U.S. DEPARTMENT OF ENERGY
SMALL BUSINESS INNOVATION RESEARCH PROGRAM
PHASE I - FY 1997
PROJECT SUMMARY

APPENDIX B
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38
Topic No. (1-41)

a
Subtopic (a-d)

FG03-97ER82356

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TITLE OF PROJECT: An acoustically controlled tetherless underwater vehicle for installation and maintenance of neutrino detectors in the deep ocean

NAME AND TITLE OF PRINCIPAL INVESTIGATOR: Dr. Philip J. Ballou, Sr. Vice President

TECHNICAL ABSTRACT (Limit to space provided. Applicants MUST use the format provided in the instructions on the reverse side.)

The task of installing and servicing high energy neutrino detectors in the deep ocean from a surface support vessel is problematic using conventional tethered systems. An array of multiple detector strings rising 500 m from the ocean floor, and forming a grid with 50 m spacing between the strings, presents a substantial entanglement hazard for equipment cables deployed from the surface. Such tasks may be accomplished with fewer risks using a tetherless underwater remotely operated vehicle that has a local acoustic telemetry link to send control commands and sensor data between the vehicle and a stationary hydrophone suspended above or just outside the perimeter of the work site. The Phase I effort involves the development of an underwater acoustic telemetry link for vehicle control and sensor feedback, the evaluation of video compression methods for real-time acoustic transmission of video through the water, and the defining of local control routines on board the vehicle to allow it to perform certain basic maneuvering tasks autonomously, or to initiate a self-rescue if the acoustic control link should be lost. In Phase II, a prototype tetherless vehicle system will be designed and constructed to demonstrate the ability to install cable interconnections within a detector array at 4 km depth. The same control technology could be used with a larger more powerful vehicle to maneuver the detector strings into desired positions as they are being lowered to the ocean floor.

COMMERCIAL APPLICATIONS AND OTHER BENEFITS as described by the applicant. (Limit to space provided).

A tetherless ROV offers a tremendous commercial advantage over tethered systems. Elimination of the umbilical cable, with its intrinsic drag and entanglement hazards, allows much smaller, lower-powered, and less expensive vehicles to be used at greater speeds and longer excursion distances from the deployment vessel. Possible applications include mapping of the ocean floor, search and recovery operations, military mine countermeasures, and fisheries research.

KEY WORDS:

tetherless umbilical cable unmanned untethered UUV remotely operated vehicle ROV neutrino
deep ocean acoustic telemetry video compression

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1.0 Identification and Significance of the Problem, and Technical Approach

The deep ocean (4 km depth) provides an ideal site for an array of high energy neutrino detectors: clear optical properties, low bioactivity, well shielded from cosmic rays impinging on the atmosphere above. The photon detectors, large area photomultiplier tube (PMT) arrays typically mounted on 500 m long strings, must cover areas of greater than 1 km² to have a good chance to discover point sources like active galactic nuclei.

Individual strings of detectors have been successfully deployed in previous experiments. When some accuracy of positioning is required, it has been standard practice to use a surface vessel with a dynamic positioning (DP) system, lowering the string into position using a winch. Next generation neutrino detector arrays may consist of a forest of strings, perhaps 200 or more, 500 m long, spread in a grid over an area of 1 km². The detector strings must be positioned in the grid with an accuracy of a few meters, and then electrically interconnected in situ to form arrays.

The task of installing and servicing multiple detector strings in close proximity on the ocean floor from a surface support vessel 4 km above the work site is problematic using conventional tethered systems. An array of multiple detector strings rising 500 m from the ocean floor, and forming a grid with 50 m spacing between the strings, presents a substantial entanglement hazard for equipment cables deployed from the surface, even using a vessel equipped with DP.

The task of interconnecting the detector strings once they are in position consists of locating an underwater pluggable connector on each string (marked with an acoustic beacon), detaching it and pulling it along with its neutrally buoyant cable to a central junction point (also marked with an acoustic beacon), and inserting the connector into a receptacle. The proposed connectors, commercially available 4-conductor devices, are pressure balanced, and therefore require less than 5 N of insertion force at 4 km depth. The connectors slide into place, and do not require any rotary motion for a locking mechanism.

A tethered underwater remotely operated vehicle (ROV), propelled by thrusters, that carries the necessary suite of tools and instruments, including video cameras, lights, sonar, depth and altitude sensors, and one or more manipulators may be used to assist with the positioning of the detector strings as they are being lowered to the ocean floor, to make the electrical interconnections once they are in place, and to carry out maintenance as required. These tasks may be accomplished more easily and with reduced risk of entanglement if one can eliminate the umbilical cable that connects the ROV to the surface. In the underwater industry, such a vehicle is often referred to as an unmanned untethered vehicle (UUV).

Since the transmission of data for any appreciable distance through water is practically limited to audio bandwidth (excluding exotic schemes such as blue-green lasers or low frequency high power radio transmission), we propose to develop a local acoustic telemetry link to send control commands and sensor data between the vehicle and a stationary hydrophone suspended above or just outside the perimeter of the work site. The reliability of communication with the UUV will be a function of the proximity of the hydrophone to the vehicle. Given that the detector strings are 500 m tall, distributed over an area of 1 km², one can anticipate that the range required of the telemetry system will be nominally 710 m or less if the cabled transponder is suspended in the middle of the array at an altitude of 500 m. For the purposes of this project, we will assume a

maximum working slant range of 1,000 m, with a depression angles ranging from 90-degrees at the center of the array to about 30 degrees at maximum range.

The Phase I effort involves the development of an underwater acoustic telemetry link for vehicle control and sensor feedback, the evaluation of video compression methods to allow real-time acoustic transmission of video through the water, and the outlining of control routines on board the vehicle to allow it to hover or to perform a self-rescue if the acoustic control link should be lost. In Phase II, a prototype tetherless vehicle system will be designed and built to demonstrate the installation of cable interconnections within the detector array at 4 km depth. The same control technology could be used with a larger more powerful vehicle to maneuver the detector strings into desired positions as they are being lowered to the ocean floor.

Illustrations of the detector array and a conceptual sketch of the detector array being serviced by an UUV are attached as FIGURES 1-3.

1.1 Acoustic Telemetry System

Excluding exotic systems such as blue-green laser or high-powered low frequency radio transmissions, the only reliable method for long distance wireless communication through water is using acoustic power. While modern telephone modems, using a bandwidth of only 4 kHz, now manage in excess of 27 kb/s with excellent reliability, today's underwater acoustic modems are much slower, being subject to greater error rates, and requiring higher levels of processing to achieve acceptable results. One of the main inhibitors of high data transfer rates is excessive multipath, especially in the horizontal channel. Bottom and surface reflections, as well as ships, piers, turbulence, and temperature gradients can all contribute to multipath effects. The variability of the multipath in the underwater environment is the greatest cause of difficulty, whereas stationary multipath could be handled with traditional techniques. Commercial acoustic telemetry systems that are designed for the most demanding channels, i.e. shallow water environments, manage maximum data rates up to 1,200 b/s using digital multiple frequency shift keying modulation (MFSK) [Porta, 1996]. Using phase shift keying (PSK), prototype transmitter and receiver modems have been demonstrated to achieve information rates of approximately 2000-4000 b/s with acceptable error rates in both shallow and deep water [Carvalho *et al.*, 1995].

One of the primary objectives of this research is to develop an acoustic telemetry system that takes maximum advantage of its well-defined application in order to increase the data rates by a significant amount while retaining acceptable robustness. In our application, the channel path is mostly vertical (although some stationary multipath effects should be anticipated from the detector strings themselves), and there should be essentially no effects from surface reflection, turbulence or temperature gradients. The deep ocean site chosen for installation of the detectors will be reasonably smooth and flat, probably covered with a thick soft layer of sediment that should absorb acoustic frequencies to a large degree. In any case, the vehicle will be operating well above the ocean floor, so multipath effects from the bottom should be minimal.

A similar application is described by C. Gray *et al.* [1994] at the University of Hawaii, where the intent is to develop a high data rate reliable underwater acoustical modem that can be used for command, control, and communication between a manned submersible and an unmanned underwater robot. This communication system is being designed for operation

primarily in the deep sea, nearly vertical underwater channel for a range of 1,000 m. A precedent has been established using coded modulation and coherent detection resulting in an underwater acoustic modem with a bandwidth efficiency of 2 b/s/Hz [Suzuki, 1989], although this link can be maintained for only a few seconds. By comparison, Gray anticipates achieving a rate of 40 kb/s by expanding the bandwidth to 20 kHz, although the carrier frequency and the coding method remains to be determined.

To achieve our objective of a 1 km range in an essentially vertical channel, one might use a 40 kHz carrier, which has an attenuation in seawater of about 10 db per km. 40 kHz underwater transponders with a bandwidth of 10 kHz are commercially available at low cost. Assuming a bandwidth efficiency of 2 b/s/Hz can be obtained, this example would permit communication rates of 20 kb/s.

Since the speed of sound in seawater is 1500 m/s, one can anticipate a transmission delay of 0.7 second for distances of 1 km. For real-time control of the UUV, it will be important to minimize the distance of the acoustic link, and to set the responsiveness of the ROV to match the amount of delay. Even so, at maximum range, the turn-around time between issuing commands from the surface and viewing the results may be as much as 1.5 seconds, so the vehicle will require some degree of autonomy allowing it to perform certain basic maneuvering tasks on its own to compensate for the time delay.

Research and development of the acoustic telemetry system will be done by DOEI engineers with informal consulting provided by a selection of manufacturers and research institutions concerned with underwater acoustic transducers, and acoustic navigation, telemetry, and voice communication systems.

1.2 Video Compression

In a separate project at DOEI concerning electronic scanning sonars with high scanning rates, it was determined that for a sequence of images to be perceived by the viewer to be a continuous "moving picture", the image must be updated at a rate of at least 7-8 frames per second. An important realization concerning human perception of a moving picture is that the eye is able to pick out real objects from the background noise, even if the image strength of the object is no greater than the noise, because the object images appear to move coherently, while background noise moves randomly. This ability allows the operator to work effectively at longer range and under poorer visibility conditions than might otherwise be possible.

The simplest black-and-white video image (256 x 256 pixels with no intermediate tones) contains 65 kbits of data, requiring approximately 3 seconds to transmit a single frame using acoustic telemetry at a 20 kb/s rate, and longer if error detection is included. A digital near-equivalent of the NTSC standard for the black-and-white picture element (luminance) increases resolution to 512 x 512 pixels, and adds 8 bits per pixel for gray scale. At 30 frames per second, the data rate is 63 Mb/s. Digitizing a composite color NTSC video signal results in an uncompressed rate of 88 Mb/s or greater. It is evident that some form of video compression will be necessary to reduce this information to allow at least 7-8 frames a second, ideally with greater resolution and perhaps color. Video compression technology used for teleconferencing and other satellite transmissions now manages data reduction of 100:1 or more, with new encoding systems under

development seeking data reduction of 200 to 1,500 times, although prodigious amounts of processing power are required, and the quality of the image deteriorates to various degrees [Lynch, 1985]. The current video compression standard, MPEG-1, offers excellent video quality (320 x 240 pixels of 3 colors at 8 bits per pixel, 30 frames per second) and CD-quality sound. However, the maximum compression for MPEG-1 is 200:1, and 50:1 is more typical of its performance in actual use [Dejesus, 1997]. New processes currently under development, such as wavelets or fractals, may give better quality images with higher compression [Hoag *et al.*, 1994].

The deep ocean environment is inherently a low contrast world with visibility limited to the penetration of the artificial lighting, and only a small percentage of the video picture will contain distinct images that need to be updated from frame to frame. Furthermore, the relevant objects (the components of the detector strings) are well-defined, so prediction coding techniques are applicable. It is probable that a significant amount of compression of underwater video images can be gained using readily available technology. The availability of sophisticated digital signal processing (DSP) in low cost personal computers should make our objective easier to achieve.

The video camera on the UUV will be used as the pilot's "eyeball", and becomes especially important when the vehicle is being maneuvered within close proximity of the detector strings or is executing a manipulative task. In this application, one does not require "broadcast quality" for the video image to be usable - a black-and-white image with limited pixel and gray scale resolution at 7-8 frames per second is probably satisfactory. At the surface, the levels of gray can be interpreted and displayed as arbitrary colors to increase the contrast for the pilot. The speed of data transmission, particularly of the video images, which constitute the largest bulk, may be further enhanced if an error-tolerant telemetry system is used. Elaborate error-checking and correction schemes will reduce the available bandwidth. In our application, errors in the telemetry that are manifested as minor noise in the video picture will be tolerable.

For longer range navigation and target location, the vehicle will be equipped with a scanning sonar. This device operates at a frequency of 300-700 kHz, and has a mechanically scanning transducer with a horizontal beam angle of 1-2 degrees. The usable range of a typical 675 kHz sonar is 80 m. The sonar data is digitized, and then processed to give a multi-colored (or grey scale) video display showing a plan view of the area. Due to the large quantity of sonar data that is necessary to generate the video image, the processing will most likely be done locally at the vehicle, and the resulting video display sent through the same compression system as the video camera. The operator will have the option of selecting the video camera or the sonar for piloting the vehicle.

Research and development of video compression systems will be done by DOEI electronic engineers in cooperation with researchers at the University of California Space Sciences Laboratory in Berkeley, California.

1.3 On-board Routines for Hovering, Maneuvering, and Self-Rescue

Given the complexity of the detector array, the time delay in the control loop, and the likelihood that the acoustic telemetry link with the vehicle may be intermittent or contain fatal errors from time to time, it would be useful for the UUV to have enough on-board "intelligence"

to perform basic maneuvers autonomously. The ability of underwater vehicles to hover or maneuver automatically has historically been achieved using inertial guidance systems (prohibitively expensive until very recently), acoustic long baseline positioning systems with high frequency transponders and high update rates (limited range - 100 m or less - and extensive set-up required), or combinations and variations thereof.

Current technology for video image processing allows images of objects to be heavily filtered, thereby extracting an "edge image". Using this reduced data and comparing it with subsequent edge images of the same object, changes in distance and orientation from one image to the next can be quickly evaluated by a computer on-board the vehicle. Based on this evaluation, commands can be issued automatically to the UUV's thrusters. One application of vision-based tracking has been successfully reported using a ROV to follow an submerged cable under autonomous control. Cable positions were accurately estimated at a rate of 4 time per second, a data rate that was sufficient to guide the ROV along the cable at a speed of 2 knots [Matsumoto *et al.*, 1995]. Vision-based station keeping for an underwater robot has been experimentally implemented by engineers at the Monterey Bay Aquarium Research Institute (MBARI) and Stanford University, allowing drift-free position keeping in four degrees of freedom (translation and yaw) [Marks *et al.*, 1994]. Related technology is used in consumer video camcorders for image stabilization, suggesting that the state of the art of this capability is advancing rapidly. In this project, we will evaluate the feasibility of applying this same technology to allow the vehicle to hover or "park" in front of any identifiable object, either when commanded by the operator or if the communication link is broken.

As a manufacturer of manned submersibles, DOEI has substantial prior experience in emergency location and self-rescue processes. Although the submersibles are manned, there are often situations in which the occupants do not know where they are with respect to the surface vessel, and in more unfortunate circumstances, may be unconscious. In this application, the vehicle would be programmed to abort its mission if it does not receive valid communication by acoustic telemetry for a pre-established period of time.

Emergency ballast weight releases may be used for vehicle self-rescue. Such releases should be fail-safe, i.e., if they fail, the vehicle automatically comes to the surface. On the two-passenger *Deep Rover* manned submersibles, DOEI used pressurized cylinders to hold the releasable ballast weights in place. If pressure is lost, whether intentionally or due to a system failure, the ballast weights will be dropped, making the vehicle positively buoyant so it will rise to the surface without power.

Once the vehicle has reached the surface, a xenon flasher beacon may be activated (by a pressure sensor), and a GPS position transmitter of the type used on buoys can indicate the vehicle's location to the surface vessel for recovery. These may be supplemented with other devices to aid in recovery, such as a VHF radio beacon and/or a radar reflector.

1.4 Summary: Innovation Through Adaptation and Modification

DOEI's engineers are noted for their ability to draw state-of-the-art technology from a wide range of industries and successfully adapt it in the harsh underwater environment. Not all technologies are suitable for this transfer, at least not in their original form. For example,

computer disk drives and general-purpose video monitors are generally unreliable because of the high humidity, salt, and excessive vibration aboard ocean-going vessels. Because of the severity of the conditions in the underwater environment, the oceanographic equipment industry's state-of-the-art tends to lag behind land-based technology. In this project, DOEI's engineers will thoroughly research existing technology that has been proven to be reliable in its intended application, and evaluate it through additional testing for its viability in the underwater environment. In many cases, equipment that is found to not be sufficiently robust in the ocean environment can be satisfactorily improved through modification. The innovation in this project is in recognizing existing technologies that have a good probability of being transferred to this application, and then designing modifications and adaptations as necessary to make them fully integrated into their new roles.

1.5 References

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2.0 Phase I Project

The following research objectives are planned for this Phase I effort:

1. Develop and test an underwater acoustic telemetry system for real-time communication between the UUV and a local hydrophone with a range of up to 1,000 m.
2. Evaluate latest video compression technology for underwater video applications with an objective of transmitting 7-8 frames per second of medium resolution black-and-white video or better through the underwater acoustic telemetry system.
3. Define on-board vehicle control routines and systems that allow the vehicle to hover using video-based tracking and to perform a self-rescue and be recovered if the acoustic control link should be lost.

2.1 Phase I Work Plan and Performance Schedule

Work on the research objectives will be conducted in three parallel paths over a period of 26 weeks (6 months) as scheduled below:

I. Acoustic telemetry system

- A. Weeks 1-5 Research and select desired power, bandwidth, and electronic communication method of acoustic telemetry system.

- B. Weeks 3-6 Research and select acoustic transceiver system for underwater telemetry.
- C. Weeks 6-10 Outline experiments to be performed, and being assembly of experimental equipment.
- D. Week 10 Receive electronic and acoustic telemetry equipment and begin in-water testing, making modifications as required.
- E. Weeks 10-15 Conduct preliminary experiments of acoustic telemetry system in DOE's test tank, making modifications as required.
- F. Week 15-18 Test acoustic telemetry system in marina environment.
- G. Week 18 Test acoustic telemetry system in DOE's high pressure test facility.
- H. Week 19 Conduct final testing of acoustic telemetry system in Offshore Model Basin.

II. Video compression

- A. Weeks 6-8 Research and identify viable video compression electronics system.
- B. Weeks 8-10 Acquire experimental components and fabricate associated electronics as required.
- C. Weeks 10-15 Conduct laboratory experiments with video compression.
- D. Weeks 15-19 Evaluate video compression electronics with acoustic telemetry system.

III. Vehicle on-board systems for maneuvering and self-rescue

- A. Weeks 5-10 Research and determine feasibility and status of systems to allow automatic maneuvering of the vehicle using video-based tracking.
- B. Weeks 10-17 Acquire experimental components and fabricate associated electronics to evaluate video-based tracking.
- C. Week 18 Research and determine feasibility of other on-board systems to allow vehicle self-rescue if communication with the surface is lost.
- D. Week 19 Research and specify emergency locating devices to assist recovery of the vehicle at sea.

IV. Generation of the Final Report

A. Weeks 20-26 Compile draft, revise, and submit Final Report

2.3 Related Research or R&D

Deep Ocean Engineering, Inc. (DOEI), founded in 1982, is a leading U.S. designer and manufacturer of underwater equipment, including ROVs, manned submersibles, robotic manipulators, and a wide variety of underwater instruments, tools, and accessories. Since the introduction of DOEI's Phantom ROV in 1985, more than 330 of these economical systems have been delivered worldwide for scientific research, environmental monitoring, military applications, police search and recovery, recreation, ship hull inspection, nuclear and hydroelectric power plant inspections, and for film and television program recording. This year, DOEI delivered a highly modified Phantom ROV to be used in the construction of the Sudbury Neutrino Observatory, a project spearheaded by the Los Alamos National Laboratory in New Mexico and the University of Washington, to install photodiode detector strings inside its acrylic vessel filled with deuterium (D_2O).

From 1992 through 1996, DOEI developed a special Phantom ROV with a "telepresent" control system and head-mounted display. This project was funded by Small Business Innovative Research (SBIR) grants (through Phase II) through NASA Ames Research Center. Designed to excel in manipulative tasks and improve pilot dexterity, the vehicle incorporated larger diameter thruster ducts with gear-reduction drives to match the motors to the propellers. This thruster design, dubbed "Tractor Drive", gave increased thruster efficiency and improved control at low speeds compared to the same thruster motor with a smaller duct and propeller. It would also be suitable for use on a battery-powered tetherless vehicle that is required to perform precision operations and to develop substantial amounts of bollard pull thrust at low speeds.

In 1994, DOEI designed and built a new ROV system, called "PHOENIX", to inspect a water-filled hydroelectric tunnel, the Mantaro Tunnel, in Peru. This tunnel, 20 km in length, was to be penetrated from each end. The Phoenix Mantaro ROV system was designed with a neutrally buoyant umbilical cable 10 km in length and 15 mm in diameter. Power was sent to the vehicle at 3,000 VAC 3-phase, 50 Hz, and control, video, and instrumentation signals were transmitted to and from the vehicle by a proprietary telemetry system on one single-mode (SM) optical fiber. Three additional SM optical fibers were made available in the umbilical cable for the customer's manipulator, three cameras, two scanning sonars, and specialized measurement tools. Because all of the vehicle control electronics were housed in the vehicle, and the communication link was by fiber optic telemetry, one could remove the umbilical cable from the system if on-board batteries were installed, and telemetry was established by acoustic link.

DOEI has built three tetherless battery-powered manned submersibles, called *Deep Rover*. These submersibles are based on transparent acrylic spherical pressure hulls that offer the occupants a panoramic view. A one-person version (DR1001) was built in 1984 for a Canadian diving company, and is rated to a depth of 900 m. A pair of two-person *Deep Rovers* (DR1002), built in 1994 for a French cable television company, are rated for operation to 1,000 m. Both submersible designs incorporate pressure-compensated battery pods that would be usable at 4 km

depth (or deeper). The DR1002 carried a rechargeable 120 VDC battery system with a capacity of 30 kW-hr, with an auxiliary 24 VDC battery supply of 140 A-hr and an emergency 24 VDC battery supply of 25 A-hr. All operational features of the submersibles, such as thrusters, manipulators, lights, cameras, and emergency systems, are remotely controlled by teleoperation from the safe, comfortable one-atmosphere cabin, as they would be on the UUV.

In 1995, DOEI was awarded a contract to build a deep towed camera sledge with a depth capability of 6 km. The vehicle carried a large suite of cameras, lights, and sensors, and included a proprietary one-atmosphere pressure housing for interface electronics and a powered thruster for rapid altitude adjustment at depth. Power and bi-directional telemetry for video and control (using a unique system developed at the Shanghai Jiao Tong University) were sent to the vehicle over a single coaxial cable 10 km in length. The vehicle was successfully tested from a Chinese research ship off the coast of Hawaii, where it found large beds of manganese nodules.

2.4 Principal Investigator and Other Key Personnel

Position: PRINCIPAL INVESTIGATOR

Name: Dr. Philip J. Ballou

Title: Senior Vice President, Engineering and New Business Development

Experience and qualifications:

Dr. Ballou has been employed by Deep Ocean Engineering, Inc. (DOEI) since 1984 as an electronics engineer with responsibilities including design and production of electrical and electronic elements of underwater remotely operated vehicles, manned submersibles, and manipulator systems. He was promoted to Vice President in 1988, and was a member of the company's Board of Directors from 1990 through 1996. From 1990 through 1994, Dr. Ballou served as the company's President and CEO. A part of DOEI's original engineering design team, Dr. Ballou has provided the company with his engineering and management leadership for 13 years. He has travelled extensively worldwide to test and demonstrate DOEI's products for potential clients, and to train and support users of its equipment in the field. In 1992, as Principal Investigator, he was awarded a Phase II SBIR from NASA to develop a ROV system with advanced telepresent control systems to enhance the user interface. He received the Governor of California's Small Business Award in 1994 in recognition of outstanding performance for export sales. In 1995, Dr. Ballou supervised a project to build a 6 km depth deep towed sledge for the China Ocean Mineral Resources Association.

Applicable years of experience: Approx. 15 years

Education: Ph.D., University of California, Berkeley (1983)

Position: ASSOCIATE INVESTIGATOR

Name: Mr. David C. Jeffrey

Title: Senior Vice President, Research and Development, and Director

Experience and Qualifications:

Mr. Jeffrey worked as Electronics Technician at the Artificial Intelligence Department of Edinburgh University from 1971 to 1974, and as a Research Associate and Research

Fellow on the Edinburgh Wave Power Project at Edinburgh University from 1975 to 1983. Since then, he has been employed as the Chief Electrical Engineer at DOEI, and also serves as Senior Vice President and Director. He is responsible for the development of electrical systems and electro-mechanical interfaces for the company's ROVs, manned submersibles, and manipulator systems. In 1994, Mr. Jeffrey managed a team of engineers to develop a new ROV system with a 10 km umbilical cable, called "Phoenix", that was used to inspect a water-filled hydroelectric tunnel in Peru.

Applicable years of experience: Approx. 25
Education: M.S., Edinburgh University

Position: ENGINEER

Name: Mr. Graham Hawkes

Title: Vice Chairman, Director, and Chief Engineer

Experience and qualifications:

Mr. Hawkes was founder and managing director of the UK company, OSEL MANTIS, Ltd., later becoming the OSEL Group, to develop and manufacture one-atmosphere deep diving systems of his design, including WASP, ARMS III, and MANTIS. While at Plessey Underwater Weapons Unit, he worked closely with the Royal Navy on submarine, torpedo, and sonar systems, and was field controller for technical operations of the atmospheric diving system, JIM. In 1982, Mr. Hawkes co-founded DOEI to design, develop, manufacture, and operate equipment in the ocean and other remote or hostile environments. Mr. Hawkes holds numerous patents, and has been extensively involved in the design of DOEI's products. In 1989, he initiated a joint venture, Scientific Search Project, for operation of deep water search and recovery systems. Mr. Hawkes continues to support DOEI as its Vice Chairman and Chief Mechanical Engineer. In addition, he pursues special engineering projects focusing on manned submersibles through his own consulting company, Hawkes Ocean Technology.

Applicable years of experience: Approx. 25 years
Education: H.N.D. with honors, Mechanical Engineering, Borough
Polytechnic Institute in London

Position: SERVICE AND FIELD TEST MANAGER

Name: Mr. John Edwards

Title: Vice President, Service Department

Experience and qualifications:

Mr. Edwards has a background in commercial diving, welding, machining, and as a SCUBA diving instructor. He has worked for DOEI since 1984: 2 years as Electronics Technician, 2 years as ROV Technician, 6 years as Production Manager, and the remaining period as Service Manager.

2.5 List of Relevant Publications by Principal Investigator and Key Personnel

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2.6 Consultants and Subcontractors

University of California personnel have agreed to provide consulting services and computer modelling facilities in relation to this project without charge. Persons known at this time participate on this basis in this project are:

Dr. Hank Crawford, Department of Space Sciences, University of California, Berkeley
Dr. Voiker Lindenstruth, Department of Space Sciences, University of California, Berkeley

Other consulting and subcontracting services will be hired on an as-needed basis. Potential companies to participate on this basis are:

Datasonics, Inc., Cataumet, Massachusetts
Desert Star Systems, Marina, California
Monterey Bay Aquarium Research Institute, Moss Landing, California
Ocean Technology Systems, Costa Mesa, California
Sonatech, Inc., Santa Barbara, California
University of Hawaii

2.6 Facilities/Equipment

DOEI has research, development, and manufacturing facilities in San Leandro, California, with 9,000 square feet, including manufacturing areas, electrical and mechanical engineering departments, and administrative offices. A test pool, a high pressure test facility, a small machine shop, and an environmentally approved paint booth are installed at this site. Manufacturing facilities include work stations, tools, test equipment, and electronics and mechanical parts inventories.

Specific factors pertinent to the proposed research includes fully equipped mechanical and electrical research and development facilities including multiple CAD/CAM stations with FEA and 3D modelling software and an extensive engineering library.

In-water experimentation will be conducted using DOEI's fleet of Phantom ROVs that are maintained for the purposes of sales demonstrations, lease, and research and development of new products. Where larger in-water test facilities are required, DOEI has access to the Brickyard Cove Marina in Richmond, California (about 30 miles north of DOEI's facilities), where heavy lifting equipment and electrical power are available. DOEI also intends to conduct a series of in-water tests at the Offshore Model Basin, a large test tank with a 29-ft deep pit, in Escondido, California. The costs for using outside facilities are included in the Budget.

DOEI employs a staff of 26, including design and manufacturing engineers, a manufacturing team, and administrative and management personnel.

Deep Ocean Engineering, Inc's facilities described above will be made available for the planned Phase I effort described in this proposal.

Dirk D. Rosen, President

3.0 Similar Grant Applications, Proposals, or Awards

DOEI has no equivalent or overlapping proposals to other federal agencies at this time.

4.0 Figures and Photos

Figures and photos are attached as Pages 17-19.

5.0 Budget

DOE F-4620.3, SBIR Grant Application Budget, is inserted as Page 20 (APPENDIX C).

PHOTOS 1 and 2: Phantom ROV for installation of detector strings at Sudbury Neutrino Observatory (Concept drawing above left).

PHOTO 3: "Telepresent" NASA Phantom ROV with large diameter "Tractor Drive" thrusters for improved maneuverability at slow speeds.

PHOTO 4 (above): *Deep Rover* DR1002 two-person manned submersible for untethered operation to 1,000 m depth.

PHOTO 5 (left): Deep Towed Sledge with video camera, still camera, lights, sensors for depth, altitude, and pitch-and-roll, thruster, and electronic telemetry system for operation to 6 km depth using a single coaxial cable.