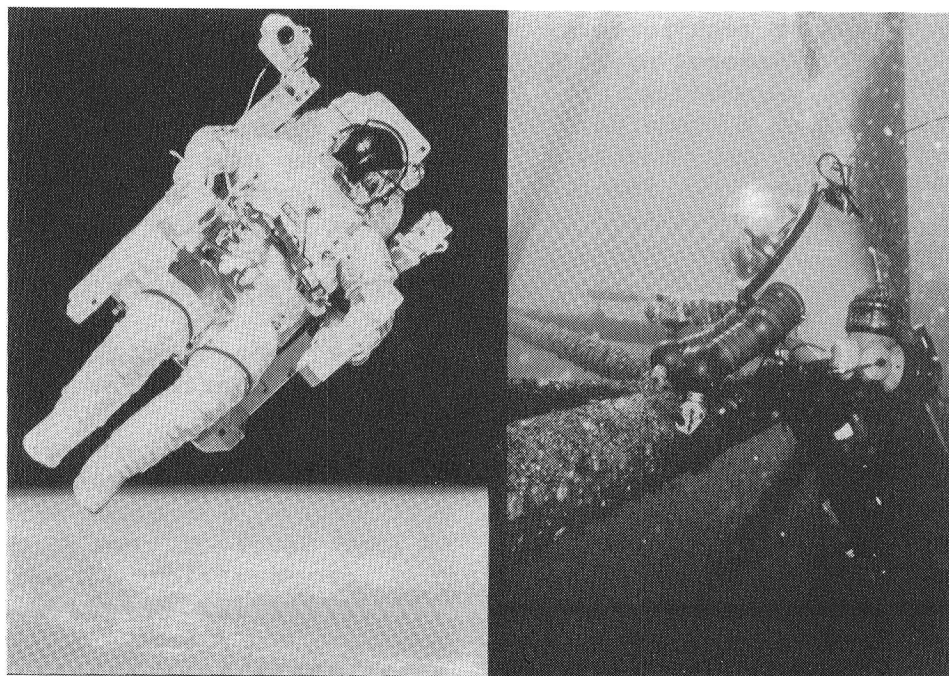


SUBSEA APPROACH TO WORK SYSTEMS DEVELOPMENT

by

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INTRODUCTION

The requirement for subsea work capabilities to support offshore oil production in increasing water depths has led to the evolution and development of a variety of work systems. These work systems range from hands-on divers to manned atmospheric diving suits with end effectors and a variety of tele-operated manipulator work systems.

Selection of the optimum work system to perform an operation depends on the work task requirements, the environmental conditions, physiological limitations, logistical requirements and economic considerations. The resulting selection may be a single work system with special modifications or a combination of work systems exploiting the strong points of each.

The commercial diving industry has more than twenty-five years experience in work systems development resulting in several million hours of underwater operations.

This paper will briefly overview the working environment, physiological limitations, work task requirements and work systems in the subsea industry.

WORKING ENVIRONMENT

The commercial underwater working environment to date is characterized by the following parameters:

- pressure: 0-3350 psi (0-7500 ft)
- temperature: 32-92° F
- visibility: 0-200 ft
- waves: 0-30 ft
- currents: 0-4 kts

In many respects, the underwater environment is a more hostile environment to work in than outer space. This is particularly true with respect to visibility and current/wave forces. The underwater environment is also dynamic and capable of radical changes over short time periods, imposing greater operating ranges on the work systems.

PHYSIOLOGICAL LIMITATIONS

The main physiological limitations are summarized as follows:

Decompression - After working underwater at increased pressures, divers must undergo a gradual decompression to sea level to avoid the bends. This decompression time can range from minutes to days, depending on the depth and duration of the dive.

Inert Gas Narcosis - For air diving below approximately 150 ft, the increased partial pressure of nitrogen creates a narcotic effect on the cen-

tral nervous system. To eliminate this effect, helium/oxygen (heliox) breathing mixes are used for deeper dives.

High-Pressure Nervous System - HPNS is associated with rapid compression on heliox to deeper depths. It can cause dizziness, disorientation and mild convulsions.

Gas Toxicity - Oxygen and carbon dioxide toxicity are critical and must be carefully controlled during diving operations.

Thermal Limitations - Temperature and humidity must be maintained within narrow limits, particularly with the greater heat capacity of heliox breathing mixtures.

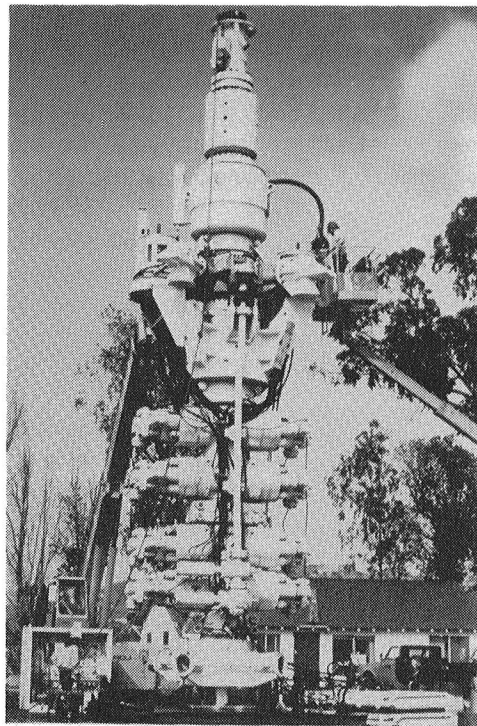
WORK TASK REQUIREMENTS

The work task requirements can be broken down into the following phases relative to the evolution of a producing oil field.

- Drilling Support
- Construction & Maintenance
- Inspection
- Repair

Drilling Support - The work requirements for this phase are primarily related to the installation, observation, maintenance and recovery of the subsea blowout preventer and associated equipment.

The basic work tasks are simple attachments, observations, vertical alignments, valve actuation, debris removal and changeouts of hydraulic hoses, electrical cables, connectors and modules.



Typical Subsea Blowout Preventer

Construction - This phase is primarily involved in the installation and hookup of offshore platforms and pipelines. The platforms are typically fabricated onshore and then towed to the offshore location.

The work task requirements in the construction phase involve complex rigging and alignments, assembling mechanical connectors, burning, welding, water jetting, special tooling and frequently onsite fabrication and modifications.

Inspection - The work requirements for inspection are primarily involved with the cleaning and inspection of in-service platforms and pipelines.

The work tasks required are observation, water jetting, cleaning with power tools, closeup photography, detailed measurements and non-destructive testing.

Repair - The work requirements for repair are primarily involved with mechanical and hyperbaric welded structural repairs of platforms and pipelines.

The work task requirements associated with repairs are detailed measurements, complex rigging and alignments, burning, welding, special tool operation and on-site fabrication and modifications.

WORK SYSTEMS

This section will overview the various types of work systems. These work systems can be classified as follows:

- Hyperbaric Diving
- Atmospheric Work Systems (Manned)
- Tele-Operated Work Systems
- Hybrid Systems

Where applicable, each type of work system will be outlined in the following format:

- Work Capabilities
- Special Interface Requirements
- Limitations

HYPERBARIC DIVING

Hyperbaric diving involves divers working in an ambient pressure, "hands-on" environment. In order to work at ambient pressures, high-pressure breathing gases must be inspired to maintain a pressure equilibrium across the lungs. This leads to tissue absorption of inert gases and a decompression requirement. Diving can be classified into three types with respect to decompression:

Surface Diving - For surface diving, divers will descend to depth, perform a task within a limited amount of bottom time, and then decompress back to the surface in accordance with a predetermined decompression schedule. This type of diving applies up to depth of 300 ft.

Bell Bounce Diving - For bell bounce diving, divers will descend to depth (300-600 ft) in a diving bell at one atmosphere. After analyzing the job requirements, the bell is rapidly compressed to ambient pressure, at which point the divers lock out and

GENERIC WORK TASKS

<p><u>DRILLING SUPPORT</u></p> <p>OBSERVATION VERTICAL ALIGNMENTS COMPLEX ALIGNMENTS HOSE CHANGEOUTS CONNECTOR CHANGEOUTS MODULE REPLACEMENTS DEBRIS REMOVAL CABLE CUTTING PLACING EXPLOSIVES</p>	<p><u>INSPECTION</u></p> <p>OBSERVATION SIMPLE ATTACHMENTS DEBRIS REMOVAL POWER TOOL USE SPECIAL TOOL USE NDT WATER JETTING MEASUREMENTS</p>
<p><u>CONSTRUCTION MAINTENANCE</u></p> <p>OBSERVATION VERTICAL ALIGNMENTS COMPLEX ALIGNMENTS DEBRIS REMOVAL CABLE CUTTING METAL BURNING WELDING RIGGING POWER TOOL USE SPECIAL TOOL USE WATER JETTING ASSEMBLING ONSITE FABRICATION MEASUREMENTS</p>	<p><u>REPAIR</u></p> <p>OBSERVATION VERTICAL ALIGNMENTS DEBRIS REMOVAL CABLE CUTTING METAL BURNING WELDING RIGGING POWER TOOL USE SPECIAL TOOL USE WATER JETTING ASSEMBLING ONSITE FABRICATION MEASUREMENTS</p>

perform the work task within a limited excursion time.

After completing the job, the diver returns to the bell and makes a pressure seal. The bell is then brought to the surface and mated to a deck decompression chamber, where the diver completes the decompression requirement. The principal limitation with this type of diving is the low working time to decompression time ratio. For 30 minutes bottom time at 500 ft, approximately 28 hours decompression is required. If a job requires long bottom times, then saturation diving will be used.

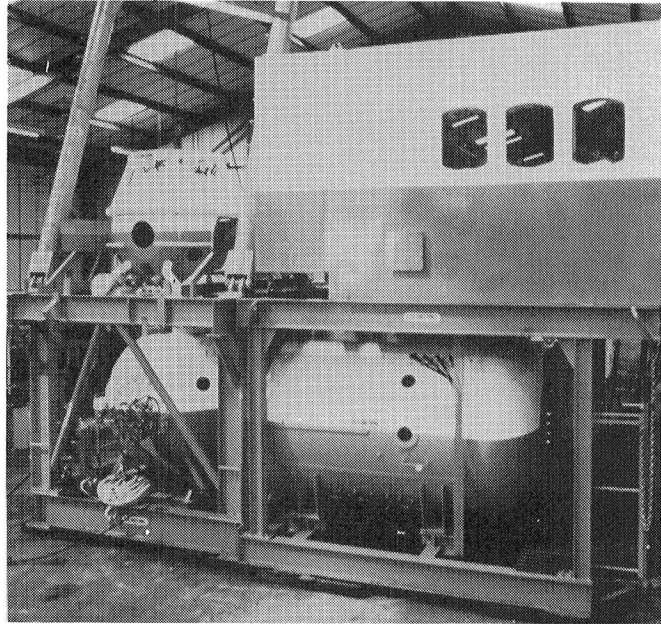
Saturation Diving - For saturation diving, the divers will remain at a pressure equivalent to their working depth for up to 40 days. Once the body is saturated with inert gas at a given depth (approximately 8 hours), then the decompression requirement is fixed, regardless of the time spent at that depth.

Saturation diving requires the use of a special modular diving system made up of the following components:

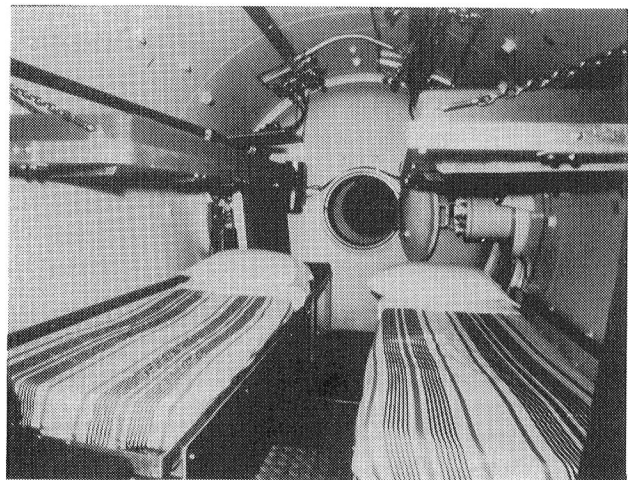
Diving Bell: The diving bell is a pressure vessel designed to be mated to a deck decompression complex, allowing diver transfer under pressure between the deck complex and the worksite.

Deck Decompression Complex: The deck decompression complex consists of two or more pressure vessels, the primary purpose of which is to provide safe living quarters for the divers while under pressure between working dives, or decompressing upon completion of the job. As the deck chambers are modular, any number can be bolted together to accommodate various crew sizes.

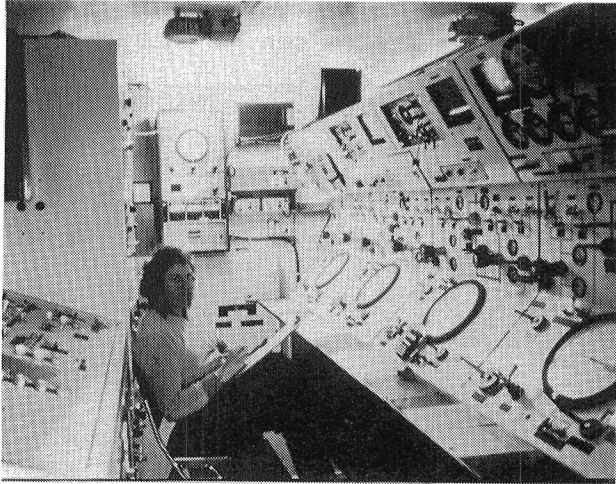
Control Van: Power, communications, gas control, gas monitoring and environmental control for the deck complex and the diving bell are all housed in a single control van. The life support systems are all modular so that in an emergency, any pressure vessel of the system can be isolated.



Six-Man Saturation Diving System



Inside View of Living Chamber



Control Van Showing Modular Life-Support Control Panels

Work Capabilities

Hyperbaric diving, because of human perception, judgment and dexterity, provides the most complete and versatile work system in the sub-sea industry. Divers were the original work system and have performed efficiently all of the underwater tasks required for offshore oil production. This baseline experience with man has provided the knowledge required to design alternate work systems, some of which can perform certain tasks more effectively than man.

Special Interface Requirements

Special man/equipment interfaces are usually not provided. Typical offshore structures are constructed from tubular trusses from 10 to 36

in. diameter. This makes it possible to attach to the structure in a variety of body positions using arms and/or legs. On larger-diameter tubulars, work restraint stations are fashioned from rope tethers and other items of opportunity.

Occasionally, on special projects, diver work stations are designed into the structure at key locations. This approach has proved to be cost-effective but tends to be the exception.

Limitations

The following are some of the limitations associated with hyperbaric diving:

- Human safety
- Depth limitations
- Dive duration limitations
- Decompression penalties
- Support crew and space requirements
- Reduced accessibility to hazardous areas



Diver Using an Impact Wrench to Tighten Bolts on a Riser Clamp. Note Use of Legs as Attachment Point



Diver Attaching Come-Along to Secure Underwater Welding Habitat

ATMOSPHERIC WORK SYSTEMS (AWS)

Atmospheric work systems utilize man in a one-atmosphere shirtsleeve environment and can be subdivided into atmospheric diving suits (ADS) with end-effectors, and manned submersibles with manipulators.

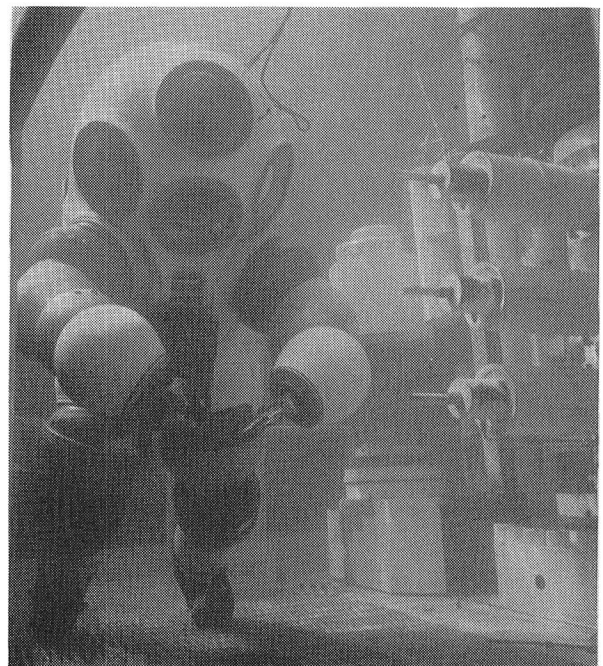
Atmospheric Diving Suits (ADS)

JIM: JIM is an atmospheric diving suit with articulated arms and legs, the limbs being neutrally buoyant so that operator effort is only required to overcome the friction of the articulated pressure balanced joints. The JIM suit receives no power from the surface with its lift umbilical containing only a communications cable.

Life support up to 72 hours is provided through onboard oxygen bottles. Since the suit does not leak, the nitrogen initially in the suit serves as a dilutant inert gas

throughout the dive, eliminating the requirement for a two-gas life support system. Carbon dioxide removal is provided through an oral-nasal lung-powered scrubber.

The end-effector assemblies work via a through-hull solid shaft penetration operated by the hand motions of the pilot. They can be continuously rotated in either direction and locked in position. The end-effectors have standardized grip surfaces and a rope hook used for sliding down guidewires. These end-effectors are able to interface with pre-engineered tools and work stations and have remained essentially unchanged throughout the entire commercial life of the suit.



JIM Working on Subsea Wellhead

WASP: The WASP is a free-flying atmospheric diving suit which utilizes the same articulated arms as JIM, but has no legs. The WASP receives power and communications through an umbilical to the surface. Translation and

station-keeping are provided through four foot-controlled thrusters.

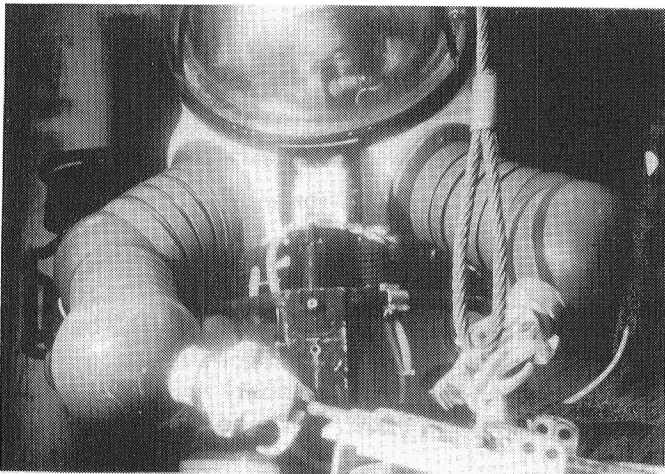
Life support is provided by an oxygen makeup system similar to JIM; however, fan-powered scrubbers are used for carbon dioxide removal.

Work Capabilities - The JIM suit is used primarily on drilling support. It has successfully performed inspections, attachments, debris removal, replaced valve assemblies and other tasks associated with drilling support.

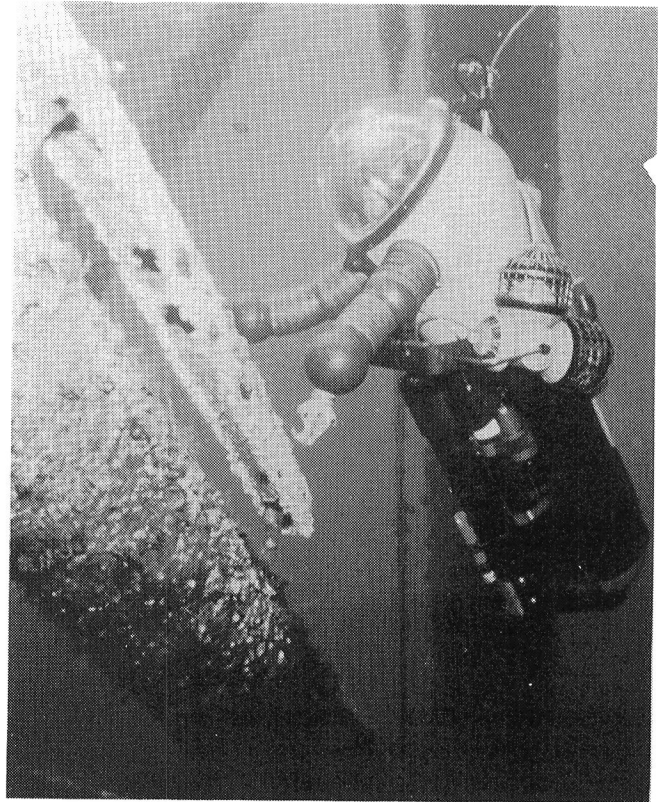
Tasks performed with JIM require interface engineering between the end-effectors and the equipment, and typically require a longer time than a hyperbaric diver.

The WASP has similar capabilities to JIM with respect to drilling support. It can also be used for mid-water work such as general platform inspection, cathodic protection measurements, waterblasting and other simple manipulative work tasks.

The WASP has been used successfully on some specially-interfaced midwater construction and repair projects such as mechanical clamp and anode installations.



JIM Operating a Lifting Jack
Using Both End-Effectors



WASP Performing Platform
Inspection

Special Interface Requirements

JIM needs a pre-installed walk deck to translate around the subsea equipment. Due to the limited ability to translate the bulk of the suit, and anthropomorphic limbs length limitations, some of the subsea equipment must be extended to JIM's work envelope. The equipment must also be designed for interfacing with the jaws of the end-effector. There are a variety of hand tools used by the JIM, each having a standardized end-effector interface, allowing multiple tools to be used without changing the end-effectors.

The WASP requires standardized equipment and tool interfaces similar to JIM. Also, depending on the job, special work-restraint systems and equipment extensions are utilized.

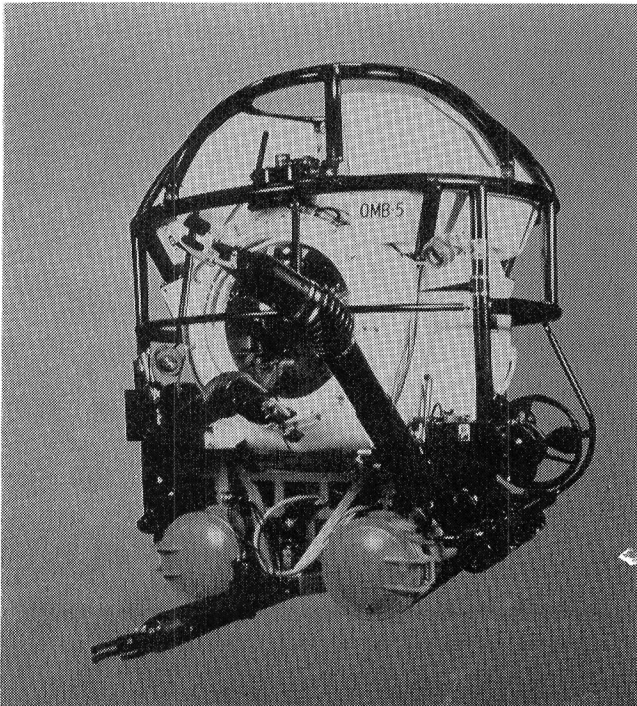
Limitations

- Human safety
- Depth
- Dive duration
- Reduced accessibility/work envelopes
- Restricted to bottom work (JIM)
- Stationkeeping when performing certain tasks in free-flying mode (WASP).

MANNED SUBMERSIBLES WITH MANIPULATORS

ARMS Bell

The ARMS bell has an interior maintained at one atmosphere, and is designed to support a two-man crew for 6 hours mission time plus 84 hours reserve. Observation of the work site is provided through a wide-angle plexiglass viewport. The bell is equipped with thrusters to provide lateral translational capabilities about the worksite.



ARMS Bell

The ARMS Bell will have up to three manipulators. The manipulator in the center of the bell has two degrees of freedom and typically is used as a work restraint system. On the left and right are either two seven-function manipulators or a seven- and five-function manipulator. The manipulators have standardized locking jaw end-effectors. Typically, the five-function manipulator is used as a grabber to initially align the work task, while the seven-function (six degrees of freedom) manipulator performs the dextrous work task. The five- and seven-function manipulators are usually spatially correspondent, utilizing a master/slave relationship. The work restraint manipulator is typically rate feed.

On some submersibles, the seven-function manipulator is equipped with force feedback, greatly enhancing the work capabilities.

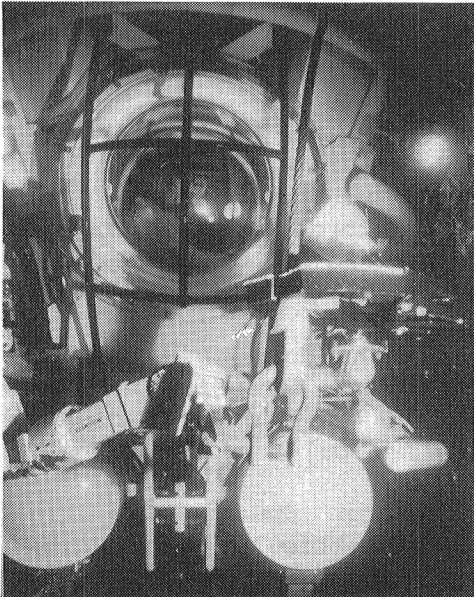
Typically, the manipulators are used only one at a time for the following reasons:

- In order to effectively use two manipulators simultaneously, both must have force feedback and dynamic compliance in order to optimize the resultant force vectors.
- Most jobs do not justify the expense of two force-feedback manipulators and can be performed using the various manipulators sequentially.
- Operator demands are greater. This is particularly true in the tele-operated systems where spatial perception is restricted by camera viewing angles and the inability of pan-and-tilt mechanisms to scan as quickly as the human eye.

In addition to the ARMS Bells, there are a variety of one-manned tethered submersibles with similar manipulator arrangements and work capabilities. These include the Mantis, Wrangler and an untethered version of the Deep Rover.

Work Capabilities

The human in a comfortable shirtsleeve environment provides high visual awareness and interpretive capability. With longer manipulators, these systems have a greater working envelope than the ADS suits, whose work envelopes are limited by anthropomorphic limbs. These capabilities have combined to produce an excellent track record in performing all the work tasks associated with drilling support. Because of size, translational capabilities and mobilization requirements, these systems are not frequently used in the other work phases.



ARMS Bell Aligning a Shackle Pin

Special Interface Requirements

- Standardized end-effector/equipment interface similar to the ADS suits
- Work restraint attachment points

Limitations

- Human safety
- Depth limitations
- Dive duration limitations
- Increased size, space, crew
- Reduced accessibility and translational capabilities

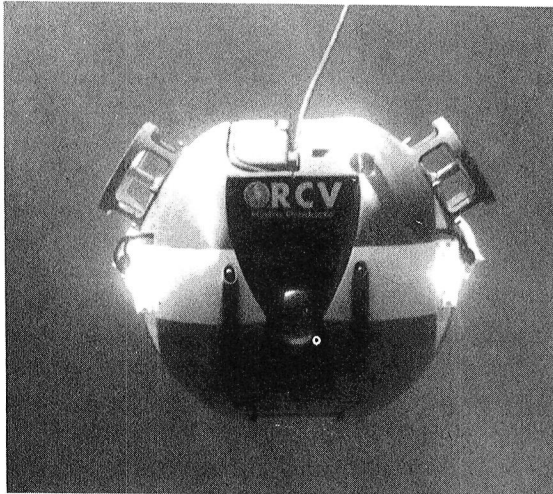
TELE-OPERATED WORK SYSTEMS

Tele-operated work systems are controlled by humans viewing television monitors remote from the work-site. The various types of systems can be classified as follows:

- Inspection Vehicles
- Light Work Vehicles
- General-Purpose Full Work Vehicles
- Modular Work Vehicles
- Special-Purpose Vehicles/Machines

INSPECTION VEHICLES

This class of tele-operated work system consists of a variety of small, tethered, remote-controlled, self-propelled observation vehicles. They have onboard video cameras typically mounted on a pan-and-tilt mechanism. This, combined with superior mobility, allows the inspection vehicle to observe underwater operations from a variety of orientations and in confined areas.



Inspection Vehicle

Work Capabilities

These vehicles are used extensively throughout all phases of oil production. In drilling support, they serve as flying eyeballs to allow surface crews to observe the underwater operation of subsea equipment and potentially identify or prevent problems.

In construction, they are used to monitor subsea operations and to locate and pre-inspect work sites, allowing the divers or other work systems to identify and plan job requirements prior to diving.

For platform inspection, they are used to perform the general visual inspection of the platform. In this role, they can be more effective than hyperbaric divers because of superior translational capabilities, depth-independent operations (within design limits), and longer dive duration capabilities. They also produce

a permanent, annotated video documentation of the entire inspection.

For platform inspection, typically the divers will be performing the detailed cleaning and inspection work, while the inspection vehicle does the general "flyby" inspection. This simultaneous operation reduces the total job time requirements. These vehicles are also used to monitor diver performance and safety.

Special Interface Requirements

There are no work interface requirements, as these vehicles do not have manipulators. On some subsea equipment, location reference systems are provided to orient the pilot.

Limitations

- Limited visual awareness
- Low interpretive capability
- No manipulative capabilities
- Limited payload capabilities
- Inadequate real-time response to changing environment

LIGHT WORK VEHICLES

This class of vehicles is similar to the inspection vehicles; however, they have increased payload capabilities and are capable of utilizing small, limited manipulators.

Work Capabilities

These vehicles can perform the same role as an inspection vehicle, with some loss of mobility and accessibility. Additionally, they can carry instrument packages, tools and can perform very simple manipulative tasks, such as attachments and placements. They play a bigger role in diver support in that they are capa-

ble of transporting tools to and from the diver at the worksite. They can also be used as a temporary tool storage platform.

Interface Requirements

- Standardized end-effector/equipment interface
- Location reference systems for pilot orientation

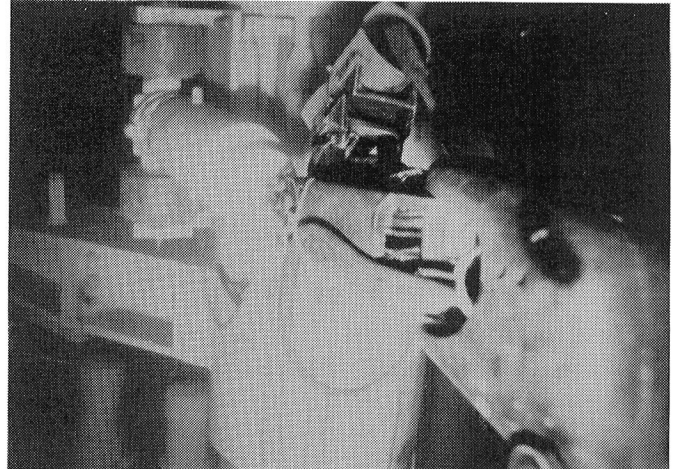
Limitations

- Can perform only simple manipulative tasks
- Other limitations same as inspection vehicle.

GENERAL PURPOSE WORK VEHICLES

These are larger vehicles designed to perform manipulative work. They are usually equipped with a five-function and seven-function spatially correspondent manipulators. These manipulators utilize a master/slave control with the speed of the slave proportional to the master. In some cases, the seven-function manipulator is enhanced with force feedback and dynamic compliance, which allows the operator to feel imposed loads. This capability greatly increases work performance due to increased sensitivity and awareness of the work task.

The manipulators are typically used sequentially with the five-function initially aligning the work task, which is then completed using the more dextrous seven-function manipulator.



View from Manipulator-Mounted Camera
of Work Vehicle on Subsea
Blowout Preventer

Work Capabilities

Although vehicles of this type are used in all phases of oilfield production, their primary application is in drilling support. The main reason for this is that most of the required tasks and subtasks have been well defined and are capable of being reduced to exactly the functions performed optimally by manipulators.

General purpose work vehicles are also used in construction for observation, diver support and pre-defined work tasks.

Interface Requirements

- Standardized manipulator/equipment interfaces
- Work restraint attachment points
- Location references

Limitations

- Limited visual awareness due to restricted camera viewing angles, inadequate scanning capabilities of pan-and-tilt mechanisms, and surface viewing monitor limitations
- Low interpretive capability
- Inadequate real-time response to changing environments
- Limited manipulative capability compared to the human hand
- Requirement for standardized manipulator/equipment interfaces
- Generally inflexible to unpredicted changes

MODULAR WORK VEHICLES

Modular work vehicles consist of a basic vehicle that provides propulsion, telemetry and control. The basic vehicle is capable of carrying, controlling and operating a number of special work packages that address specific tasks. Modular work vehicles are large systems with excess power and control functions in order to accommodate a number of add-on packages, including contingencies for future expansion.

Work Capabilities

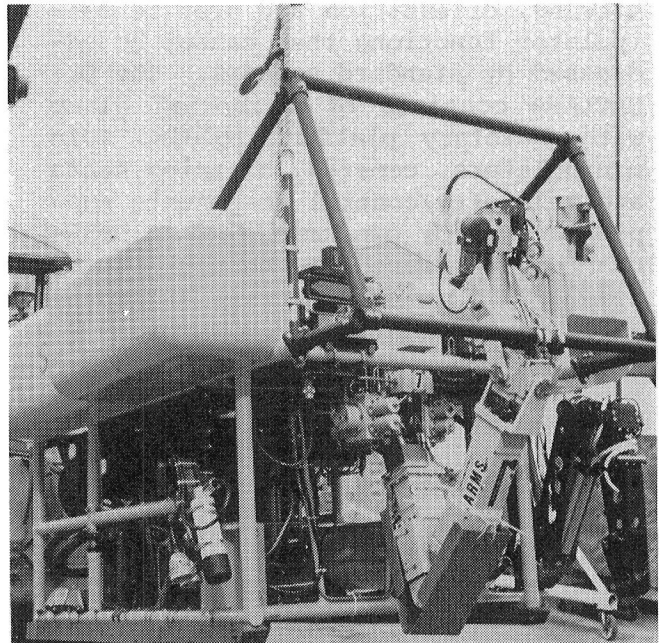
The modular work vehicle's capabilities are based on the propulsion and control characteristics available on the basic vehicle. The work packages can be tailored to drilling activities, as well as support, inspection and maintenance tasks. The success of the modular work vehicle is dependent on the functional specifications and the tradeoffs of a wide range of requirements within a single basic vehicle. If necessary, opposing requirements can be eliminated from the basic unit by incorporating their characteristics within the work package itself.

Interface Requirements

- Same as General Purpose Full Work Vehicle.

Limitations

- Basic unit size and complexity increased to support range of work packages
- Accessibility limitations due to overall system size
- Other limitations same as General Purpose Full Work Vehicle



Typical Modular Work Vehicle
with Force Feedback Arm

SPECIAL-PURPOSE WORK SYSTEMS

These units are designed from the outset to carry out a specific set of tasks. The power, telemetry, configuration, manipulation, tooling, etc. are selected and/or developed to support the defined scope of work.

Special purpose systems are extremely effective in carrying out the required work, and represent a highly productive and reliable method of performing work. Two examples of special purpose vehicles are DYNACLAMP and RIG BANDIT.

Dynaclamp: The DYNACLAMP is a special purpose machine designed to carry out the cleaning, photographing and detailed inspection of the welds found at the nodal joints of tubular members. This highly complex work imposes constraints on accessibility, viewing, orientation and precise manipulator functions that cannot be addressed by standard systems. The DYNACLAMP consists of a special clamp with a rotary platform holding twin manipulators, cameras, cleaning heads and telemetry/control components supported by its own umbilical. DYNACLAMP is delivered to the worksite by diver, ADS or ROV, greatly expanding their work capabilities.

Rig Bandit: The RIG BANDIT is a passive work system designed for guidewire-supported drilling support. The RIG BANDIT consists of a frame holding manipulators, lighting and cameras that is attached to guidewire and lowered from the surface. The RIG BANDIT can be clamped to the guidewires at the working depth to provide a stable platform. This configuration restricts translational capabilities. However, the system carries out certain tasks effectively with a less complex system than would result from adaptation of a general-purpose unit.

HYBRID WORK SYSTEMS

Operational experience with the various work systems has led to sufficient understanding of their work capabilities to allow hybrid work

systems to be designed. This section will briefly describe some of the hybrid work systems used in the subsea industry.

Mobile Diving Unit (MDU): The MDU is a combination of an ARMS manipulator bell and a saturation diving system. This combination provides the crew member the opportunity to complete the work task in a one-atmosphere environment without incurring any decompression penalty.

If the job cannot be completed using manipulators, then the diver can compress the bell to ambient pressure, lock out and perform the task in a hands-on environment.

Mantis Duplus: This vehicle is a combination of a manned submersible with manipulators and a tele-operated work system. It can be used in either the manned or remote-operated mode, depending on the difficulty of the task and the requirement for human perception and judgment. This type of system has the secondary advantage of allowing the submersible to be piloted remotely from the surface, while the crew member concentrates on the manipulative work task.

Dynaclamp: The DYNACLAMP is specially designed for performing detailed cleaning, inspection and maintenance tasks in restricted nodal areas. For this reason, it can perform these tasks much better than any other work system except possibly hyperbaric divers.

The DYNACLAMP can be delivered to the work site by a general purpose work system such as a WASP or general work vehicle. The DYNACLAMP then works through tele-operated control, while the delivery work system performs other, less complicated tasks

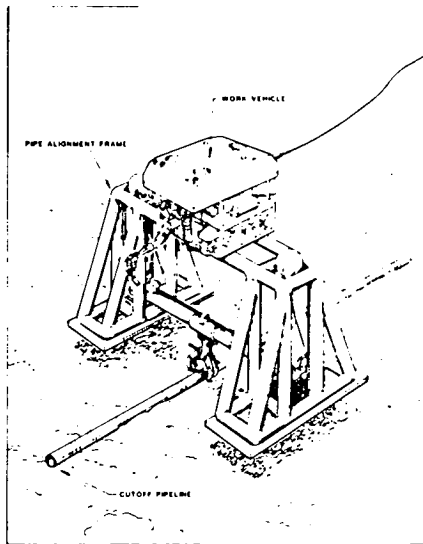
simultaneously. This combination greatly extends the work capabilities of general-purpose systems.

DEEPWATER PIPELINE REPAIR SYSTEMS

The deepwater pipeline repair system is a combination of a modular work vehicle and a variety of special purpose work systems.

This system was designed to address one major task - the remote repair of deepwater pipelines. Within this task are multiple subtasks that are individually addressed by special purpose work packages which are interchangeable on the modular work vehicle.

The integrated system can carry out a range of specific inspection, installation and work tasks, including the precision alignment of mechanical connectors, the lifting and alignment of pipe sections, the cutting and bevelling of pipe faces and a number of measurement tasks.



Deepwater Pipeline Repair System
Showing a Modular Work Vehicle
Operating a Pipeline Alignment Frame

The system uses a combination of sensors, manipulators, special tools and work packages to carry out the designated work.

OPERATIONAL PHILOSOPHIES

Through operational experience, a number of very clear lessons have been learned. Some of these lessons are as follows:

- Design Equipment for Intervention - This has proven to be cost-effective. The small increase in initial cost is paid for the first time the equipment breaks down. Triple-redundant fail-proof systems cost more up front and more to repair when they do break down.
- Standardize End-Effector/Equipment Interfaces - This can make pre-planning and job execution a lot easier. It is also a more sensible approach than changing end-effectors for each task or designing complex multi-finger end-effectors.
- Design Simple Job Requirements - A job can be done in a number of ways and with a variety of methods. It is important not to over-engineer the job.
- Documentation - Poor documentation of subsea equipment can lead to inadequate planning, useless tool design and ineffective operations. When possible, equipment should be documented extensively with photographs and scale drawings.
- Select the Most Effective Work System - A number of work systems may be able to do the job, but how productive and cost-effective? In selecting the optimum work system, it is important to start at the task and work backwards as opposed to trying

to fit the wrong work system where it does not apply.

A sensible approach to this process is as follows:

- Define the work tasks
- Determine work envelopes
- Determine required functions
- Incorporate operational considerations
- Select/design optimum work systems
- Perform interface engineering
- Design/manufacture special tooling
- Perform testing and optimization

For many work tasks, the answer may be hands-on divers or gloved astronauts. In other cases, hybrid work or special-purpose systems would be more effective.

CONCLUSIONS

The evolution of work systems in the subsea industry has been the result of direct operational experience in a competitive market. This experience should help to make the evolution of work systems more efficient for space operations.