. In addition to the fiber-optic communication system, this mode adds a work package containing a 6 degree-of-freedom electro-hydraulic robot arm, sampling tools, sample containers, an additional high-resolution digital camera, two utility cameras, and several LED arrays (Figure 5). The *Nereus* work system consists of a 2.4 × 1.2-m platform with a custom-designed Kraft TeleRobotics manipulator and a WHOI-designed hydraulic power unit (Bowen et al., 2008, 2009a, b).

FIGURE 5

The *Nereus* in tethered ROV mode aboard the *R/V Kilo Moana* showing main ceramic pressure housings, lateral and vertical thrusters, auxiliary ROV-mode flotation spheres mounted in 12 red-capped cylinders, robotic arm, digital imaging cameras, LED lighting arrays, biological and geological sample containers, scanning sonar, acoustic modem transducer, and LBL transducer.



Fiber-Optic Tether System

A novel part of the *Nereus* system is the lightweight fiber-optic tether used when operating in the ROV mode (Table 1). In order to meet the vehicle requirements, an expendable tether system similar to that used in expendable bathythermographs and torpedoes was developed (Fletcher et al., 2008; Young et al., 2006). The design analysis of this cable for deep ocean deployments is reported in (Bowen et al., 2009 a, b).

The tether deployment system employs a snag-resistant depressor and a

TABLE 1

Fiber characteristics.

	Sanmina-SCI Fiber
Diameter (mm)	0.25
SG (fresh water)	1.36
Weight of 11 km in water (kg)	0.173
Working strength (N)	8
Breaking strength (N)	108

vehicle float pack, each holding a canister of fiber. The depressor was designed to get the upper tether deployment point below surface currents and below the most energetic and biologically active part of the water column. The vehicle float pack, containing an optical fiber canister, brake, fiber counter, and cutter, is attached to the vehicle via a 20-m neutrally buoyant cable. The float pack floats above the vehicle and is designed to minimize the chance of snagging the fiber on either the vehicle or the sea floor. The depressor and the float pack are mated together during launch as shown in Figure 6, protecting the fiber during the transition through the air–water interface. The depressor-float pack and the vehicle descend together to a designated depth. Once an appropriate depth has been reached, the vehicle and the float pack separate from the depressor. As the vehicle moves through the water, the tether is paid out from both the vehicle and the depressor, minimizing motion of the tether through the water. The cable deployment system was first integrated with the actual *Nereus* HROV vehicle in fall 2007 and is reported in further detail elsewhere (Fletcher et al., 2008, 2009; Webster and Bowen, 2003; Young et al., 2006).

FIGURE 6

Tether deployment system (depressor and float pack) with the vehicle in the water in background.

Nereus Development Chronology

The *Nereus* development program had several important milestones, many of which were based on the development and validation of certain key technologies or concepts, leading up to successful testing of the vehicle at 11,000 m. These milestones were comprised of three main activities: determination of a suitable concept of operations, development of the required technologies, and field trials to validate assumptions and solutions.

The Beginning

The concept of a light tethered vehicle for 11,000-m operations appears to have been first proposed by James MacFarlane of International Submarine Engineering Company in 1990 (McFarlane, 1990). Since that time, development work at JAMSTEC realized a self-powered vehicle based on a small diameter fiber tether (Nakajoh et al., 1998).

In 2001, using internal funds awarded to Senior Technical Staff at WHOI for high-risk/high-payoff activities, we examined the potential and feasibility of a lightly tethered vehicle in representative current profiles of the deep ocean. By adapting the WHOI cable simulation program (Gobat and Grosenbaugh, 2006), we were able to determine that a vehicle of this type was feasible. With this internal study complete, we submitted a proposal to the NSF, the NOAA, and the Office of Naval Research (ONR) to develop a vehicle capable of reaching 11,000 m. In 2002, this proposal was funded, with NSF as the lead agency. To support the fiber system development, ONR funded Space and Naval Warfare Systems Center Pacific (SSC Pacific) to build on its previous work in light fiber systems for this project.

With this funding in place, work began on the critical high-risk elements of the project. In particular, these were identified as the tether, lightweight structures (ceramics), and large-scale energy storage.

Initial Design and Testing: 2004–2005

A significant amount of early work centered on the fiber tether and ceramics development to insure systems capable of sustaining vehicle operations to 11,000 m. In addition to expanding the WHOI cable program, we engaged senior members of the Physical Oceanography Department to provide the best understanding of current profiles within expected operating regimes: trenches, polar regions, and mid-ocean ridges. In parallel, several fiber tether types were evaluated for performance at pressure. Several field trials were conducted, with each step in the test program intended to provide an increasing level of confidence, leading to a final system. In parallel, prototypes of the ceramic flotation were being developed by Deep Sea Power and Light and a second source. Similarly, cylindrical ceramic components were designed, developed, and tested (Stachiw and Peters, 2005; Stachiw et al., 2006). The required navigation and control systems were also assembled in a prototypical environment, drawing together elements from the *Jason* ROV and the ABE vehicles (Yoerger, et al., 1998; Whitcomb, et al., 2003; Kinsey, et al., 2004; Yoerger, et al., 2007).

Testing was performed to verify the concept and numerical simulations of passive payout of a fiber-optic data link in deep water. In November 2004, both fiber-optic microcable and the buffered fiber were successfully deployed in 2000 m, indicating the feasibility of the approach. In December 2005, the ABE vehicle was used to demonstrate the vehicle fiber-optic tether as it would be used in HROV operations. The longest dive was nearly 17 h, proving the feasibility of using a fiber with a mobile vehicle. Many lessons were learned that affected the subsequent deployment system development, in particular, the need for control of fiber tension payout and maneuvering of the vehicle once on the sea floor (Young et al., 2006).

System Development: 2006–2007

System development continued through 2006 and 2007. The lessons learned from the December 2005 tests were incorporated into a fiber deployment system design that was constructed and tested in May 2006. The deployment system consisted of a long, snag-resistant depressor and a float pack attached to a test platform. Four deployments of the system were made to 4000 m during this test period, with one deployment in excess of 18 h and another close to 12 h, demonstrating the feasibility and utility of the deployment concept (Young et al., 2006).

Sea Trials: 2007

In November 2007, we conducted full-scale sea trials of the entire *Nereus* vehicle system from the *R/V Kilo Moana* off the coast of Oahu, Hawaii. By this time, all critical components of *Nereus* had been tested independently. Previous tests confirmed and refined the microfiber tether and its two-stage deployment as described above. Ceramic housings, ROV work package, LED lighting, and lithium ion batteries had been tested separately. What remained was to test all these parts as a complete system in a suitable at-sea setting. Operational procedures for launch and recovery were developed and tested, and both AUV and ROV modes were exercised (Table 2). AUV features demonstrated included automated flight control, terrain following, autonomous navigation, real-time uplink of navigation data, and preprogrammed high-level mission control. Five dives were made in the ROV configuration using the fiber, culminating in a 4.5-h dive to 2257 m, returning samples and tube cores. During all ROV dives, the fiber remained intact until purposely cut during operations (Fletcher et al., 2008). Dr. Patty Fryer (University of Hawaii) and Dr. Tim Shank (WHOI) participated in the trials as the science party. These sea trials demonstrated

TABLE 2

Nereus Dives: November 2007.

DATE (UTC) (mm/dd/yyyy)	Dive	Vehicle Mode	Depth (m) Vehicle	Depth (m) Depressor	Time (h:min) Submerged	Time (h:min) Bottom	Fiber Payout (m) Vehicle	Fiber Payout (m) Depressor	Fiber Payout (m) Total
11/20/2007	Freejoy	AUV	2	–	05:56	00:00	–	–	–
11/21/2007	0	AUV	4	–	02:12	00:00	–	–	–
11/23/2007	1	ROV	18	0	00:57	00:00	–	–	–
11/23/2007	2	ROV	398	100	05:56	04:55	556	422	977
11/24/2007	3	ROV	400	400	01:20	00:00	191	1,177	1,368
11/24/2007	4	ROV	569	200	03:47	02:43	679	743	1,422
11/25/2007	5	ROV	2,270	1,000	06:50	03:21	1,214	1,138	2,352
11/26/2007	6	AUV	22	–	11:33	00:12	–	–	–

the viability of the hybrid ROV concept.

Preparation for the Deep: 2008–2009

Following the successful shallow water trials of the vehicle in late 2007, the vehicle returned to Woods Hole where work continued on completing the system. Further dock trials were held in early spring 2009, before the system was shipped to Guam for the initial deep trials.

2009 Mariana Sea Trial Operations

This section briefly summarizes vehicle operations of the 2009 *Nereus* sea trials. The dive locations were concentrated in the southeastern part of the Mariana arc region and the south axis of the Mariana Trench. The principal engineering objective of these field trials was to test the *Nereus* mechanical, electrical, and optical subsystems and its buoyancy at progressively greater depths—and therefore higher pressures (Table 3). The *Nereus* expedition mobilized and demobilized aboard the *R/V Kilo Moana* at the U.S. Naval Base Guam, Apra Harbor, Guam.

Dive 007

Dive 007 was to 900 m. This mission included a ballast test to verify the buoyancy model, lighting and imaging tests, a manipulator test, a DS7000 range test, and a test of the performance of the Doppler Velocity Log (DVL). Sensor tests showed all sensors to be functional. Scientific observation and sampling operations (coral and sponges) were conducted.

Dive 008

Dive 008 was to 3500 m. Similar to Dive 007, this mission included a ballast test to verify the buoyancy model, lighting and imaging tests, and a manipulator test. The dive was terminated because of an intermittent (biodegradable) oil leak from the manipulator throughout the dive because of a defective seal. Sensor tests showed most sensors to be functional. Scientific observation and sampling operations were conducted.

Dive 009

Dive 009 was to 6500 m, equivalent near to the maximum achievable by existing tethered systems. The descent weight dropped prematurely after separation from the depressor. Shortly after reaching the sea floor, fiber telemetry became intermittent and then lost permanently because of a fiber break. The mission was aborted by an acoustic abort command. Postmission analysis revealed that the tether break was a consequence of tether entanglement with the depressor, caused by a torsion-induced rotation of the depressor when the float pack separated from the depressor. This was due to the relaxation of a new depressor cable and was not seen in subsequent dives.

Dive 010

The goal of Dive 010 was to deploy *Nereus* to 9000 m—a depth deeper than the capability of any other currently operational underwater vehicle. DVL water lock tests were performed at 1,900 m. This mission included a ballast test to verify our buoyancy model, lighting and imaging tests, navigation sensor tests, a manipulator test, DVL tests, lighting and imaging tests, and a test of the scanning sonar. Tube cores, rock samples, and biological samples were collected. The vehicle fiber cutter failed to cut the fiber tether

TABLE 3

Nereus Dives: May–June 2009. All dives were done in ROV mode.

DATE (UTC) (mm/dd/yyyy)	Dive	Vehicle Mode	Depth (m) Vehicle	Depth (m) Depressor	Time (h:min) Submerged	Time (h:min) Bottom	Fiber Payout (m) Vehicle	Fiber Payout (m) Depressor	Fiber Payout (m) Total
05/25/2009	7	ROV	912	587	05:48	03:46	699	331	1,030
05/26/2009	8	ROV	3,510	3,022	11:06	02:13	626	400	1,026
05/27/2009	9	ROV	6,424	5,887	11:18	00:34	41	1,353	1,394
05/28/2009	10	ROV	9,029	5,777	18:03	04:50	8,424	1.969	10,393
05/30/2009	11	ROV	10,903	5,869	25:38	10:40	3,479	3,308	6,787
06/01/2009	12	ROV	10,902	5,871	18:03	02:30	2,058	4,014	6,072
06/03/2009	14	ROV	10,166	5,706	13:06	00:00	1,943	2,965	4,908
06/04/2009	15	ROV	2,960	2,406	11:48	06:56	802	556	1,358

before ascent, resulting in excessive fiber payout from the vehicle during ascent and recovery.

Dive 011: Challenger Deep

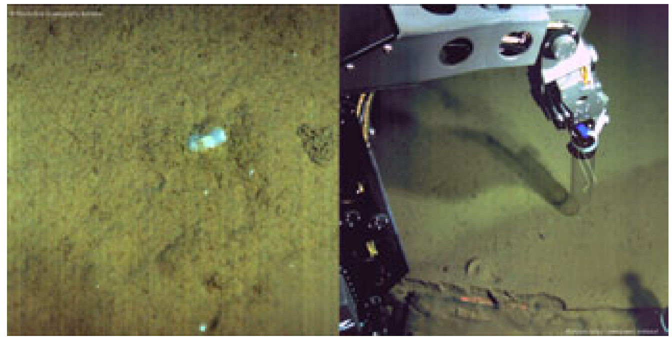
Nereus reached a depth of 10,903 m at 11 22.1′N, 142 34.4′E on our first dive attempt in the Challenger Deep. The vehicle started near the deepest known spot in the Challenger Deep and then transited south approximately 0.5 km and explored the edge of the subducting plate, taking rock samples with the manipulator, which was fully operational. The vehicle then moved northwest across the trench floor toward the overriding plate, taking tube cores and biological samples for approximately 2 km (Figure 7). Acoustic communications between the vehicle and the surface were operational throughout the dive.

Dive 012

Dive 012 was to 10,902 m. On descent, a mid-water DVL Test was performed. Tube cores and biological samples were collected (Figure 8). Dive 12 terminated due to fiber tether failure after 2 h on the bottom, after which the onboard mission controller autonomously commanded the vehicle to the surface.

FIGURE 8

Core sampling at 10,898 m depth; *Nereus* dive 12: June 2, 2009.

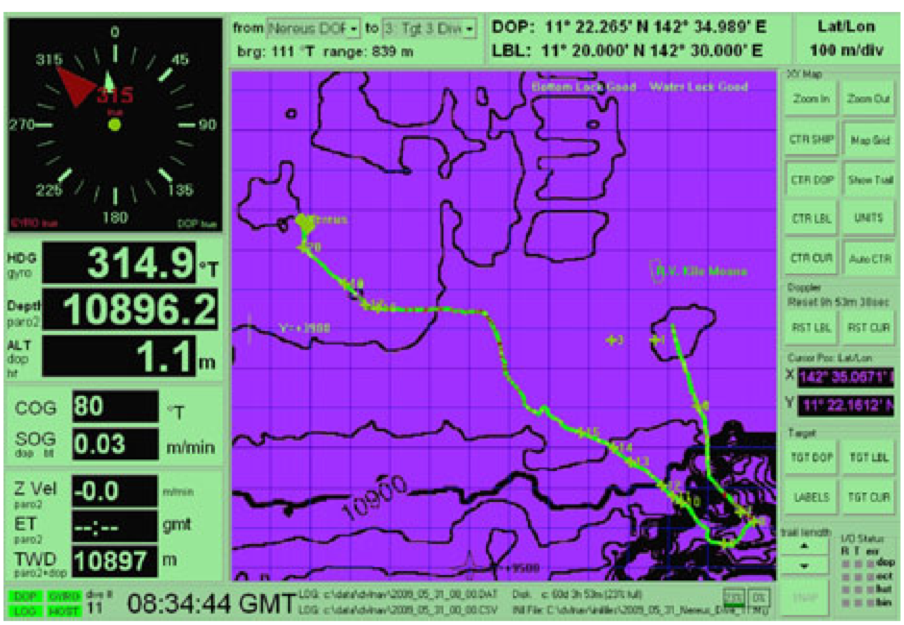


Dive 014

The goal of Dive 014 was to deploy *Nereus* to 10,900 m. The dive was aborted because of failure of fiber tether near the depressor during vehicle descent. The dive was aborted automatically by the mission controller when the fiber-optic telemetry was lost for over 30 min, and the ascent weights were dropped 15 min later following an acoustic abort command.

FIGURE 7

Nereus screen shot of the DVLNAV program (Kinsey and Whitcomb, 2004) during dive NER011, showing *Nereus*'s extreme horizontal mobility in tethered ROV mode enabled by its light fiber-optic tether. The plot shows the position of the *R/V Kilo Moana*, *Nereus*'s position, and *Nereus*'s bottom track after 8 h and 45 min bottom time.



Dive 015

Dive 015 was to 3,000 m at a known hydrothermally active site. It was occasionally difficult to maneuver *Nereus* because of high currents at the site. Numerous geological and biological samples were collected. The mission was terminated via an acoustic abort command upon completion of the sampling tasks.

Conclusions

For the past 50 years, vehicle limitations have restricted *routine* benthic access to depths of 7,000 m or less. Only a few previously reported vehicles capable of diving below 7,000 m have ever been developed and successfully deployed, and none of these vehicles are presently operational. The scientific community has established substantive imperative to investigate the deep ocean floor at depths below 7,000 m, yet a lack of practical technology has prevented routine access to the deepest ocean. These largely unexplored areas of the ocean offer the potential to make important biological and geologic discoveries. Preliminary sea trials with *Nereus* in May–June 2009 demonstrated basic functionality of capabilities in ceramic housings, fiber-optic tether systems, manipulators, cameras and lighting, navigation, control, and acoustic telemetry. This development points to a way forward for both scientific and commercial operations through the use of a unique combination of technologies.

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In March 2004, WHOI engaged the noted ceramics experts Dr. Jerry Stachiw and Dr. Joan Stachiw of Stachiw Asssociates to assist with the development of ceramic pressure housings and flotation for the vehicle. They led the effort to develop, procure, and test the ceramic components on *Nereus* and provided invaluable technical support throughout the program. We regret that Jerry Stachiw passed away on April 25, 2007. Our heartfelt thanks go to Joan for all of her and Jerry's contributions to the *Nereus* project.

FIGURE 9

The May–June 2009 *Nereus* Sea Trial Team.

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TECHNICAL NOTE

Revisiting the Challenger Deep Using the ROV *Kaiko*

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After the remotely operated vehicle *Kaiko* (Figure 1) was launched from the deck of its support ship, the research vessel *Kairei*, it descended for more than 3 h through nearly 11 km from the surface of the calm seas ~320 km SW of Guam to the seabed at the bottom of the Challenger Deep in the Marianas Trench. Even watching the *Kaiko* system in operation, it is difficult to imagine just how deep 11 km is until you put it in the context of normal human experience—it is the same distance as the altitude of a commercial transcontinental or transoceanic flight. Although sitting in the ROV control room (Figure 2) aboard the *Kairei* in 1998 could not have equaled the intensity of a descent inside the cramped sphere of the *Trieste* 38 years earlier, watching as the display of *Kaiko*'s depth sensor in the ROV control room counted past 5,000, 7,000, and 10,000 m was captivating, to say the least. When the seabed finally appeared through the darkness as the ROV reached 10,924 m, we knew we had witnessed something very special.

FIGURE 1

ROV *Kaiko* during recovery from the Challenger Deep. The launcher (top half) and vehicle (lower half) are both visible.

FIGURE 2

ROV control room on the R/V *Kairei* during descent of the *Kaiko* in the Challenger Deep. Two primary pilots operate the *Kaiko* thrusters and manipulators while other support personnel and researchers watch.

JAMSTEC, the Japan Agency for Marine-Earth Science and Technology, developed the ROV *Kaiko* in 1995 to enable scientific research in the deepest trenches of the oceans. The *Kaiko* is a two-body system with a smaller mobile *vehicle* latched to the *launcher* during descent. The *launcher*, about 5.2 m in length, 2.6 m wide, and 3.2 m high, acts as a heavy weight (5.8 tons in air) to help the *Kaiko* system to sink rapidly to depth. It has limited capabilities for operation near the seabed, but can be used without the *vehicle* as a towed system equipped with side-scan sonar, a sub-bottom profiling system, and a sensor package (CTD). For use with the *Kaiko vehicle*, the two are mated through a 250 m long tether that unreels from a spool mounted in the *launcher*, allowing the *vehicle* a relatively short but unconstrained ambit. The *vehicle* is the heart of the *Kaiko* system, and once released from the *launcher*, it can use its four horizontal and three vertical thrusters (~5 kW each) to maneuver freely near the *launcher*, exploring and sampling the seabed. It is smaller (3.0 m long × 2.0 m wide, and 2.1 m long) and lighter (3.9 tons in air) than the *launcher* and is equipped with several CCD and wide angle color video cameras, a digital still camera, several high-intensity lights, and several sensors (forward looking sonar, altimeter, depth, compass, GPS). Two highly dexterous manipulator arms (six axes and seven axes of motion) enable operators to deploy and recover samples or gear from the front-mounted sample basket.

Deployment, positioning, and recovery of a massive system like the *Kaiko* are complicated operations. At 106 m length and 4500 tons displacement, the R/V *Kairei* is a very capable support ship, with berthing for 22 researchers, and is outfitted with a large multipurpose A-frame and winch system. The *Kaiko* is protected in a hanger when aboard the *Kairei* (Figure 3). Before each dive, it is rolled to the aft deck deployment station on rails. Upon deployment, the A-frame lifts the nearly 10-ton mated *Kaiko* system over the stern. The primary tether, ~4.5 cm diameter with optical and copper conductors, is then paid out at ~1 m/s from a single massive (>7 m in diameter) steel spool (Figure 4) holding 12,000 m of cable, through a cable-tensioning system, across the aft deck to the A-frame pulley, and over the side. Very accurate navigation of the *Kaiko* is accomplished using a set of three acoustic transponders arranged as a long-baseline system that can be pinged from the *launcher* and *vehicle*. Once the *Kaiko* system is within 100 m of the seabed, the *vehicle* is unlatched from the *launcher* and the secondary cable (~3 cm diameter) is paid out to allow the *vehicle* to wander the nearby seabed. Transiting long distances (several hundred m or more) while the *Kaiko* is deployed is difficult but possible by towing the *launcher* using the *Kairei*. Recovery of the *Kaiko* first requires re-reeling the primary cable on the *launcher* and re-mating the *vehicle*, then rewinding the primary cable until the *Kaiko* can be reattached to the A-frame and lifted aboard the *Kairei*. The *Kaiko* made numerous dives in various trench systems until 2003, when the *vehicle* was lost near the surface when the secondary tether was severed during a storm. Unfortunately, a power failure on the *vehicle* had prevented re-mating it with the *launcher* prior to ascent. The *Kaiko* was returned to service in 2004 as the *Kaiko 7000 II* (rated to 7,000 m) after adapting a 7,000 m rated ROV as a *vehicle* compatible with the original *launcher*.

FIGURE 3

Aft hanger for ROV *Kaiko* maintenance, looking toward the stern A-frame. The primary tether is visible above the coarse net.

FIGURE 4

Primary tether spool for ROV *Kaiko*.

The ROV *Kaiko* completed a series of dives at the Challenger Deep in 1998 and succeeding years during which researchers saw very sparse life on the seabed (Figure 5). Two major factors—great ocean pressure and potentially severe food limitation—make the Challenger Deep one of the most extreme environments on Earth. The weight of seawater reaching nearly 1,100 atmospheres affects protein stability and membrane permeability in all organisms, such that any capable of inhabiting hadal depths must have proteins, enzymes, and membranes tuned to extreme pressures. Food is another problem. Deep-sea ecosystems depend on the rain of organic debris derived from surface production, which in the oligotrophic waters over the Challenger Deep is typically quite low. In addition, consumption and recycling of organic material as it sinks toward hadal depths burn much of its nutritional value through each kilometer of depth, resulting in well less than 1% of surface levels expected to reach ~11 km. Consequently, little food is available for any life tolerant of the high pressures in the Challenger Deep. Future visits to the Challenger Deep using new deep-diving vehicles will allow researchers to test hypotheses related to the role of extreme pressure, food limitation, or perhaps other factors in defining the boundaries of life in this extreme environment.

FIGURE 5

Collection of sediment core samples at 10,924 m in the Challenger Deep.

PAPER

From the Bathyscaph *Trieste* to the Submersibles *Mir*

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Introduction

The endless, roaring ocean… Three men out of the Earth's six billion inhabitants are now 5,000 m under the waves of the Central Atlantic. They alone can experience this unique sensation, as no one else in the entire world has ventured down to such a depth in this area. Only the thin steel of their submersible's hull separates them from the crushing weight that surrounds them; they do not feel the pressure reaching 500 atmospheres (518.4 kg/cm^2 or 7,350 lb/inch^2).

Their three viewports allow observation of everything around them. The central viewport is made from a plastic acrylic with an inner diameter of 200 mm that has to withstand the force of 145 metric tons (160 U.S. tons), the weight of four heavy tanks. However, the men are safe because their Deep Manned Submersible (DMS) has been developed and tested well beyond the maximum operating depth of the submersible. They even forget where they are, so absorbed are they in what they see. They have become as one with nature.

I was fortunate to be one of these adventurers, and this is the story of our journey and, in a larger sense, the saga of deep sea exploration.

For anyone fortunate to experience "the deep," this sense of the depth is subconsciously ever-present, from the moment the hatch closes, to touching the seabed, to departing from the underwater landscape, and finally to surfacing. However, even after the hatch is opened and friends and colleagues are met on board the mother ship, this extraordinary feeling does not simply disappear—it lives on somewhere inside.

For myself, now that so many of these dives are behind me and after having spent thousands of hours underwater, I feel that this sense of the deep is always with me when I meet with people, whether they are friends or relatives and at work or at home. It is part of my life. It is an insatiable passion. Every dive brings not only great pleasure but also new sensations from the deep.

From Bathysphere to Modern Six-Thousanders

On October 26, 1948, Auguste Piccard, a Swiss scientist and engineer, along with French biologist Dr. Theodore Monod, made the first deep dive in a free-diving, manned submersible. It was a bathyscaph, the *FNRS-2*, and it reached a depth of 1,515 m (4,970 feet). This could be considered the birthday of DMSs.

The bathyscaph played a considerable role in the exploration and research of the ocean depths. In 1954, the *FNRS-3*, with a calculated diving depth of 4,000 m (13,123 feet), reached 4,050 m. This record was set by the French pilots Georges Houot and Pierre Willm. The *Trieste* bathyscaph, originally designed by Auguste Piccard, then modified for the deepest depths by the American Navy, reached 10,916 m (35,814 feet), the bottom of the Challenger Deep of the Marianas Trench, on January 23, 1960. The crew was Swiss scientist Jacques Piccard (Auguste Piccard's son) and American Naval officer Lt. Don Walsh. The record set by the *Trieste* still stands. Why? Today, the development of a DMS with an operating depth of 11,000 m presents no technical problem. The hurdle is the huge amount of capital needed to design and build such a vehicle that would need to be recouped during its future missions. So far, no organization or sponsor has come forward to finance scientific projects to look deeper into the secrets, the hidden nooks and crannies of the world's oceans (Figure 1).

The main goal in the 1950s for the majority of deep dives was to locate and to reach record depths. In the

FIGURE 1

Don Walsh, Anatoly, and Larry Shumaker in Kaliningrad (2001).

1960s, after the conquering of the Marianas Trench, the development of submersibles focused on the solution of certain practical and scientific problems.

In the entire history of deep dives, only eight DMSs have been built that can reach a depth of 6,000 m (19,685 feet). Three of them were of the bathyscaph type; that is, they used a float filled with gasoline to provide the vehicle with buoyancy. Before each dive, about 200 tons of gasoline were pumped into the float, which took most of a day. After each dive, the gasoline had to be pumped out, which also took a long time. There was the danger of fire, and swimmers did not enjoy when petroleum fuel was in the water. These vehicles were heavy and bulky.

However, they were a beginning, and their use led to improvements in materials and design. The five modern submersibles built in the second half of the 1980s had smaller dimensions, lighter weight, good maneuverability, and higher speed.

The critical event that sped the development of the new underwater technology was the loss of the American nuclear submarine *Thresher* in April 1963. The sub sank to an approximate depth of 2,500 m (8,200 feet). At this depth, the only possible way to search for and survey the sunken submarine was with the bathyscaph *Trieste.* Unfortunately, its preparation and delivery to the scene of the tragedy took some 2 months. After several dives with unsuccessful results, the bathyscaph needed repairs and she was towed to an American coastal base. After that, problems appeared with the navigational positioning of the *Trieste* while it was in the operational search mode; there was no method of doing this with the seabed hydroacoustic transponders in use at that time. Instead rescuers used a system of marking the route with flags of different colors that the pilots fixed on the seabed using the manipulator arms of the *Trieste.* These difficulties forced the leading American firms dealing with underwater technology to develop new submersibles that were compact, light, and could be transported to the disaster or research site by ship or plane. Syntactic rigid foam, a new, hard, floating material that was able to withstand the high pressure of great depths, played the main role in the development of a new generation of deepwater craft. This material is a composite of glass microspheres bound together by epoxy resin. The introduction of this new material allowed submersibles to be designed and developed without a bulky float, and this allowed their weight to be lowered considerably and their size reduced by a factor of two to three times.

During 1960s to 1980s, over 100 manned submersibles were built all over the world. All of them can be subdivided into two categories by operating depth: less than 6,000 m and over 6,000 m. The "six-thousanders" can be nominated "universal" because they are able to work on 98% of the ocean. Only 2% of oceanic trenches and troughs are inaccessible for them.

According to published data, there have been only five bathyscaphs in the world, two of them were the *Trieste-I* and the *Archimede*, which were developed for the maximum known depth of the ocean, 11,000 m. The *Trieste-II* had a diving depth of 6,000 m, and the *FNRS-2* and *FRNS-3* were rated to depths of 2,000 and 4,000 m, respectively. For more than 25 years, the *Trieste-II* and the *Archimede* were the only underwater craft that could reach the depth of 6,000 m.

In 1984 in San Diego, a farewell party was organized for the last of the bathyscaphs, the *Trieste-II.* By that time, the U.S. Navy had already prepared a new six-thousander, the *Sea Cliff.* It started as an old submersible but was modernized and reequipped. Its steel pressure sphere was replaced with one made of titanium, and many operating systems were improved, essentially creating a new vehicle, but it kept the same name.

The era of the bathyscaphs was over, but there were still no submersibles of a deeper class. As it happened, there developed a need in the 1980s for DMSs with an operating depth of 6,000 m. The discovery of hydrothermal vents and other discoveries on ocean bottom required the development of submersibles with an operating depth of 6,000 m. The submersibles could also be used for applied tasks like surveying, video-recording, photographing different objects, salvaging lost instruments, conducting search operations, and so on. These urgent needs caused the appearance of five modern submersibles with an operating depth of 6,000 m in the 1980s.

The deepest diving DMSs are given in Table 1. Three of them were built on the bathyscaph principle in the 1950s and 1960s and another five are modern DMSs developed in the 1980s. Since the *Sea Cliff* was decommissioned, U.S. scientists' remaining access is to the *Alvin* DMS, which was retrofitted in 1972 to operate at 4,500 m (14,760 feet) instead of the 2,000-m (6,560 feet) depth she had when commissioned in the middle of the 1960s.

The technical data regarding the compact, light, and maneuverable six-thousanders are shown in Table 2. Only four such submersibles are still in

TABLE 1

DMSs with operating depth of 6,000 m and more.

Submersible	Country	Operating Depth (m)	Launched	Withdrawn From Service
Bathyscaph *Trieste-1*	Switzerland; after 1958—United States	12,000	1953	1964
Bathyscaph *Trieste-II*	United States	6,000	1964	1984
Bathyscaph *Archimede-1*	France	12,000	1961	1981
Nautile	France	6,000	1985	
Sea Cliff	United States	6,000	1986	1998
Mir-1	Russia	6,000	1987	
Mir-2	Russia	6,000	1987	
Shinkai-6500	Japan	6,500	1989	

use: the French *Nautile*, the Japanese *Shinkai-6500*, and the two Russian *Mirs*. A comparison of their technical data shows that the *Mirs* have several advantages, including twice the battery power and a higher underwater speed, both of which are important for effective and economical use.

These submersibles have led long and interesting lives while conducting scientific research in different regions of the world's oceans, searching for and surveying many objects on the seabeds, taking tourists on dives, and participating in professional film shoots. As many scientists and engineers testify, the *Mirs* are the best designed of all the DMSs in use today.

TABLE 2

Technical data of the modern DMSs with an operating depth of 6,000 m and more.

Vehicle Basic Data	*Nautile* France	*Mir-1* and *Mir-2* Russia	*Shinkai-6500* Japan
Dry weight (tons)	18.5	18.6	25.2
Length (m)	8.0	7.8	8.2
Width (m)	2.7	3.8	3.6
Height (m)	3.45	3.0	3.45
Energy reserves (kW/h)	50	100	55
Life support (man/h)	390	246	300
Maximum speed (knots)	2.5	5.0	2.0
Buoyancy reserve (kg)	200	290	220
Crew	3	3	3
Pressure sphere			
Diameter (m)	2.1	2.1	2.1
Pressure sphere material	Titanium alloy	Nickel–steel	Titanium alloy
Batteries type	Lead–acid	NiCd	Silver–zinc

I remember some of our meetings and first dives with our foreign colleagues. In 1988, the *Keldysh* was returning from her maiden trip to the Atlantic. On the way home, we had to make a call at Amsterdam, I had sent invitations to come and see the new underwater vehicles to Jacques Piccard, Don Walsh, and Frank Busby, who was the leading American expert in the design and use of manned submersibles in those days. Piccard and Busby came to Amsterdam (Figure 2).

FIGURE 2

Frank Busby on board R/V *Akademik Mstislav Keldysh*, Washington, DC (1989).

Apart from diving into the Marianas Trench, Jacques Piccard was also a designer for the tourist vehicle *Auguste Piccard*, and the submersible that was used to research the Gulf Stream during a month-long drift in The Deep, *Ben Franklin*. Finally, there was the *Forel*, a submersible that allowed research operations to be conducted in Lake Geneva, Switzerland, and in the Mediterranean (Figure 3).

After Piccard and Busby had studied the *Mirs* on the outside, they entered one of them and spent 2 h inside, after which they both pronounced that this was a unique craft. They liked the streamlined style, the logical technology, and the internal setup that was both modern and spacious. When

FIGURE 3

Jacques Piccard with Anatoly, academician Lisitsin, Amsterdam (1988).

he returned to the United States, Busby informed the interested scientists and undersea researchers about the new vehicles. After that, we received a request for an article from *Sea Technology* magazine and invitations to go to the Marine Technology Society OCEANS Conference in Baltimore and to the Underwater Intervention conference on undersea vehicles in New Orleans.

All of this helped to promote the *Mir* name among scientists and experts in underwater research during the difficult economic situation that was developing in Russia. It also paved the way to some extent for the United States' participation in international projects. In 1989, the International Geological Congress opened in Washington, and the *Keldysh* with the *Mirs* on board was present.

An exhibition opened on the ship showing the achievements of Russian scientists in marine geology. The *Keldysh* brought a group of our leading geologists to the congress. While crossing the Atlantic, we made a stop to conduct several dives on the Kings Trough, a very interesting geological structure. There were foreign specialists working with us, among whom were deep diving experts Emory Kristof and Ralph White from the National Geographic Society and Joseph MacInnis from Canada. These were the first dives of the *Mirs* with Americans and a Canadian on board. Two dives to the depth of 5,100 m surpassed all their expectations, and they praised the technical capabilities of the *Mirs*. Understandably, they have not missed an opportunity to dive on the *Mirs* since.

The *Keldysh* stayed in the United States for 2 weeks, and many scientists and deep ocean experts visited the ship with the aim of getting to know the *Mirs*. The experts included Allyn Vine, the designer of the *Alvin* DMS, Barrie Walden, who headed *Alvin* DMS operations, and Dudley Foster, its chief pilot. The situation was much the same as it had been when Piccard and Busby were in Amsterdam; the experts sat inside the *Mirs* without asking any questions, reading the English inscriptions under the switches and indicators, studying the submersible. When leaving the ship, Allyn Vine said to me, "The best," high praise from one of the most outstanding men in the design and development of deep sea equipment.

The Creation of the *Mirs*

The development of the construction and use of the submersibles in the P.P. Shirshov Institute of Oceanology Russian Academy of Sciences started from the building of *Pisces* submersibles in Canada, at International Hydrodynamics Co. in Vancouver. The first attempt to purchase the *Pisces IV* vehicle in 1971–1972 was unsuccessful because an embargo blocked the delivery of the vehicle to the Soviet Union.

The Canadian government, under pressure from the U.S. Navy, canceled the export license for the almost completed *Pisces IV*. I was somewhat aware of the finer points of these events and was informed of more details by Pierre Trudeau, the former prime minister of Canada who accompanied me during a *Mir-1* dive in Monterey Bay, California, in 1990. As it turned out, a highly positioned U.S. admiral personally arrived in Ottawa in November 1971 to meet with Trudeau. In those days, the export of all equipment for underwater operations at a depth of more than 1,000 m to communist countries was prohibited. That is why the export license previously approved by the Canadian government was revoked. The *Pisces IV* was bought from HYCO by the Canadian government and given to the Oceanographic Institute in Victoria.

However, the next attempt in 1974–1976 was successful with the delivery of the *Pisces VII* and *Pisces XI* to USSR. As soon as we received the *Pisces*, we started using them. First they worked in the Black Sea where we installed navigation and other scientific equipment bought separately (also due to the embargo). In Gelendjik, a resort city on the Black Sea, the Institute of Oceanology had its southernmost site. There we installed a coastal launch system to launch and recover the *Pisces* vehicles with the use of powerful winches. This was done without a surface support ship.

At the same time, a group of pilots took training courses and then in the summer of 1977, during an expedition to Lake Baikal, both *Pisces* made 42 dives and collected very interesting scientific data. After that, an expedition was organized that went to the Pacific Ocean and another to the Red Sea where we did research into the rift zones. During these trips, we accumulated considerable experience in working in the undersea environment that came in quite handy later during the *Mir* design phase.

During the operations with the *Pisces* submersibles, we found that the main objects of scientific interest in the ocean are located deeper than 2,000 m, the operating depth of the *Pisces*. Our scientists required deeper submersibles. A 6,000-m vehicle was considered the most reasonable because it could be used to reach 98% of the ocean bottom. After a worldwide search, the Finnish company *Rauma Repola* was chosen to build our new 6,000 m submersibles.

In the design of the new submersibles, all the problems we had during the operation of the *Pisces* were taken into account. The *Pisces* pilots very often had problems with the thrusters and hydraulic power unit that used HYMAK DC motors. In addition, the high-pressure ballast pump refused to work during dives deeper than 1,500 m, presenting a limitation to getting to full-design depth. Our designers also considered the design features of other vehicles from around the world. This detailed and thoughtful review by our joint Soviet-Finnish design team became the basis for our new 6-km submersibles.

The *Mir* Submersibles

The safety of men at great depth is first and foremost due to the pressure hull; the other elements and systems are meant to bring the hull to the necessary depth, to move at that depth, and to return to the surface. The majority of the modern DMSs use rechargeable batteries as their power source.

The pressure hull and the separate element, the basic units of the systems, are put together on a solid frame and united in an assembly covered by a light outer hull called the fairing that is usually made of fiberglass, and this gives the vehicle its streamlined form. This is the principal construction setup of any manned submersible.

The pressure hull or main sphere of the *Mirs* is made of high nickel steel. Two cast half-spheres undergo the necessary machine tooling and then are put together and fastened with bolts. The sphere has three viewports: one central with the inner diameter of 200 mm (7.87 inches) and one on each side with a 120-mm (4.72 inches) inner diameter. These viewports provide the crew with an adequate field of vision during their work under the surface. We installed more efficient nickel–cadmium (NiCd) batteries to replace the iron–nickel (FeNi) batteries. The energy capacity of *Mir* is 100 kW/h.

The *Mirs* have three ballast systems: main, fine/trim, and emergency. The main ballast consists of two fiberglass tanks, and their combined capacity is 1,500 L (396 gal). While diving, these tanks are filled with seawater, bringing the vehicle close to neutral buoyancy. Fine ballasting allows us to descend and ascend at speeds of up to 35–40 m/min. The *Mirs* can also suspend at any depth. When surfacing, the tanks of the main ballast are blown with compressed air, giving the vehicle positive buoyancy up to +1,500 kg. That amount of lift also keeps the craft steady on the surface.

The system of fine ballasting consists of three pressure tanks: two at the bow and one aft, with combined capacity of 999 L (264 gal). When the *Mirs* dive, these tanks take in seawater, so they have no buoyancy. To give the *Mirs* positive buoyancy, the water is evacuated with high-pressure pumps. This *Mirs* work with water ballast alone, unlike their counterparts that continue to use the bathyscaph system in which cast iron pigs or sandbags are dropped.

The high-pressure pumps are hydraulically operated. Each *Mir* has three hydraulic systems: the first, with 15 kW of power, operates the main high-pressure pump and the propulsion system. The energy from the batteries is fed into a special AC/DC converter that drives the electric motor for the hydraulic pump. Control of the high-pressure pump and the propulsion system is effected through a system of valves fixed on the outside of the vessel in an oil box that is controlled by the pilot from inside the *Mir*.

The second hydraulic system works along the same lines but with less power, using only 5 kW. It operates all the exterior equipment such as the manipulator arms, rods, booms, and the trim pump that pumps the water back and forth between the bow and aft ballast tanks, providing the necessary trim angle. Besides this, the second hydraulic system also operates a second high-pressure pump that is only used in an emergency. If the main pump breaks down, the second pump allows us to pump out the water ballast and bring the vehicle to the surface.

The third hydraulic system is used only in an emergency. It allows us to drop some detachable parts in case of a serious problem. The DC motor that drives the pump of this system is fed directly from the main batteries or from the emergency backup battery. The emergency release of certain elements of the submersible may also be done with the second hydraulic system.

The *Mir* can detach some parts in the case of entanglement or emergency. First, there are the parts that jut out from the hull by which the vehicle can get caught on objects lying on the seabed such as cables and ropes. These include the main and the side thrusters, the wing, the manipulator wrists (if the arm picks up something and the release mechanism does not work), and the rescue buoy that surfaces after its release on a thin nylon cable 8,000 m long. Also, the lower battery box of the main power source, weighing about 1,000 kg, can be released and dropped as well.

The *Mirs* also have a system of emergency ballast (it is referred to above as the third ballast system). It consists 300 kg of nickel shot located in two rigid fiberglass containers. This ballast is kept in place by two electronic magnets that allow us to drop the shot partially or completely by switching off the current, much as the bathyscaph *Trieste* did, giving us a measure of adjustable positive buoyancy.

The propulsion systems are a very important part of these vehicles. The main stern thruster has 12 kW of power. It swivels in a horizontal plane, turning up 60° to each side. Two side thrusters, with 3.5 kW of power each, are equipped with turning devices that allow us to swivel them in a vertical plane within 180° limits. This gives the *Mirs* the ability to thrust vertically while the main thruster moves us forward. We can also use these to move forward if the main thruster breaks down. This redundant construction of the propulsion system provides us flexible control of the *Mirs*, making them highly maneuverable, an important ability while working close to the seabed in difficult terrain or on objects with complex configurations.

Interior cabin pressure is maintained at one atmosphere. The life support system consists of oxygen tanks from which the air is replenished by computer control. There is a carbon dioxide scrubber with replaceable cassettes filled with a chemical absorber, such as lithium or potassium hydroxide. Ventilators continuously pump the air through this absorber and then through a special filter that contains carbon and palladium to remove any harmful impurities. The crew monitors the levels of oxygen, carbon dioxide, and carbon monoxide with gauges that show the ambient levels at all times. There are also pressure and humidity gauges.

The *Mirs* are fitted with precision underwater navigation systems. This allows us to accurately determine the position of the vehicle in relation to the ocean floor. Acoustic transponders are deployed and surveyed from the ship with the use of the GPS. While submerged, the pilot can see the route on a display. Later, we implemented ultrashort base acoustic navigation and inertial navigation based on fiber-optic gyro. We have used both systems quite successfully. An underwater acoustic communication system provides us with voice communication to the Keldysh at distances of up to 10 miles. The sonars can discern objects as small as 10 cm (4 inches) on the bottom. Both submersibles have physical and chemical sensors tied to a data acquisition system. Two identical starboard and port manipulator arms allow four degrees of freedom, making it possible to collect different samples from tiny and fragile to those that weigh up to 80 kg (176 lbs).

The *Mirs* have multiple video cameras for underwater video-recording along with state-of-the-art photographic equipment. During 22 years of the operation, we upgraded the video systems as that technology has advanced. Three-dimensional HD cameras were operated for the James Cameron project during shooting of his movies *Bismarck*, *Ghosts of the Abyss*, and *Aliens of the Deep*. For the safety on the surface, there are outside strobe lights and radio beacons that can be spotted after a *Mir* surfaces. The radio receiver system on board the support ship receives the signals of the radio beacon after a *Mir* surfaces and directs the captain to the awaiting submersible.

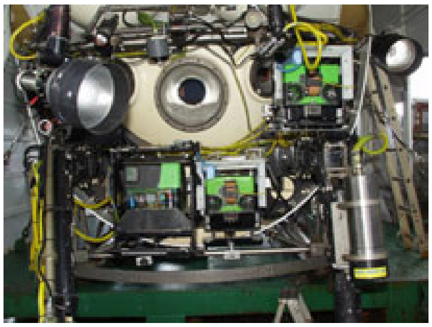
The building of the *Mirs* was completed in October 1987, and in December they were tested in the Central Atlantic at a depth 6,170 m (*Mir-1*) and 1,620 m (*Mir-2*). Ocean operations of the *Mirs* began in 1988.

The basic structure of the *Mirs* and the design and makeup of their systems remain the same as they were in 1985–1987 when these unique submersibles were built. At the same time, the modernization of the *Mirs* and the installation of new, state-of-the-art equipment considerably expands their capabilities. As a result, they are in great demand from organizations interested in underwater exploration.

The *Mirs* are constantly being improved, as navigational and scientific instruments and devices, video and photo cameras, and other systems and controls advance. Because the vehicles were commissioned, considerable improvements include the navigation system, the collection and recording of scientific data, photo and video equipment, new exterior lights, new sonars, and other important innovations. In the Laboratory of the Deep Manned Submersibles at the Institute of Oceanology in Moscow, a number of small, remotely operated vehicles (ROVs) with TV cameras and underwater lights have been developed and built to operate from the *Mirs*. These mini-ROVs are used for exploring confines too small for the *Mirs* to enter, such as the inner spaces of shipwrecks. They are controlled through a cable from the *Mir* and can be operated at a distance of 60 m (200 feet). Other ROVs developed by Jim Cameron could be operated up to 2 miles from the *Mir* by fiber-optic cable (Figure 4).

FIGURE 4

Mir-2 submersible with three ROVs during a live TV broadcast from the *Titanic.*



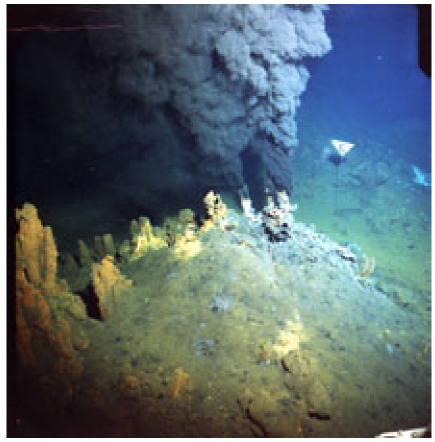
A revolutionary step in underwater cinematography was the development of deepwater, powerful 1,200-W HMI (Hydrargyrum Medium-arc Iodide) lights, developed by Mark Olsson at DeepSea Power & Light. They were first used in 1991 when we shot the film *Titanica* with Stephen Low and IMAX. After that, the HMIs were included as normal *Mir* equipment. Later, with Jim Cameron and the movie *Titanic*, we used up to eight 1,200-W HMIs at a time during filming.

Scientific Research Studies Using the *Mirs*

During 22 years, the *Mirs* were a part of a wide range of underwater operations. Some 22 hydrothermal vent sites in the Atlantic, Pacific, Indian, and Arctic were investigated. Many discoveries were made during the dives. James Cameron made an excellent film, *Aliens of the Deep,* using film of hydrothermal vents of the Atlantic and Pacific taken by the *Mirs*. The film was shown in IMAX theatres in 3-D HD format (Figure 5).

FIGURE 5

Black smokers at the hydrothermal field, Rainbow.



On the *Titanic* wreck, the *Mirs* conducted nine expeditions from 1991 to 2005. The film *Titanica* with IMAX, *Titanic* and *Ghosts of Abyss* with James Cameron, and *Treasure of the Deep* with Al Giddings were done during the dives.

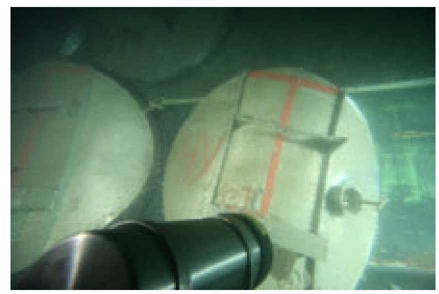
The *Mirs* are the only submersibles that have taken tourists to the great depth of the *Titanic* (3,800 m), the *Bismarck* (4,700 m), and the hydrothermal vents of the Atlantic and Pacific.

An unusual operation was done with the *Mirs* in July 2005 on *Titanic*, when the first live TV broadcast in history from a 3,800-m depth was made. During the 2.5-h program, people worldwide watched a live broadcast as three ROVs explored the interior of the *Titanic.* This operation can be compared with the first live radio broadcast from the Beebe bathysphere from the depth 934 m in 1934.

The *Mirs* performed survey and containment work on the sunken Russian nuclear submarines, *Komsomolets* and *Kursk*. On *Komsomolets*, eight expeditions were done with the *Mir* submersibles, totaling 80 dives. Constant radiation monitoring was conducted by moored instruments installed by the *Mirs* near the wreck. In 1994 and 1995, titanium caps were installed by the *Mirs* to encapsulate part of the bow to prevent the exit of radionuclides out of the nuclear warheads of the submarine's forward torpedoes. By measurements and observations conducted during following years, the work of the *Mirs* was shown to have been done effectively (Figure 6).

FIGURE 6

Titanium caps on the bow of the *Komsomolets* wreck.



One expedition on the wreck of submarine *Kursk* was made in September 2000 right after the accident. The *Mirs* made 10 dives during 5 days and established the reason for the loss of the submarine. On the basis of data obtained by the *Mirs*, the decision about recovering the wreck was made.

In 2007, the *Mirs* dove on the geographical North Pole. The dives were done under thick ice (2.5 m) entered through a quite narrow, unfrozen patch of water (50 × 80 m), then dove to a depth 4,300 m. These dramatic dives were the first in the history of Arctic Exploration. The *Mir-1* and the *Mir-2* spent over 9 h under the ice. The crew of the *Mir-1* planted a Russian flag in this untouchable location. It was a tremendous technical and human achievement.

During the last 2 years, the *Mirs* have conducted scientific research in the deepest fresh lake on our planet, Lake Baikal. We made 122 dives during the summers of 2008–2009. Many discoveries were made, including the discovery of large deposits of gas hydrates at 900 m depth, found on the first dive. These formations look like ice, a strange sight to submersible pilots at a 900-m depth (Figure 7).

For 22 years, the *Mir-1* and *Mir-2* submersibles have performed an incredibly wide range of deep ocean operations. They have fulfilled all tasks demanded of them underwater by science, engineering, national interests, filming, and even tourism. In 1989, now 20 years ago, my friend, Emory Kristof, called the *Mirs* "The submersibles of the 21st century." They have already operated 9 years in this century and remain the premiere submersibles of our age.

Fifty years ago, the best DMS was a huge bathyscaph using gasoline for flotation. She was cumbersome to operate but made the valiant pioneering dive to the greatest depth in the ocean. The *Mirs* are proud to join the *Trieste* with their own record: the first manned dive to the seafloor at the geographic North Pole. Both *Mirs* made the journey safely under the Arctic ice. These achievements will be remembered for centuries (Figure 8).

FIGURE 7

The *Mir* on Baikal Lake.

FIGURE 8

The launching of the *Mir-2* submersible on the North Pole.

PAPER

The *ABISMO* Mud and Water Sampling ROV for Surveys at 11,000 m Depth

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ABSTRACT

Recently, a number of novel bacteria have been isolated from a mud sample taken in the Challenger Deep of the Mariana Trench. Although the need exists for taking sediment samples at full ocean depth, no high-power remotely operated vehicle (ROV) with full depth capability and the ability to take sediment samples existed anywhere in the world as of April 2005. JAMSTEC started developing such a sediment sampling system beginning in April 2005. The system consists of a sampling launcher and a pre-observation probe vehicle. The launcher contains a water sampler as well as sediment samplers. It launches the probe vehicle to make a preliminary survey, dropping the sediment sampler to obtain a sample. We carried out four sea trials from January 2007 to June 2008, including dives in the Mariana Trench, and we were able to obtain sediment samples from the deepest part of the Challenger Deep.
Keywords: ROV, Full depth, Sediment sampling, Water sampling

Introduction

Recently, a number of novel bacteria have been isolated from sediment samples collected in the Challenger Deep of the Mariana Trench. Those sediment samples were collected with the remotely operated vehicle (ROV) *Kaiko* (Takai et al., 1999). Scientists want access to the deepest parts of the world's oceans using a vehicle equipped with sediment samplers and believe that it is important to survey the bacterial community of the Mariana Trench as soon as possible to provide a baseline for further studies.

The ROV *Kaiko* (Kyo et al., 1995), which JAMSTEC developed and was operating for scientific research surveys in the deep sea, was able to respond to such demands. In actuality, the ROV *Kaiko* had achieved various milestones such as obtaining sediment samples from the Challenger Deep in the Mariana Trench. However, on May 29, 2003, the vehicle portion of the launcher/vehicle complex *Kaiko* was lost because of snapping of the secondary cable linking the launcher with the vehicle after completion of a research mission in the Nankai Trough off Japan (Momma et al., 2004; Tashiro et al., 2004; Watanabe et al., 2004). Not only JAMSTEC scientists but scientists all around the world thereby lost their only way to access full ocean depths for scientific research.

After this incident, JAMSTEC developed the ROV *Kaiko 7000* (Nakajoh et al., 2005; Murashima et al., 2004, 2005), composed of the original launcher from the ROV *Kaiko* and a newly developed 7,000 m class vehicle. This system has played an active role in research in the deep sea up to 7,000 m but is not able to reach full ocean depth. In 2005, we thus started the development of a new full depth ROV, *ABISMO* (Automatic Bottom Sampling and Inspection Mobile), with the capability to sample both sediments and water. The concept behind this system was reported in 2006 (Yoshida et al., 2006). In 2007, the first sea trials were carried out, and these results have been reported (Yoshida et al., 2007). The system configuration of this ROV is illustrated in Figure 1. In June 2008, we successfully sampled sediment and water from the Mariana Trench and completed by-and-large the development of the *ABISMO* system.

Since this, Andy Bowen (Bowen et al., 2009) at WHOI successfully completed the first dive of the *Nereus* new concept Hybrid ROV to a depth of 10,903 m on May 31, 2009. The major difference in performance between the *ABISMO* and the *Nereus* is their sampling capability. The *ABISMO* is connected to its mother ship via a thick cable and can therefore retrieve a large amount of sample material with long core samplers. The vehicle maneuverability is limited by the cable. The *Nereus* is highly maneuverable and can retrieve only small amounts of samples because it is connected to the surface solely through a thin fiber-optic cable. Both vehicles have full depth dive capability, but their sampling applications do not overlap to any great degree.

FIGURE 1

The vehicle system configuration.

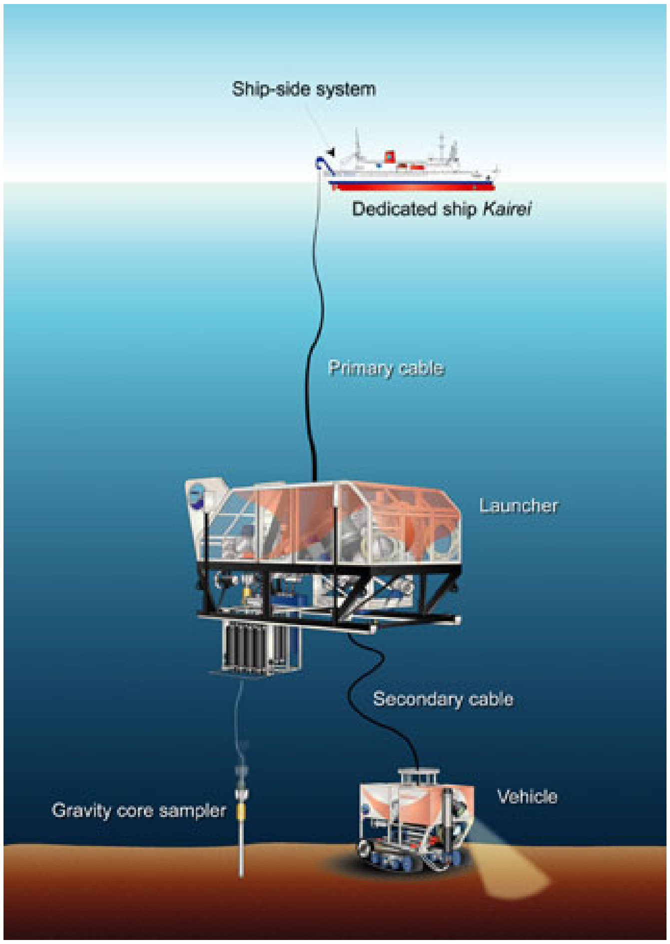
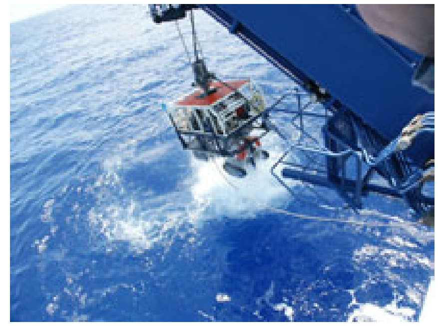


FIGURE 2

The full-depth ROV *ABISMO*.



In this paper, we present an overview of the ABISMO ROV system followed by detailed information on the system. We then describe the sea trial results, including the dive in the Mariana Trench, and draw conclusions.

Design Overview

The *ABISMO* system is a full ocean depth ROV system with the capability to collect sediment and water samples. The system is configured as a launcher-vehicle system, similar to the *Kaiko* system. The total budget allocated for the development of *ABISMO* was only 2 million dollars. We therefore used/re-used the *Kaiko*'s cable system and power supply as a part of the *ABISMO* ship-side system.

The *ABISMO* system is mounted on the dedicated mothership, R/V *Kairei*. The *ABISMO* system consists of a ship-side system, a launcher, a vehicle, and two samplers. The ship-side system is composed of a ship-side controller and the *Kaiko* 11,000 m-cable storage winch system with a high voltage power supply. Figure 2 shows a recovery scene of the launcher/vehicle complex. The ship-side controller is connected with the launcher via the primary cable, which is a legacy of the *Kaiko* system. The secondary cable, which has been newly developed, connects the launcher and the newly developed vehicle. The launcher houses the vehicle and mud and water samplers in the bottom cage. The launcher is mounted with a docking-undocking system and a secondary cable drum for the vehicle, a sampler release trigger system, and a rope-hoisting winch for the mud sampler. The launcher furthermore serves as a repeater between the ship-side controller and the vehicle. The vehicle cruises below the launcher freely within the reach of the 160-m-long cable to survey the sea floor with a TV camera. Two types of mud samplers—a gravity core sampler and a grab bottom sampler—have been prepared. Scientists can choose either sampler in accordance with the intended use. The launcher is also equipped with a water sampler. The system specifications are shown in Table 1.

The electrical diagram is shown in Figure 3. There are three major parts: the ship-side system, the launcher, and the vehicle. The electrical ship-side system consists of the *Kaiko* power supply and the ship-side controller. The controller consists of two optical communication systems, which were designed by JAMSTEC, a data converter, and six personal computers. All control software was developed originally, based on Visual C++ and Visual Basic. The launcher's electrical

TABLE 1

Specifications of *ABISMO*.

Item	Launcher	Vehicle
Rated depth	11,000 m	11,000 m
Dimensions	3.28 × 2.09 × 1.76(2.78[a]) m	1.22 × 1.30 × 1.215 m
Weight in air	3,070 kg[b]	327 kg
Weight in water	2,300 kg[b]	97 kg

[a]Overall height including the vehicle.
[b]Excluding core samplers and water samplers.

parts consist of two transformers, a main pressure hull, a winch control pressure hull, a thruster driver pressure hull, and peripheral devices. The vehicle's electrical parts consist of a main pressure hull housing a serial data transceiver (COM TRX) and a CPU, a power pressure hull housing a rectifier and a power unit, and peripherals including a TV camera. More detailed information concerning the launcher and the vehicle configurations will be given in the launcher and the vehicle section, respectively.

Power Design Policy

As mentioned previously, the legacy cable system of the *Kaiko* was used for development of the *ABISMO* system. This cable system can supply power to the launcher at up to 3,000 V using the 4-cm-diameter cable. We of course used this power system to reduce development costs. Figure 4 shows the power diagram of the *ABISMO* system. The small vehicle with four thrusters consumes power of 2 kW. The launcher with two 900 W thrusters and two winches consumes 8 kW. Total power consumption of the launcher and the

FIGURE 3

Electrical diagram of the *ABISMO* system.

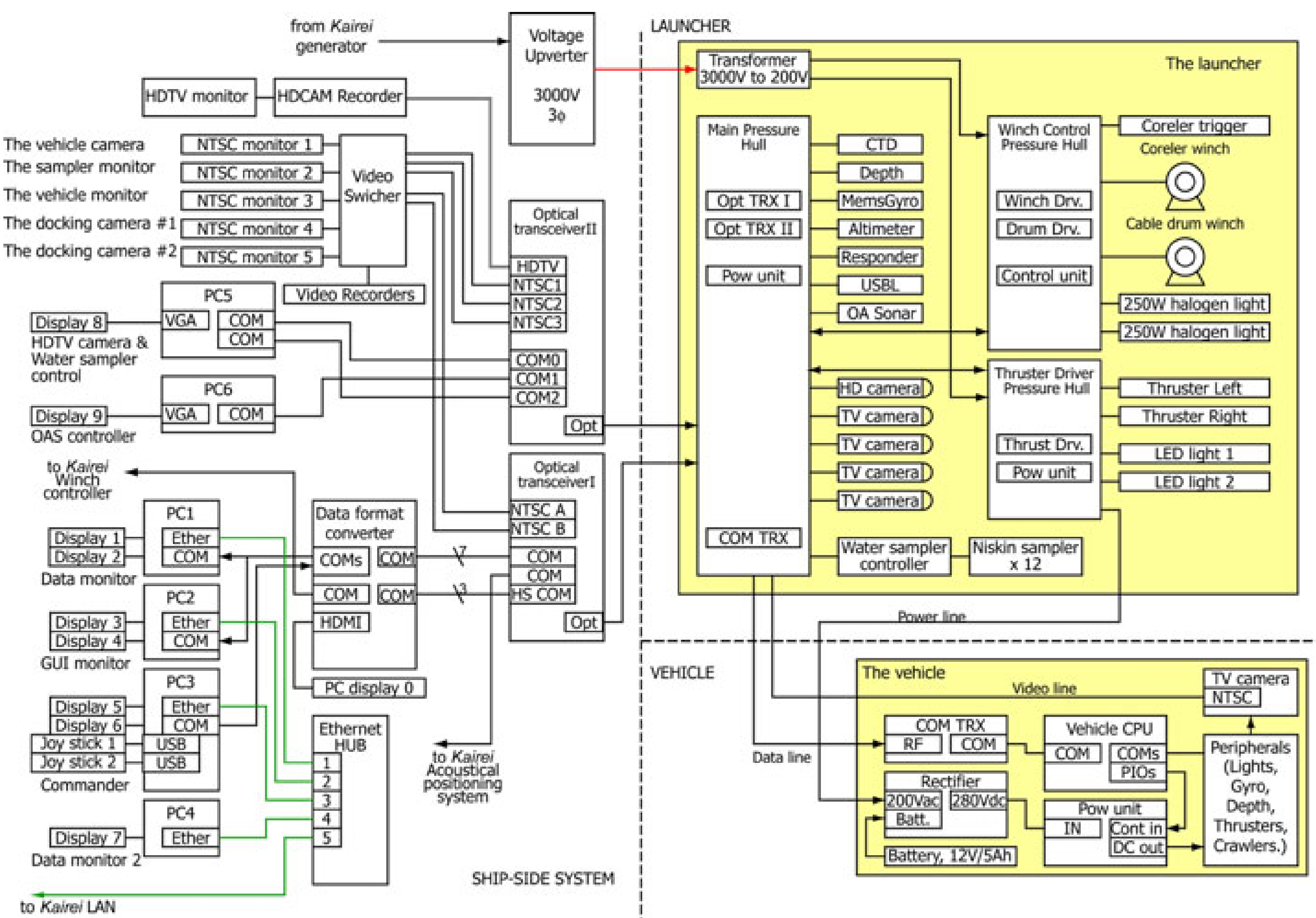
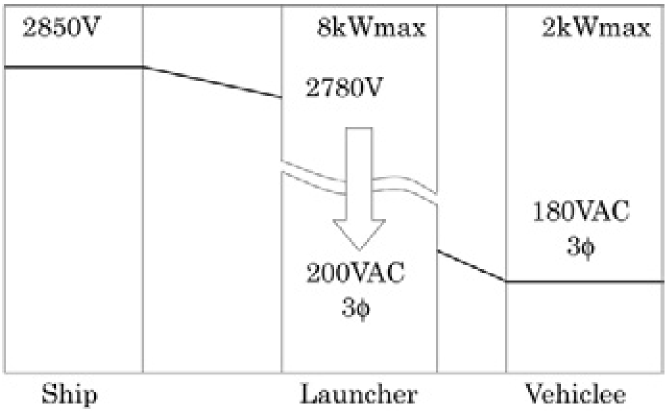


FIGURE 4

Power diagram of the ABISMO system.



vehicle system is about 10 kW. To keep costs minimal, the launcher and vehicle do not have any hydraulic actuator systems. Supplied voltage from the support vessel was a set voltage of 2,850 V. Three-phase 3,000 VAC is supplied to the launcher via a power cable within the primary cable. We prepared two three-phase 5 kW transformers, which were installed into pressure-balanced cases on the launcher. The transformers convert voltage of 3,000 V to 200 V. Part of power at 200 V is delivered to the vehicle via the secondary cable.

Data Communication

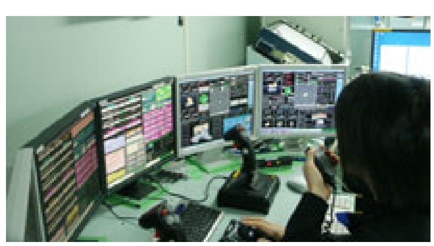
Signal communication between the support ship and the launcher-vehicle system is through two single mode optical cables within the primary cable. One is a 622 Mbps transceiver for system control, and the other is a 2.5 Gbps transceiver for the additional devices such as the high definition TV (HDTV) camera, the obstacle avoidance sonar (OAS), and the water sampler. The optical signal for system control is converted to electrical signals (RS232C and NTSC) by means of an optical/electrical converter within the launcher. Conversion of the signals meant that optical rotary joints could be eliminated in the launcher in order to reduce development costs, since no single mode optical rotary joints, which work at the depth of 11,000 m, are commercially available.

The Ship-Side Controller

The control interface (Figure 5) was newly developed as a separate control block to that of the original *Kaiko* system. Two commercial joysticks with USB interfaces were utilized to control the actuators of the *ABISMO*. The user interfaces are through computers running Windows. The graphical interfaces were developed with OPEN-GL program support for the operator of the *ABISMO* system (Ishibashi et al., 2008).

FIGURE 5

One of the *ABISMO* development engineers (Ishibashi-san) operating the control interface.



The Launcher

Figure 6 shows the general arrangement of the launcher. The launcher consists of a body frame, two transformers, a drum winch system for the secondary cable, a vehicle docking system, sediment samplers, a winch system for the core sampler, a water sampling system, two 900 W thrusters, cameras, lights, sensing devices, and pressure hulls in which electronic circuits are situated. Principal specifications of devices in the launcher are shown in Table 2.

The drum winch system with a 1.5 kW DC brush-less motor can wind the secondary cable with a force of approximately 4.5 kN and is therefore capable of hoisting the vehicle even in air. A tension modulator, which acts to maintain tension on the secondary cable, prevents cable slack on the drum. The vehicle docking system consists of a docking device, a motor, and magnetic sensors. There are two cameras to monitor docking or undocking operations because failure of this operation can cause a critical incident. The thrusters control the launcher heading because horizontal rotation of the launcher will lead to twisting of the primary cable.

In order to monitor operations, to observe the condition of the launcher, as well as to conduct underwater surveys, the vehicle is equipped with two NTSC color cameras and an HDTV camera. Two 500 W halogen lights illuminate the area around the launcher for observations, and the light emitting diode (LED) arrays provide illumination to monitor devices on the launcher. Gyro data are important for launcher rotation control as described above. The launcher also has an acoustic positioning system using the super-short base line (SSBL) method for relative positioning of the vehicle (Watanabe et al., 2008).

FIGURE 6

General arrangement of the launcher.

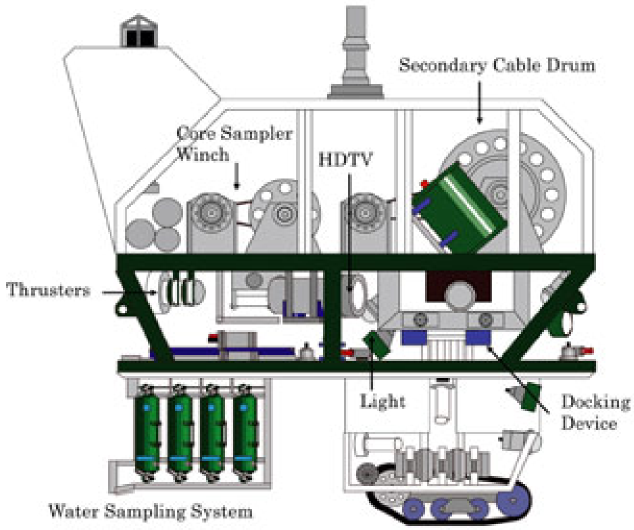


TABLE 2

Principal specifications of the launcher.

Item	Specification
Thrusters	2 × 900 W (horizontal thrusters)
Cameras	1 × NTSC camera
	1 × pan-tilt NTSC camera
	2 × micro NTSC cameras (Fixed)
	1 × HDTV camera
Lights	2 × 500 W halogen
	2 × 20 W LED array
Navigation devices	1 × MEMS gyro
	1 × obstacle avoidance sonar (MS1000)
	1 × altimeter (200 kHz, 300-m range)
	1 × depth meter (Paroscientific)
Launcher positioning system	1 × responder (around 7 kHz)
	1 × small transponder (around 14 kHz)
Vehicle positioning system	SSBL (21.3 kHz), BPSK mod. with M-sequence
	1 × transducer (ITC-3019)
	4 × hydrophones
Scientific tools	1 m/2 m gravity core sampler or grabber
	12 × 5-L Niskin sampler
	CTD (SBE49)

Secondary Cable

We developed a new cable in 2005 using para-aramid fiber with a tensile strength of 350 kg/mm^2. This rod type aramid fiber does not lead to stress concentration. The cable (ϕ20 mm × 160 m) consists of this aramid fiber, two coaxial cables, four single wire cables for power lines, a cable sheath, and resin. The cable is covered with a polypropylene coating. Specific gravity of the cable is around 1.3 and rupture strength is about 70 kN.

Low-Cost LED array

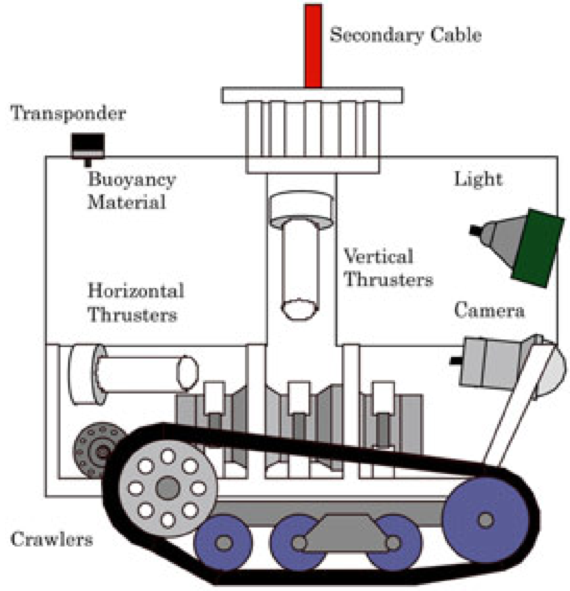
There are very few lights able to be used at full ocean depth. The deep sea light manufacturer DeepSea Power & Light (San Diego, CA) produces a halogen light, which is full depth rated for 11 km. We naturally chose this light model for the main lights on both the launcher and vehicle. However, we needed another light to illuminate the launcher internally in order to check for proper function, including observing the vehicle and its docking unit, the core sampler, and the water sampler. The vehicle must be equipped with a light on its roof because we need to keep visual track of the vehicle from the launcher when the vehicle is undocking. However, lights are expensive and the budget was limited.

For such a purpose, a rod-type light composed of a number of LEDs was deemed suitable. To keep costs down, rather than use a pressure hull structure, we tried to make an oil-filled pressure-balanced LED light. We immediately found some white LEDs that work at a pressure of 110 MPa. One of these LEDs was the surface mount type 1 W LED. This LED has a lens that gives a beam angle of about 30°. We made the first prototype of the pressure-balanced LED array using 20 LEDs. The prototype worked well for a week or so, but a problem occurred after several weeks. A few LEDs blew out. This is because oil dissolved the bond between the LED body and the lens. We tested the relation between the bond and various oils (silicon oil, mechanical oil, high voltage insulating oil, paraffin oil, etc.). As a result, all industrial oils were found to dissolve the bond, but castor oil did not affect the bond. Castor oil is a vegetable oil obtained from the castor bean. It has good low temperature viscosity properties and is slightly soluble in petroleum solvent.

We made 10 LED arrays, and the *ABISMO* system is equipped with these light arrays. The lights were put to practical use in the Marianas Trench.

FIGURE 7

General arrangement of the vehicle.



The Vehicle

The vehicle consists of an aluminum body frame, buoyancy materials, four thrusters, two crawlers, an NTSC camera, a halogen light, sensors, and pressure hulls in which electronic circuits are installed. Figure 7 depicts the vehicle configuration. Table 3 lists the specifications of the vehicle.

The vehicle is equipped with four 400 W thrusters with the Kort nozzles: two horizontal ones on the aft and two vertical ones on the upper part. It also has a crawler system. Each thruster generates a thrust force of about 150 N. The vehicle also has an acoustic transponder for the SSBL in order to estimate the position of the vehicle relative to the launcher.

Crawlers

As a new attempt, the vehicle was equipped with a crawler system. The horizontal thrusters and the crawlers can be switched alternatively as needed. The vehicle was designed to be light to keep it at neutral buoyancy. However, such neutral buoyancy influences the mobility of the crawler system (Inoue et al., 2008). In order to realize proper mobility, further development is needed to find a way to keep a proper balance between the center of buoyancy and the center of gravity. Furthermore, the crawler system could be improved as the vehicle's TV camera images became obscured by a plume of fine sediment raised as the vehicle moves on the sea floor, too. This will be discussed further on in the paper.

TABLE 3

Principal specifications of the vehicle.

Item	Specification
Thrusters	2 × 400 kW (horizontal thrusters)
	2 × 400 kW (vertical thrusters)
Crawlers	2 × 400 kW electric motor drive
Camera	NTSC camera with pan-tilt
Light	500 W halogen
	LED array on the roof top
Navigation Device	MEMS gyro
	Depth meter
Transponder	21.3 kHz

Buoyancy Materials

JAMSTEC wanted to use the same proven buoyancy materials as the original *Kaiko* vehicle flotation. However, the only practical full-depth buoyancy materials made from micro-glass balloons had been discontinued. Therefore, new buoyancy material was developed. The prototypes were applied to the *ABISMO* vehicle. The specifications of the prototypes are a crush pressure of 156 MPa and a specific gravity of 0.63.

ABISMO Sampling Systems

Mud Core Samplers

One-meter-long and one 2-m-long gravity core samplers, and a 220 mm × 220 mm grabber may be installed on the *ABISMO* launcher. The overall lengths of the 1-m sampler and the 2-m sampler are about 2 m and 4 m, respectively. They have an inner core tube of 1,000-mm length and 76-mm diameter. The length and weight of the gravity core samplers are changeable depending on the property of the sediment. A core sampler recovery scene is shown in Figure 8. Each sampler is wound up for retrieval by the winch system. The safe working load and breaking load are 9.8 kN and 19.6 kN, respectively. For the gravity core sampler, the launcher is equipped with a release mechanism that is triggered electrically and a rope spooler for free fall.

Water Sampler

The water sampling system as shown in Figure 9 consists of 12 5-L Niskin water samplers and a trigger system. The original trigger system activates a trigger to close the lids of the samplers upon command by the ship-side controller.

FIGURE 8

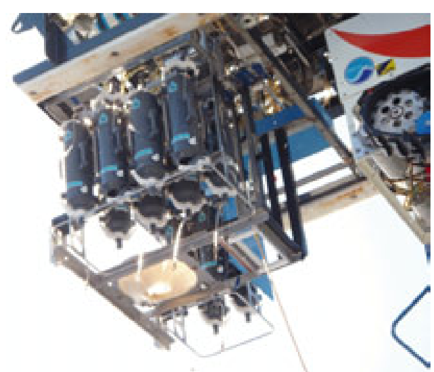
Recovering the 2-m core sampler after sampling at the Mariana Trench.

Sea Trial Operations

We have performed 14 vehicle deployments of the *ABSIMO* system during sea trials since 2007 as listed in Table 4. The aims of these trials were to test the mechanical and electrical functions of *ABISMO* and to sample mud and water for scientific research on life at full ocean depth. Through all of the sea trials, the R/V *Kairei* was used as the dedicated mother ship. This section summarizes these sea trials.

FIGURE 9

The water samplers mounted on the launcher. The gray bottles are 5-L Niskin samplers.



Dive 3 in Sagami Bay

The first dive (Dive 1) was made at Yokosuka 4th district in Tokyo bay to check system functions. The system did not have any problems, and we therefore headed for Sagami Bay. During Dive 2, we tested whether the launcher's thrusters could constrain its self-rotational motion caused by twisting of the primary cable. The thrusters behaved well during the 200 meter dive. On January 8, Dive 3, we tried sampling with the 1-m gravity core sampler at a location where the bottom sediment was softish at a depth of 480 m. The launcher was controlled to keep a stable heading, coming as close as about 80 m off the bottom. Keeping its altitude, the sampler was dropped. The sampler was recovered after about 10 min. A sediment sample about 200 mm long was obtained (Figure 10).

Dive 4 in Sagami Bay

In September 2007 in Sagami Bay, only one dive, Dive 4, was conducted because a typhoon was approaching and the weather was deteriorating. In this sea trial, automatic control of the thrusters to prevent rotation was also implemented. During the pre-dive check on board, we encountered a serious problem when the launcher thruster suddenly stopped working. The problem was found to be the mixed electrical noise from the ship and the launcher interfering with the thruster controller. The arrangement

TABLE 4

The ABISMO dives.

Dives	Date	Depth	Place	Remarks
1	January 5, 2007	30 m	Tokyo Bay	Function test
2	January 6, 2007	200 m	Sagami Bay	Function test
3	January 8, 2007	480 m	Sagami Bay	Perform sampling
4	September 2007	400 m	Sagami Bay	Function test
5	December 5, 2007	–	Tokyo Bay	Function test
6	December 6, 2007	1,050 m	Sagami Bay	Function test
7	December 9, 2007	9,707 m	Izu-Ogasawara Trench	Mud sampling at 9,760 m
8	December 10, 2007	~300 m	Izu-Ogasawara Trench	SSBL test
9	May 2008	–	Sagami Bay	Crawler test
10	May 2008	~1,000 m	Izu-Ogasawara trench	Function test
				OAS test
11	June 1, 2008	~10,000 m	Mariana Trench	Mud and water sampling
12	June 2, 2008	~10,000 m	Mariana Trench	Mud and water sampling
13	June 3, 2008	10,257 m	Mariana Trench	Mud and water sampling
14	June 4, 2008	1,914 m	Toto Caldera	Water sampling

of the internal power supply lines of the launcher was improved, and noise suppressors were added on the power circuits. Through this, the thruster problem was solved. However, when *ABISMO* dived to a depth deeper than around 300 m, the right thruster of the launcher started to malfunction. Rotational control of the launcher was achieved using only the left thruster. After this sea trial, a test to identify the bug was conducted. A communication protocol error between the thruster driver and the main processor in the driver software was found. Despite these problems, the automatic control of the thrusters was successful.

The primary functions of the system and the status of power, control, and communication systems were confirmed up to and during this dive.

FIGURE 10

A mud sample obtained with the 1-m core sampler in Sagami Bay.

Dives 7 and 8 in the Izu-Ogasawara Trench

The third sea trial was conducted from December 3 to 12, 2007 in the Izu-Ogasawara Trench. A couple of dives in the Mariana Trench were originally scheduled, but because of bad sea conditions in the Mariana area, it was decided to do tests in the Izu-Ogasawara Trench instead. Two dives were carried out in the Izu-Ogasawara Trench (29 10.9989N, 142 48.9896E) on December 8 and 10. During Dive 7, *ABISMO* reached 9,707 m depth and the 1-m core sampler was deployed and succeeded in obtaining a sediment sample from the sea floor at 9,760 m. At that time, the *ABISMO* system was the only vehicle with a diving capability of up to 10,000 m. During Dive 8, the full depth SSBL system was tested to fix a bug that manifested at shallow depths. The vehicle was not tested during the dive because of a problem on the launcher frame.

After this 8th dive, major *ABISMO* system configuration changes were made in order to improve operability and functionality. New components, such as an HDTV system, an OAS, and the water sampler, were added to the system. The length of launcher frame was shortened to avoid the interference between the vehicle and the launcher.

Dives 11-14 in the Mariana Trench

The fourth sea trial, including dives in the Mariana Trench, was carried out from May 26 to June 8, 2008. Before going to the Mariana Trench, a dive in Sagami Bay (Dive 9) and a dive in the Izu-Ogasawara Trench (Dive 10) were conducted to test and confirm the performance of the additional devices and functions. A crawler drive test on the sea floor was also done during Dive 9. The crawler system was found to need improvement because the vehicle's TV camera images were obscured by a plume of fine sediment raised as the vehicle moved. In the Mariana trench, *ABISMO* did three dives straight (Dives 11-13) deeper than 10,000 m with a maximum depth reached of 10,257 m. Unfortunately, we were unable to dive to the sea floor because the legacy primary cable of the *Kaiko* system was a little bit short to reach the bottom. The 2-m-long gravity core sampler was dropped in free fall, and sediment samples of 1.6 m length were obtained (Figure 11). Twelve bottles of water samples were also obtained at various depths to research the vertical seawater composition profiles. The small full depth transponder that was developed was tested successfully, and good results were obtained (Sawa et al., 2009).

Dive 14 was done at the TOTO caldera (12 42.7777N, 143 32.4055E), where we successfully obtained 12 bottles of water samples as well as video images of the hydrothermal plume using the HDTV camera.

FIGURE 11

Mud sample obtained from the sea floor in the Mariana Trench (2-m core sampler).

Concluding Remarks

After the loss of the ROV *Kaiko* system, no one was able to access depths of 7,000 m or more. However, the science community remained deeply interested in investigating areas below this depth, particularly biologists and microbiologists. JAMSTEC developed the *ABISMO* system and restarted surveys of full ocean depths. We carried out 14 dives, including three dives that reached below 10,000 m depth. The sampling systems that were developed were used successfully.

The *ABISMO* system was mainly designed to make pre-site surveys of the sea floor and to sample mud and water for biological research. A low-cost design policy was also incorporated. The total development cost was only $2 million because the legacy primary cable-winch system of the *Kaiko* was re-used. The development of the basic *ABSIMO* system has mostly been completed, but further work on operations and to develop additional functions is still necessary to realize its full potential. One goal is to make a new cable to enable *ABISMO* to reach the bottom of the Challenger Deep.

Acknowledgments

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PAPER

Crawler System for Deep Sea ROVs

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ABSTRACT

In order to reduce tension on a cable and process movability, a deep sea remotely operated vehicle (ROV) is designed to reduce its weight. However, a lightweight ROV is apt to wheelie when running by means of a crawler system. To run stably in counterpoise, the combination of the center of gravity and the center of buoyancy should be in an adequate area called the "stable area," which by theory can be obtained as corresponding to the weight and the buoyancy. The stable area becomes small as the weight is light. The combination of the center of gravity and the center of buoyancy is designed to be in the stable area. However, it is important for the ROV to run forward and backward, which results in changing the discrimination of the stable area. This sometimes causes the center of gravity and the center of buoyancy to be outside the stable area. Thus, it is advantageous to increase the weight only when running by crawler system and to change the center of gravity meaningfully. Furthermore, the flipper-type crawler system is advantageous when running on the sea floor with inclination or undulation. This paper proposes a method to virtually increase the weight and to change the center of gravity by using thrusters. This paper also describes the flipper-type crawler system that improves movability when running on the sea floor with inclination or undulation. Furthermore, we conducted preliminary experiments in a water tank using a small-size ROV having four thrusters and a crawler system, a normal-type crawler, and a flipper-type crawler system, to confirm the advantages.

Keywords: Crawler System, Deep sea ROV, Stable running

Introduction

Japan Agency for Marine-Earth Science and Technology (JAMSTEC) has developed the remotely operated vehicle (ROV) ABISMO (Automatic Bottom Inspection and Sampling Mobile) (Inoue et al., 2008a; Ishibashi et al., 2007, 2008; Yoshida et al., 2007), which is capable of diving to the deepest sea and obtaining sediment samples from the sea floor. The ABISMO consists of a launcher and a vehicle, as shown in Figure 1, that launches from the launcher to survey the sea floor. The ABISMO has, among its features, a crawler system in addition to thrusters as a mobility function when moving on the seabed.

FIGURE 1

ABISMO.

An ROV is lowered and hung by a cable from a vessel. In deep sea operation, tension on the cable becomes greater, and the cable will be damaged in extreme cases. Thus, from the viewpoint of reducing such tension, a deep sea ROV like ABISMO is designed to reduce its weight in water. It is also generally difficult for a heavy ROV to run on the inclined sea floor because the surface sediment layer may crumble and the ROV may slide down. However, such a light weight influences the movability characteristic of the crawler system (Inoue et al., 2008b, 2009; Murakami et al., 2008).

As an initial investigation, we conducted experiments using the ABISMO vehicle in a water tank to observe the movability of the crawler system in water. The experiments involved changing the weight and the buoyancy as well as the center of gravity and the center of buoyancy. It was observed in the experiments that the vehicle ran in wheelie in some cases, as shown in Figure 2, in spite of the fact that the vehicle could run stably on land (Inoue et al., 2008b, 2009). It seemed that the ROV could not run on the sea floor in such cases. However, the ROV ran stably, keeping a horizontally even posture, when the ROV had an adequate weight in water as well as an adequate center of gravity and center of buoyancy.

The fundamental theory of stable running by crawler, which means running stably in counterpoise, expresses the discriminant of stable running

FIGURE 2

The vehicle of ABISMO running in wheelie.

called the "stable area" for the combination of the center of gravity and the center of buoyancy corresponding to the weight and the buoyancy (Inoue et al., 2008b, 2009; Murakami et al, 2008). The ROV should be designed to have an adequate center of gravity and center of buoyancy, which are in the stable area. It is important, however, that the ROV runs forward and also backward. This results in a change in the positional relation of the center of gravity and the center of buoyancy, with such combination causing the center of gravity and the center of buoyancy to be outside of the stable area. Consequently, this leads to the wheelie run in one of the forward and backward directions. Actually, it is sometimes difficult to run stably in running both forward and backward when the weight is light (Inoue et al., 2008b, 2009).

Thus, it is advantageous to increase the weight only when running by crawler system and to change the center of gravity meaningfully. This paper proposes a method to virtually increase the weight and to change the center of gravity by using thrusters. To confirm the advantageous effect, we conducted preliminary experiments using a small-size ROV having four thrusters and the crawler system in a water tank.

Another method to improve movability characteristics is to have a function of broadening out the contact points and changing the attitude, which will improve movability when running on the inclined sea floor, running over an obstacle, or grabbing the object by a manipulator.

Two approaches are investigated to develop the crawler system for deep sea ROVs.

Fundamental Theory of Crawler System Running in Counterpoise in Water

Dynamic Model in Steady Running

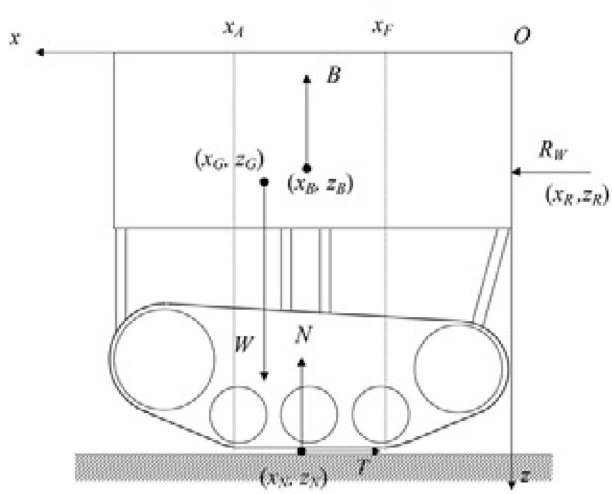
The fundamental theory of stable running by the crawler system is presented (Inoue et al., 2008b, 2009; Murakami et al., 2008). The theory gives the discriminant of stable running in counterpoise, which is called the "stable area" for the combination of the center of gravity and the center of buoyancy corresponding to the weight and the buoyancy.

The ROV in steady running is subjected to a water resistance force R_W and a shear force T in addition to a gravity force W, a buoyant force B, and a normal force N due to a ground reaction, as shown in Figure 3. The shear force is acted as the reaction force from the soil when running, and it is equivalent to a driving force.

The ground pressure distribution is obtained by Bekker's equation (Bekker, 1956) using parameters decided depending on the property of soils. The normal force N, however, is assumed to be presented as a concentrated force. It is also assumed that crawler belts will not be flexible. Then, the point of application of the normal force x_N is obtained by equation (1) from vertical

FIGURE 3

ROV in steady running in water.



and horizontal equilibrium equations and moment equilibrium.

$$x_N = \frac{Wx_G - Bx_B + R_W(z_N - z_R)}{W - B} \tag{1}$$

The following equation should be satisfied so that the ROV does not fall down in static condition.

$$x_F < \frac{Wx_G - Bx_B}{W - B} < x_A \tag{2}$$

This equation describes that longer length between x_N and x_A can give wider stability range. However, the length of the crawler system of ABSIMO is very short as shown in Figure 1. It is for the reason that the rise-up angle was designed to be large because it seemed to have better movability when riding straight.

Since equation (2) is satisfied in static condition, $x_N < x_A$ is required for stable running. Then, equation (3) must be satisfied in order for the vehicle not to fall down but to run stably. Also, equation (4) is obtained for running backward.

$$\frac{Wx_G - Bx_B + R_W(z_N - z_R)}{W - B} < x_A \tag{3}$$

$$\frac{Wx_G - Bx_B - R_W(z_N - z_R)}{W - B} > x_F \tag{4}$$

The following equation is then obtained from equations (2) to (4) to express the stable running condition. It reveals that the stable area becomes small as the weight in water becomes light.

$$\frac{B}{W}x_B + \frac{W - B}{W}x_F + \frac{R_W}{W}(z_N - z_R) < x_G < \frac{B}{W}x_B + \frac{W - B}{W}x_A - \frac{R_W}{W}(z_N - z_R) \tag{5}$$

Evaluation by Experiments Using a Model

Evaluation experiments were conducted using the ABISMO vehicle and models (Inoue et al., 2008b; Murakami et al., 2008). Some of the results of the experiments using the ABISMO vehicle do not meet the theory because it was difficult to change the center of gravity and the center of buoyancy of the ABISMO vehicle and to produce the static running condition. Further experiments using the models were conducted changing the center of gravity and the center of buoyancy to obtain the discriminant boundary condition. When the model ran in wheelie, the center of buoyancy was changed to reach stable running in counterpoise. Several combinations of the center of gravity and the center of buoyancy to just reach stable running were then obtained. The results meet the theory, as shown in Figure 4 as a sample (Murakami et al., 2008). The length of the model was 160 mm. The weight and the buoyancy were 640 gf and 390 gf, respectively. The condition of the experiments shown in Figure 4 was that a block of weight of 200 gf, and a block of the buoyancy material of 200 gf was added.

Thruster-Assisted Crawler System

Method to Generate Downward Force as Needed

According to equation (5), the stable area broadens out when the weight increases. However, as described from the viewpoint of the tension on the cable, it is desired that the weight of the ROV be light. Thus, it is advantageous to possess a function or a system that increases the weight or decreases the buoyancy only when running by crawler.

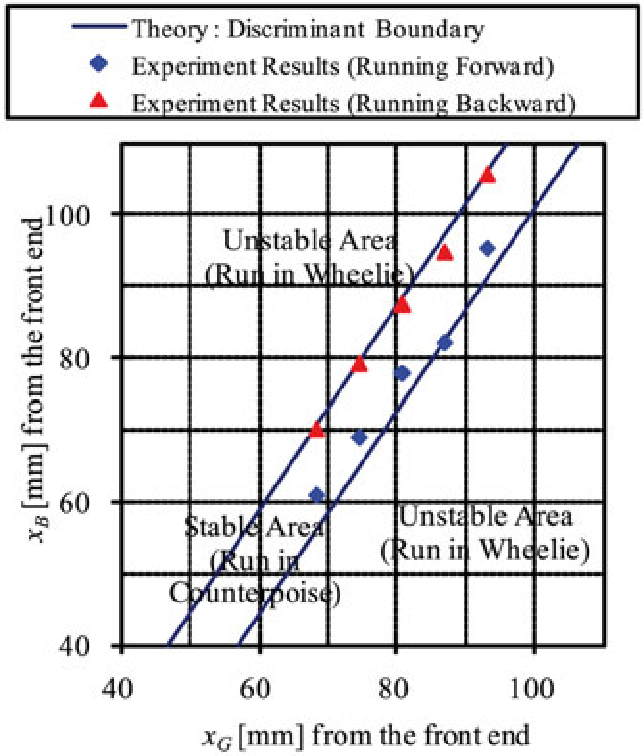
A buoyancy adjusting system using a cylinder is well known as one of the methods to increase or decrease the buoyancy. However, no buoyancy adjustable system has enough capacity for the deep sea. This paper therefore proposes a method that uses thrusters to generate vertical force as the additional weight (patent pending) whenever necessary, as when the ROV runs by crawlers on the sea floor. The vertical thrusters can generate downward force as the additional weight and broaden the stable area when the center of gravity and the center of buoyancy are out of the stable area. The vertical thrusters can also change the center of gravity by controlling each thruster to obtain its desired thrust force and direction (patent pending).

Schematic Diagram of Crawler Running Experiments

Experiments using a small-size crawler-driven ROV, as shown in Figure 5, were conducted in a JAMSTEC water tank to confirm the advantageous effect of the thruster-assisted crawler system. Table 1 shows the principal specifications of the ROV. The thrust force was measured by the thruster performance test corresponding to the input voltage

FIGURE 4

Results of the experiment using the model.



and the motor rotation. The thrust force was about 9.0 N at a rated input voltage.

The dimensions of the water tank were 40 m in length, 4 m in width, and 2 m in depth. The motion of the vehicle in the water tank was observed from above and from observation windows provided on a side wall. The attitude of the ROV was also obtained by means of a gyro.

The experiments involved changing the buoyancy by adding blocks of buoyancy material.

FIGURE 5

Picture of the small-size, crawler-driven ROV.

TABLE 1

Principal specifications of the crawler-driven, small-size ROV.

Items	Specification
Dimensions	600 mm (length)
	717 mm (overall width including crawlers)
	540 mm (from the bottom of crawler to top cover)
Thrusters	4 × 48 W (maximum output) motor with an encoder
	Installation position can be changed
Crawler	2 × 48 W (maximum output) motor with an encoder
Weight	34.0 kgf (333.2 N)
Buoyancy	17.9 kgf (175.4 N)

Resistance Measurement Test

According to equation (5), water resistance (R_W) and the point of its application (0, z_R) are parameters of the stable running characteristics. The resistance measurement test was conducted in the tank of Osaka University. The results are shown in Figure 6.

Results of Crawler Running Experiments

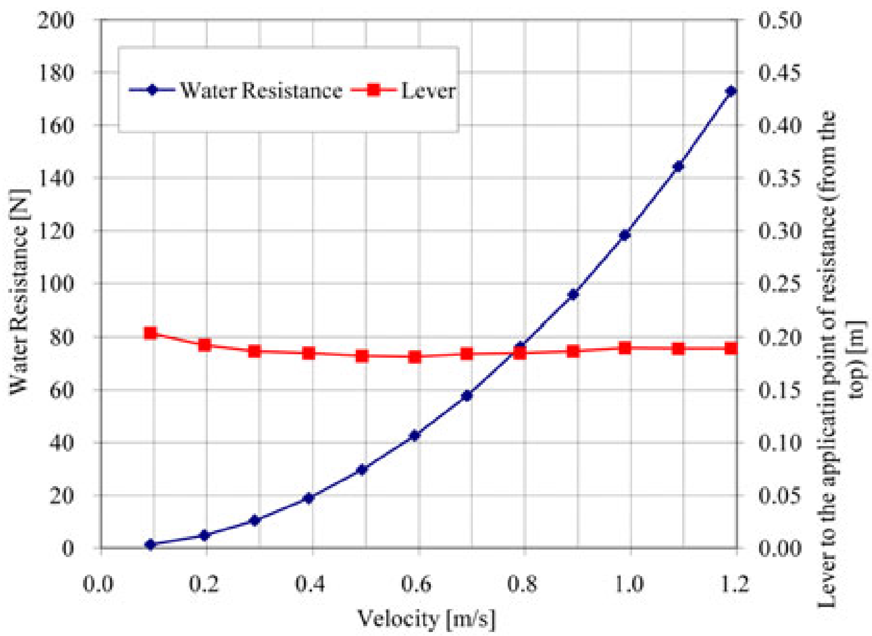
It was observed in some cases that the vehicle became or was apt to run in wheelie. However, applying thrusters improved movability characteristics for the vehicle to run stably in counterpoise in some cases.

Table 2 shows the result of the experiments when running forward in a crawler drive motor rotation speed of 3,000 rpm, which is equivalent to being in a running speed of about 0.3 m/s. The experiments in such low speed and low acceleration are expected to lessen the dynamic effect observed in start running.

When the buoyancy is lower to a certain degree, the ROV can run stably in counterpoise. Figure 7 shows the discriminant chart obtained by the theory described above and the

FIGURE 6

Water resistance and the lever to the application point of resistance obtained by the towing test.



experiment running conditions for typical cases in which the ROV ran in counterpoise.

However, when the buoyancy was great enough, the ROV ran in wheelie even when the center of buoyancy was in the same ambit, as in cases 6 and 7. Thus, the vertical thrusters were applied to virtually increase the weight and to change the center of gravity. As a result, the ROV could run stably in counterpoise. Figure 8 shows the discriminant chart and the experiment running conditions for the case without thrusters and the case with thrusters applied. The result of case 6 meets the theory. However, according to the theory, the ROV does not run in wheelie in case 7 even without assistance of the thrust force. However, the ROV ran in wheelie. The accuracy of measurement of the center of buoyancy and the center of the gravity as well as the influence of dynamic effect is considered as a reason. At all events, Figure 8 expresses that the application of thrusters is an effective method to broaden the stable area and to change the center of gravity meaningfully in order to move into the stable area.

Experiments at a crawler motor speed of 5,000 rpm were also conducted. In this case, acceleration was higher. This meant that dynamic effect would be observed when starting. Actually, the ROV was apt to wheelie, as shown in Table 3. In some cases, however, the ROV ran stably with the application of vertical thrusters.

TABLE 2

Result of experiments when running forward in a motor rotation speed of 3,000 rpm.

Case	Weight (kgf)	Buoyancy (kgf)	x-coord. of COG (mm)	x-coord. of COB (mm)	Run Without Thrusters	Run with Thrusters[a]
1	34.5	18.6	285.6	308.3	Stable	–
2	34.5	20.6	285.6	280.1	Stable	–
3	34.5	22.6	285.6	306.8	Stable	–
4	34.5	24.6	285.6	283.3	Stable	–
5	34.5	26.6	285.6	305.3	Stable	–
6	34.5	28.6	285.6	285.1	Wheelie	Stable
7	34.5	30.7	285.6	305.9	Wheelie	Stable

[a]The thruster force is estimated to be 0.92 kgf each.
COG, center of gravity; COB, center of buoyancy.

Flipper-Type Crawler System

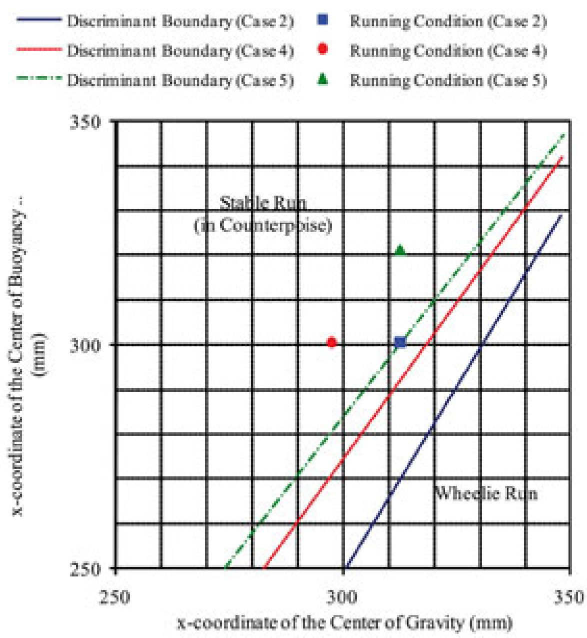
Another method to improve movability characteristics is to have a function of broadening out the contact points and changing the attitude. This will improve movability when running on an inclined sea floor, running over an obstacle, or grabbing an object with a manipulator.

The flipper-type crawler system with the abovementioned function is one of the advanced crawler systems used on land. It can also be advanced for ROVs to run on the sea floor because the sea floor has the geographical feature of an inclination or undulation. The flipper-type crawler system is composed of the crawler mechanisms, motors to run, and flipper mechanisms with motors to rotate crawler mechanisms.

The flipper-type crawler system has four crawlers, two at the forepart and two at the afterpart that were manufac-

FIGURE 7

Results of the experiments when the ROV ran in stable with keeping even posture.



tured to confirm its advanced movability. Each crawler can rotate 180° by flipper mechanism, and the crawler will be operated according to the sea floor. The flipper-type crawler system was designed for the small-size ROV mentioned above to be changeable from the normal type to the flipper type, as shown in Figure 9.

Experiments

Preliminary experiments were conducted in the water tank and at sea to observe its advantageous mobility. The experiments in the water tank confirmed the functions of the flipper-type crawler system. The small-size ROV with the flipper-type crawler system could run over a bump having a height of about 150 mm by changing the flipper angle and running on the slope.

The experiments at sea were conducted for the small-size ROV with the normal crawler and with the flipper-type crawler, as shown in Figure 10. The experiments confirmed the advantageous movability of the flipper-type crawler system. The small-size ROV with the normal crawler could run only on the flat sea floor. Of course, using the vertical thrusters will improve the movability as described above to some extent.

However, the small-size ROV with the flipper-type crawler system could run on the sea floor with undulation by activating the flipper. In the experiments, an underwater camera system was used to observe the motion of the small-size ROV, and it facilitated the operation of the flipper because the situation of the small-size ROV and the sea floor condition could be easily observed. In the actual operation, however, an operator should operate the crawler system and flipper relying on the images captured by the camera in the ROV.

Further experiments in the water tank and at sea are scheduled in 2009. Also, the flipper-type crawler system for the vehicle of ABISMO is under construction. After completion of construction, the ABISMO with the flipper-type crawler system will be tested at deep sea via the function test at sea.

Conclusion

The light weight desired in a deep sea ROV will influence the movability characteristic of the crawler system. Actually, a wheelie run was observed in the experiments using the ABISMO vehicle. To clarify the motion of the vehicle in steady running, the fundamental theory of stable running of the vehicle running in steady was presented and verified by the experiments using the model. The theory expresses the discriminant of stable running for the combination of the center of gravity and the center of buoyancy. The theory also reveals that the stable area becomes narrow as the weight in water becomes light.

From the view points of the movability of the ROV in water and the tension on the cable, light weight is desired. However, the weight should be heavy when running by crawler. Thus, the paper proposes a method to apply vertical thrusters to generate down forces when running by crawler. The advantageous effect was confirmed by experiments using the small-size ROV in a water tank. Actually, the stable area can be broadened out, and the center of gravity can be changed effectively to reach the stable running in counterpoise.

The flipper-type crawler system is also advantageous when running on the sea floor because the sea floor has the geographical feature of inclination or undulation. Preliminary experiments in the water tank and at sea were conducted to confirm the advantage.

FIGURE 8

Results of the experiments when applying thrusters (thruster-assisted crawler system).

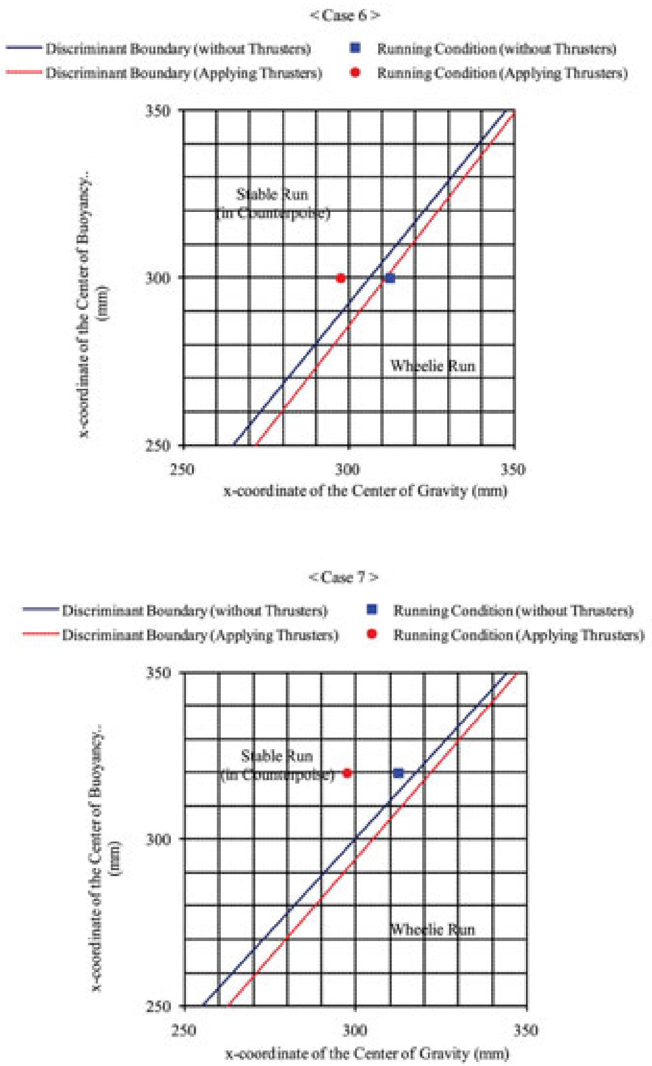


TABLE 3

Result of experiments when running forward in a motor rotation speed of 5,000 rpm.

Case	Weight (kgf)	Buoyancy (kgf)	x-coord. of COG (mm)	x-coord. of COB (mm)	Run Without Thrusters	Run with Thrusters[a]
1	34.5	18.6	285.6	308.3	Stable	–
2	34.5	20.6	285.6	280.1	Wheelie	Stable
3	34.5	22.6	285.6	306.8	Wheelie	Stable
4	34.5	24.6	285.6	283.3	Wheelie	Wheelie
5	34.5	26.6	285.6	305.3	Wheelie	Stable
6	34.5	28.6	285.6	285.1	Wheelie	Wheelie
7	34.5	30.7	285.6	305.9	Wheelie	Stable

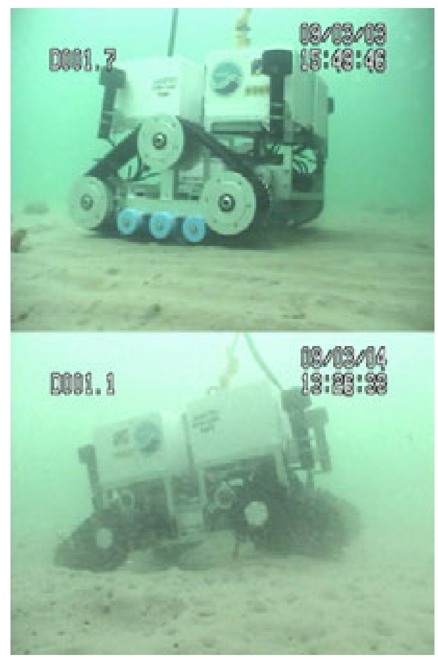
[a]The thruster force is estimated to be 0.92 kgf each.

FIGURE 9

Small-size ROV with flipper-type crawler.

FIGURE 10

Small-size ROV with normal-type crawler (above) and flipper-type crawler (below) running on the sea floor.



In the future, it is necessary to establish the theory incorporating the driving torque and the dynamic effect and to conduct experiments on the stability of the flipper-type crawler system. Although the preliminary experiment confirmed the advantages of the thruster-assisted crawler system and the flipper-type crawler system, further experiments on the actual sea floor are scheduled. Moreover, the flipper-type crawler system for the ABISMO vehicle is under construction. After completion of construction, the ABISMO with the flipper-type crawler system will be tested at deep sea via the function test at sea.

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