Techniques in Diving and Submersibles

P. R. Christopher

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Techniques in diving and submersibles

By P. R. Christopher

Admiralty Marine Technology Establishment (*Experimental Diving Unit*),
H.M.S. Vernon, *Portsmouth, U.K.*

This paper attempts to give an elementary picture of some of the techniques that ambient-pressure divers and submersibles may use to carry out tasks underwater during the next decade. It begins by outlining options for the ambient-pressure diver and underwater vehicles, manned or unmanned, and possibilities for further development to accomplish work tasks.

The safe deployment of ambient-pressure divers and submersibles upon selected tasks in the working environment is considered, taking into account aids to operations available (communications, position fixing and tools for survey and work tasks). Two depths, 140 and 480 m, representing present and possible future working depths for common usage for ambient-pressure divers, are assumed. The use of techniques at much greater depths is discussed in relation to feasible tasks.

Finally the supporting facilities, available and needed, for research and development to give the optimum life support and manipulator techniques for the 1990s are discussed from the points of view of supporting them and stretching the scope.

1. INTRODUCTION

It is important to remember that underwater intervention, with ambient divers or submersibles, is an evolving technology that needs special facilities for development. Scientific understanding of the human factors involved, technical knowledge and the need to check design procedures have for example given rise to the development of mathematical models used in conjunction with breathing machines and hyperbaric facilities. Such combinations are important for both diving and submersible techniques for the 1990s.

At 300 m depth it is now possible to deploy divers subjected to ambient pressure. It will soon be possible to go much deeper. Indeed, divers have been deployed in experimental dry chambers to do tasks at about 650 m. One-atmosphere armoured suits and submersibles can reach these orders of depth. Cable-controlled unmanned vehicles can descend to much deeper zones. Such is the state of the art at present.

At a colloquium held in November 1979 (Thornton & Christopher 1981), Sir Hermann Bondi suggested that economic pressures may force the development of underwater resources including mining of the seabed. This will require conservative solutions and to some extent change the role of the human operator from one of carrying out underwater tasks to controlling machines to do the job for him. This is a state of the art far removed from present practice but there is a certain amount of progress in this direction with the development of remote-operated vehicles allowing for some types of manipulation and programmable operations.

In order to take a practical look at the state of technology to be expected in the 1990s it is pertinent to ask a number of simple questions, for example:

What are the options for working underwater and what are the choices of option for specific tasks?

What are the likely changes over the next decade, i.e. changes in requirement and solution?

What will be needed to develop the necessary technology, i.e. the necessary resources and the likelihood of these being available?

This paper attempts to explore some of the solutions in relation to equipment, using, in a general way, the substance of a scene-setting scenario at the recent Divetech '81 conference organized by the Society for Underwater Technology, and the ideas and thoughts of many friends and colleagues.

The aspects of human factors relating to physiology and psychology are outside the scope of this paper, but it is pertinent to remember that they impose limitations on any equipment used in the sea. In the 1990s these may be related as much to control and intelligence as they are now to the wellbeing of the diver at his task.

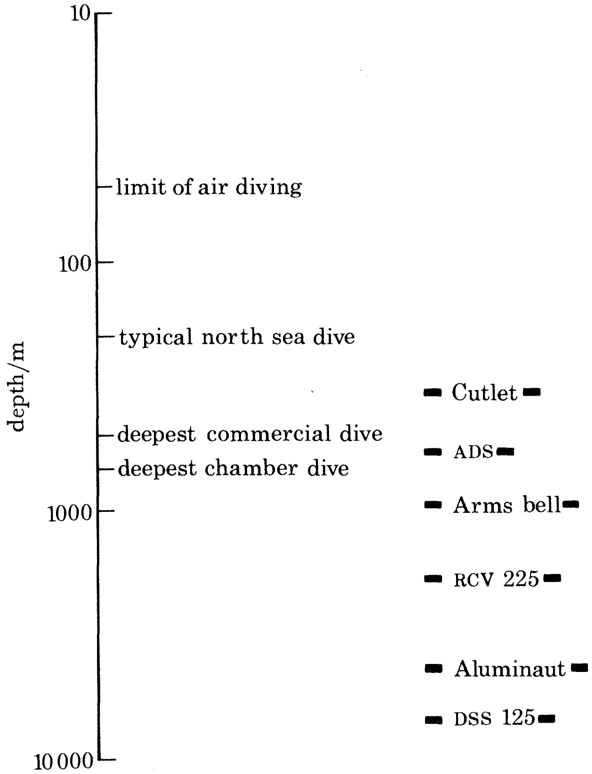

FIGURE 1. Limitations of equipment.

2. OPTIONS FOR UNDERWATER INTERVENTION

In or out of the water it is important that the human operator be maintained in as efficient and safe a state as possible, complying with statutory regulations. Warmth and good breathing are vital: comfort and good voice communications give confidence; reliability of equipment is mandatory. In order to assess the options, very briefly, a sketch is given, in the next paragraphs, of what these amount to for the ambient-pressure open-sea diver, the diver in shallow waters, the need to keep warm, the need to communicate with the atmospheric vehicle and the remotely operated vehicle.

(*a*) *Ambient-pressure diver in open sea*

Figure 1 indicates the depth limitations with conventional types of equipment now available. Down to 50 m air diving is practical but deeper diving normally involves the use of mixed gas (usually oxygen–nitrogen or oxygen–helium). The depth and duration of the dive determine the subsequent rate of return to the surface which may include decompression stops that are stipulated in order to control the absorption and release of inert gas in the bloodstream.

Figure 2 indicates a few profiles for diving to different depths, showing how the time on the bottom and decompression is affected. The human body on compression at depth becomes saturated with inert gas after a period of time. After this it does not matter how long it stays in this state, but decompression must be gradual at a rate of about 30 m per day.

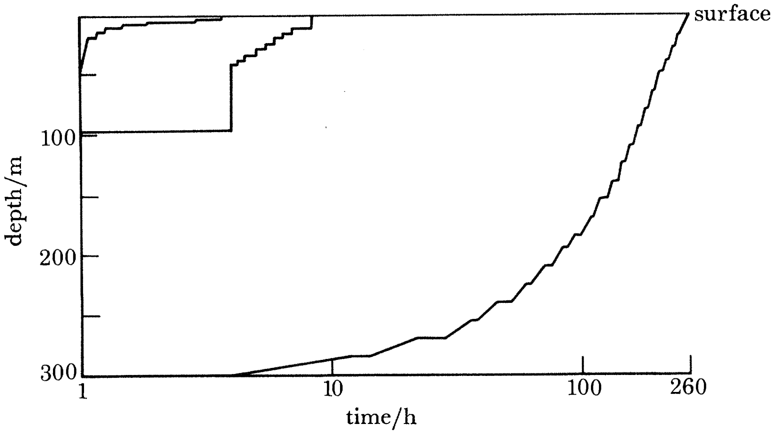

FIGURE 2. Dive profiles.

If the diver can be kept in saturation at storage depth, and eventually decompressed in a compression chamber after the task is completed, then there is no specific time limit for staying at depth with a schedule of working and resting. Beyond a depth of about 50 m it is often impractical to keep the diver in the water, ascending from stop to stop. The diver can carry out a variety of tasks deployed from a diving bell or from a lock-out submersible. Normally the diving bell can be locked on to a transfer under pressure chamber that connects into the living chambers at the same pressure. A diving support ship or platform usually carries these pressurized living quarters (Sear 1981). Seabed operations have been carried out from an underwater habitat, but this is not widely used at present. Saturation diving can be carried out within physiological limitations, and there may be advantages in relatively shallow air-saturation diving but this is not common practice today. Lock-out submersibles are highly specialized and rarely used because of difficulties of deployment and limited endurance.

It is not possible to say what the practical limits of saturation diving are at present: 450 m is attainable and experimental dives have taken place in hyperbaric dry chambers at about 650 m. The successful, and safe, demonstration of a deep dive in a hyperbaric chamber must include the ability to do tasks: in this respect facilities are needed to enable the diver to work underwater. Even then it is necessary to show that diving can safely take place in the seabed environment. Later on in the paper reference will be made to hyperbaric facilities.

An important consideration is the work done by the human body in breathing and the peak pressures reached during inhalation and exhalation in each breathing cycle. It is possible to construct an empirical relation between work and rate of breathing and to suggest desirable limits to both work of breathing and maximum differential pressures experienced during rest periods, light work and heavy work. Figure 3 (Morrison 1981) illustrates this. Rest periods involve breathing rates of about 15 breaths per minute at a tidal intake volume of 1 l, and heavy work involves about 25 breaths per minute at a tidal volume of 2.5 l. The equipment used to assess the capacity of breathing apparatus at A.M.T.E. (E.D.U.), to cope with such gas flows, is illustrated in figure 4. There is now sufficient agreement internationally (e.g. in the U.K. and U.S.A.) for a common standard (Morrison 1981) outlining a testing procedure that can be applied to any breathing equipment. What is required in an agreed interpretation of results obtained from such tests in order to establish safe limits of working.

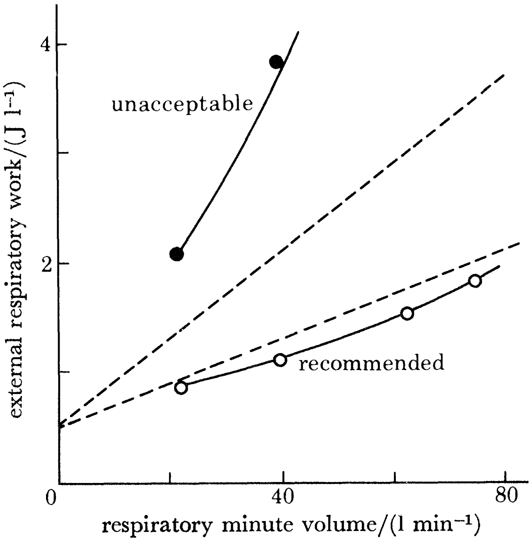

FIGURE 3. External respiratory work plotted against respiratory minute volume, for air at 50 m of sea water.

Breathing gas may be supplied through a demand valve to a diver and after breathing exhausted into the sea. It can also be delivered by free flow past his face but the amount of gas used in this way would be large. There are a variety of equipment choices relating to various kinds of diving. In making a choice for a particular purpose it is most desirable to know how the equipment behaves at a particular depth but it is often difficult to get this information. Because of this there is a lack of awareness of the real effect of simple design differences on performance.

It is desirable to conserve the inert gas, if helium is used, since this is expensive, it may become scarce, and it may be difficult to store enough gas in cylinders on the ship or platform if it is not conserved but is vented to atmosphere. The human respiratory system acts rather as an ambient pressure pump and at 300 m the mass of gas being used up is about 30 times as great as that which would be used on the surface at 1 atmosphere. Over about 20 years the cost of deploying two divers at 300 m depth, for about one-tenth of this time, is of the order of millions of pounds if gas is wasted: thus there is a great interest in closed-circuit systems, which supply gas to the diver, remove the carbon dioxide in a canister and then recirculate the breathing gas with replenished O_2. There are several ways of doing this: (*a*) by mounting pumps at the surface and supplying directly to the diver by umbilical, the diver operating from a bell; (*b*) by mounting push and pull pumps on the bell, in which case at 300 m the diver's umbilical length for gas supply can be reduced by a factor of well over 10:1; here the gas is returned from the diver to the bell; (*c*) closed-circuit systems independent of umbilical support.

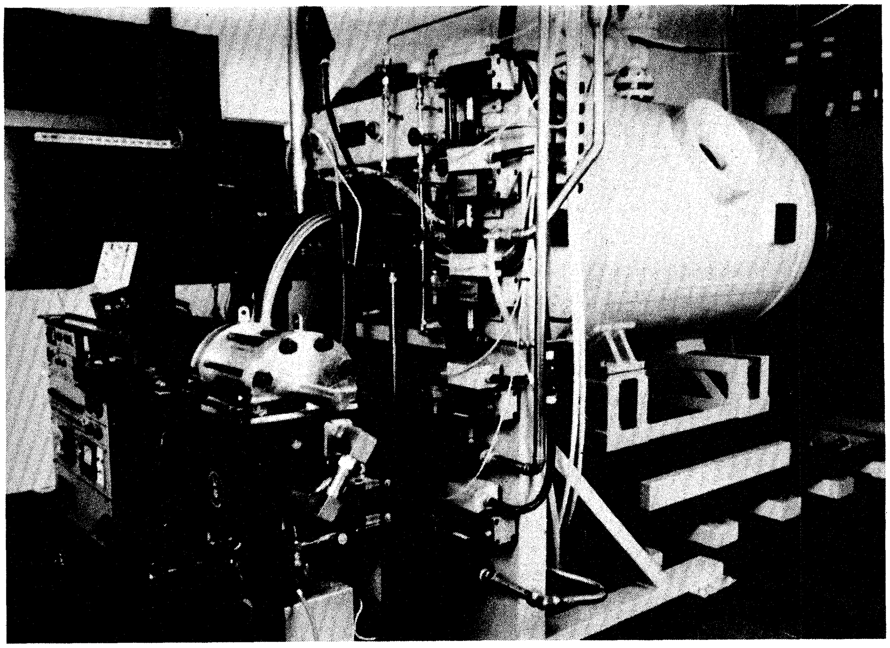

FIGURE 4. Breathing machine and pressure chamber for testing equipment under pressure.

Krasberg (1981), Carnegie (1981) and Normalair–Garrett Ltd, Yeovil (personal communication) give a number of examples of such systems. Subjectively it is the confidence that a diver has in his equipment that overrides other considerations. Thus in the North Sea the diving system pumps used are mainly surface-mounted. However, the bell-mounted system permits a smaller umbilical bundle from surface to bell, and may be more flexible with respect to changing gas mixtures.

The pump power needed to circulate breathing gas depends upon any changes in ambient pressure and upon friction and circulation losses in the equipment; it is very large indeed compared with the work needed by the human respiratory system. In a bell-mounted system there is a need to cope with changes in ambient pressure of the diver relative to the bell. When the diver is above the bell the gas density is less and a separate pump is needed to return the gas from the diver. As can be seen from figure 5 this also necessitates special measures to control the supply of gas, and its removal from the diver's helmet: the pressure in the helmet must be maintained several centimetres of water pressure above ambient and an 'anti-suck' valve is needed to prevent the return pump deflating the diver if the supply pump fails. The design and construction of these pumps is specialized if they are to operate with helium mixtures without undue leakage and wear (Carnegie 1981).

Several of the North Sea closed-circuit equipments use special-demand, or semi-demand valves, which are duplicated for fail-safe usage. The question arises as to whether it is best to

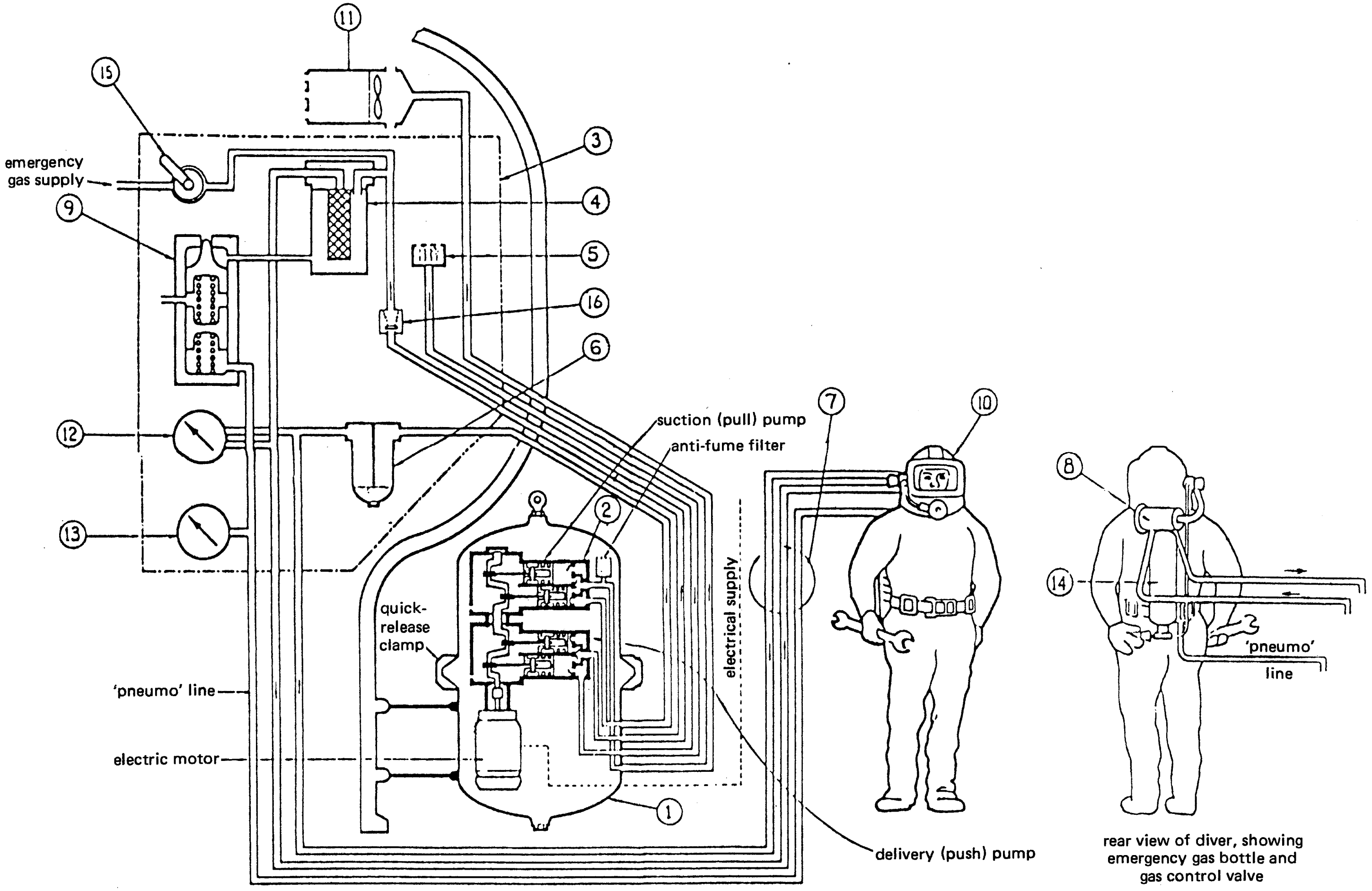

FIGURE 5. Bell-mounted push–pull system: 1, pressure vessel assembly; 2, combined pump assembly; 3, gas control panel; 4, delivery filter; 5, inlet filter; 6, water separator; 7, diver's excursion umbilical; 8, gas control valve; 9, variable datum relief valve; 10, diver's helmet assembly; 11, bell-mounted scrubber; 12, differential pressure gauge; 13, diver's location indicator; 14, emergency gas bottle; 15, change-over valve; 16, non-return valve.

use an orinasal mask or to have a free flow of gas past the face. There are many considerations relating to comfort, fit to the face, carbon dioxide build-up, which is detrimental, and the provision of good communication. The orinasal mask coupled to a demand system requires less gas flow and is therefore attractive for surface-supported equipment, and the reduced dead space limits carbon dioxide build-up. It is, however, restrictive and may be less comfortable and make communications difficult.

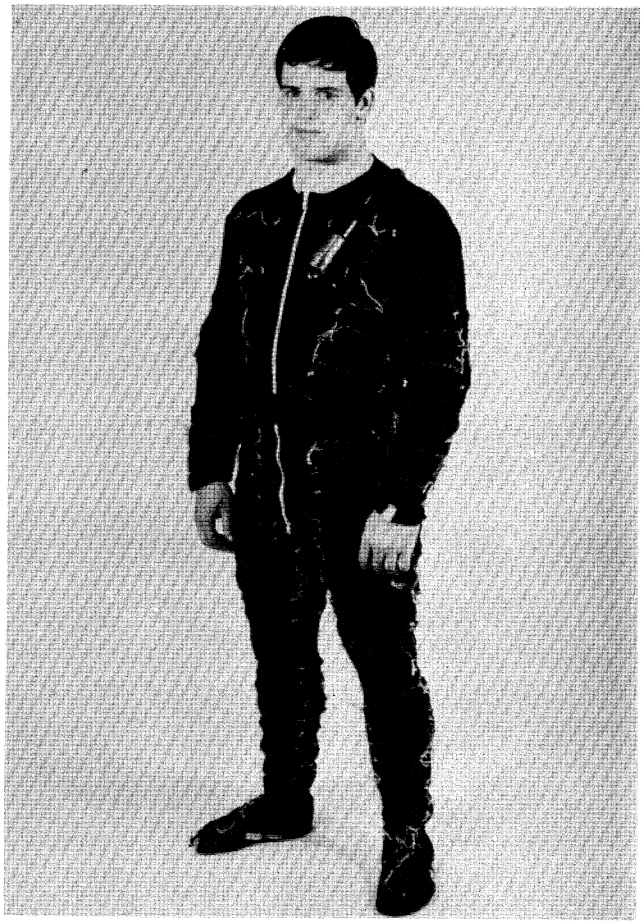

FIGURE 6. Electrically heated suit.

There are developments involving self-contained closed (Normalair–Garrett, personal communication) and semi-closed (Taylor 1981) equipments for use in both shallow and deep water, some of which control the partial pressure of oxygen by means of sensors that regulate the oxygen in the gas mix. These equipments require a counterlung to maintain pendulum breathing through a carbon dioxide absorbent canister. It is necessary to restrict the changes in partial pressure of oxygen during breathing and have acceptable breathing resistance, much of the work needed to drive breathing gas through the carbon dioxide absorbent canister being provided by the diver. It is noteworthy that the density of air at 50 m is about the same as that of oxygen–helium at 350 m and there is a marked decrease in time to 'break through' of a carbon dioxide absorbent canister with depth (Thornton 1981).

(*b*) *Ambient-pressure diver in shallow waters*

The shallow-water diver can use self-contained breathing apparatus with comfort, but the task must be such that enough gas can be carried by him. If not he must use surface-supported equipment in which the breathing gas is supplied by umbilical, as in the standard copper-hat diving dress. As depth increases it is necessary to have longer in-water decompression times, which are tedious. Various mixtures of oxygen, nitrogen and helium have been used to dive to 75 m with the object of decreasing this in-water decompression time. For some long tasks, shallow-water saturation diving may be attractive. In shallow waters the visibility may be obscured and impose difficulties in working.

(*c*) *Bounce diving* (*non-saturation diving*)

It is possible to bounce-dive to greater depths for periods of time shorter than that needed for full saturation to occur. Thus it is possible to take a diving bell, at atmospheric pressure inside, to a bounce depth and deploy divers for a limited time, thereby greatly reducing the time necessary for decompression. This practice, which is commonly used, requires strict adherence to physiological tables.

(*d*) *The need to keep warm*

A diver loses heat from the surface of his body, mainly by the processes of conduction and convection, and from his lungs as a result of respiration. Body surface losses increase with depth because the insulating quality of clothing is reduced by pressure and the presence of helium used in breathing gas supplied. The mass of gas that must be passed through the lungs, removing heat from the body core, increases with depth.

Suit heating below 50 m, and heating of breathing gas below 150 m, are statutory requirements. The conventional method of providing heat to the diver is to pump hot water from the surface; this hot water circulates around the diver beneath an oversuit to provide his body with a warm environment and through a heat exchanger to heat his breathing gas, and is then 'dumped' into the sea. While effective and reliable, this 'open circuit' method of providing the diver with 'active' thermal protection has a very low (1 %) efficiency, and requires a large surface boiler facility. It can also cause some discomfort to a diver as a result of prolonged exposure of his skin to water. An alternative is to use a closed-circuit hot-water heater from which the hot water is circulated around the diver by tubes and pumped back to the heater. Such systems, while offering some improvements over open-circuit systems, are still relatively inefficient, requiring a circulating pump and heaters (which may, however, be conveniently situated on the diving bell rather than at the surface).

Another alternative, currently available for shallow-water diving (Taylor 1979), is to use electric heating. Beneath a dry oversuit and possibly additional insulating clothing the diver wears an undergarment into which an 'electric blanket type' heating element is incorporated (see figure 6). This is energized through an umbilical cable at typically 24 V with a portable battery unit at the surface for shallow diving, or a supply mounted on a diving bell or lock-out submersible for deep diving. For gas heating, the diver's breathing gas flows through a heat exchanger on his back. The heat exchanger incorporates a heating element, possibly similar to that used in an electric kettle, which can be energized from a remote electrical supply through an umbilical cable. An important feature is electrical protection, which ensures that the electricity supply is interrupted, in approximately 1 ms in the event of insulation failure between the heating element and an earthed screen that surrounds it, and also if the earthed screen itself is broken.

Electric heating offers the advantages of high efficiency, a dry environment for the diver, and minimal support facilities; it is therefore particularly suitable for operation from a lock-out submersible or limited surface facilities such as can be provided from an inflatable craft.

(*e*) *The need to communicate*

A diver needs to be able to communicate with the surface controller and in this way he is able to give some assurance of his wellbeing. A reliable communications equipment is needed that is rugged and has hard-wire, and possibly through-water, capability. A new system is now being developed that combines these features in a single modular portable surface unit and has a compact helmet configuration (Hicks 1981).

Within a watertight mainframe case the following modules can be plugged into a motherboard: (*a*) a common up-link loudspeaker and power supply unit, (*b*) a helium speech unscrambler, (*c*) a through-water communications module, and (*d*) a hard-wire communications module. Modules can be withdrawn from the mainframe and replaced with a blanking plate if not required. In this way the equipment may be 'tailored' to the mode of diving in hand, i.e. air or He–O_2, tethered or free. Since size and weight are important in a portable equipment, they have been kept to a minimum by commonality of standard components, e.g. loudspeaker, up-link amplifier and power supplies between the various modules. A further significant saving has been made possible by using a new miniaturized helium speech unscrambler.

Where the helmet configuration has an orinasal mask within a rigid helmet, a microphone may be used, and a new device has been developed that has a frequency response that is consistent with the broad-band spectrum of helium speech (in excess of 10 kHz). This microphone incorporates a miniature pre-amplifier and, since this is only used in the hard-wired mode, the power for the pre-amplifier is supplied by the umbilical cable by 'ghosting' over the signal lines. Where the breathing configuration uses a rubber bite with a soft hood, provision of a microphone is more difficult. A microphone of the 'bone conductor' type may be worn under the hood but there is insufficient space within the breathing cavity to insert a microphone. Because of this a new approach is being followed. This is to provide a tape device that is sensitive to mechanical vibration in the audio band and can be fastened to the face plate of the mask, which then acts as a 'sounding board'. It must be small enough so that it does not obscure vision. Thus a tape microphone approximately 4 cm long by 1 cm wide has been developed, which, it is hoped, will overcome the present communication limitations imposed by bite-type apparatus (Hicks 1981) used in shallow non-saturation diving.

(*f*) *Submersible vehicles*

An alternative to using a diver is to work inside a submersible vehicle at atmospheric pressure or to operate a remotely controlled vehicle. A special case is the atmospheric diving suit (ADS). One form, JIM (Fridge 1977), is anthromorphic (manlike), and can walk in a normal upright position and use two articulated pressure balanced arms fitted with simple claw-type manipulators; although slow and somewhat sluggish it can carry out simple tasks. 'WASP' is fitted with propulsors in place of legs, which give it a midwater capability. A new form of JIM is being developed to give a midwater capability with thrusters. A British submersible, MANTIS (Hampson 1982), which is a small one-man submarine controlled by cable from the surface, is fitted with manipulator arms operated from within the vehicle. These vehicles can be deployed from a vessel of opportunity and require only a suitable crane or gantry. However, the use of a stern A-frame allows the vehicles to be deployed more conveniently and in more severe sea states.

Another special case is the large submersible (Forbes 1981). One of the drawbacks of the large free-operating lock-out submersibles is the limited endurance on batteries, which take some time to recharge; another is the actual deployment. Improved endurance would allow more flexibility and would make more time available for tasks. The development of more suitable power units (including possibly a closed-cycle diesel engine) would be more advantageous. They could work with the use of oxygen–nitrogen or HTP on a closed or semi-closed cycle. Such power units might be necessary to operate high-powered tool suites.

(*g*) *Remotely operated vehicle*

An interesting development is the new towed unmanned submersible (TUMS) to be fitted to H.M.S. *Challenger* and deployed from a stern gantry for deep operation. In this application, a light towed body is launched in a 'garage', which protects the vehicle at the air–sea interface. Once submerged the garage acts as a depressor, taking the submersible to depth. At the operating depth the TUMS (Sear 1981) can be dispensed from the depressor on a neutrally buoyant cable to a position some 300 m from the depressor.

The TUMS is equipped with lateral and vertical thrusters and can be manoeuvred in its towing position. If the speed of tow is eased to bring the bodies to a stationary position, then the TUMS can be manoeuvred over an area of the bottom around the depressor to achieve a useful footprinted area for close scrutiny.

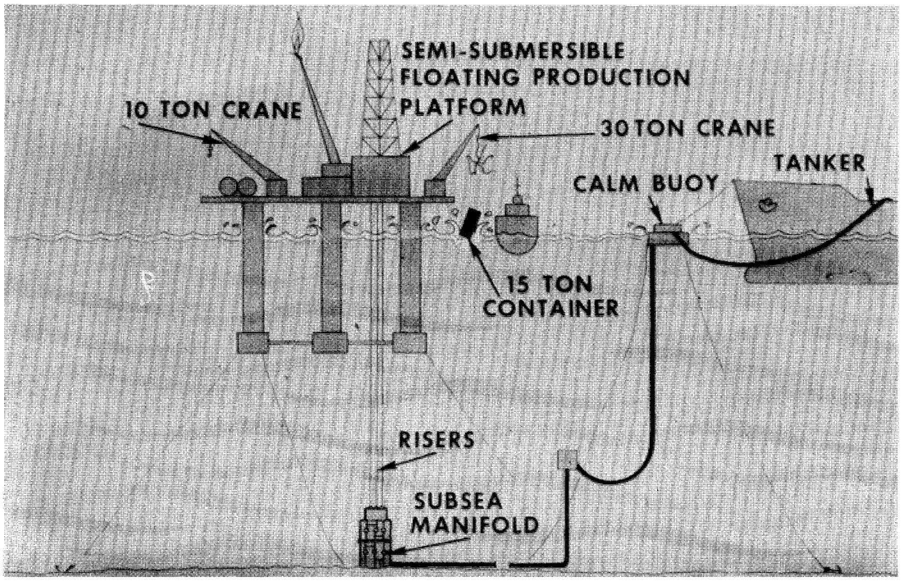

FIGURE 7. The setting for the task.

3. A CHOICE OF OPTIONS

Tasks vary from a simple inspection to a more complex survey, involving measurements, to the completion of a task. The environment (sea state, visibility underwater and season of year), complexity of task, location and the surface facilities are important, but in an emergency the quickness of deployment may be paramount – indeed there may be a case for trying everything that comes to hand. In a situation where production is held up, differences in cost of deployment may be of secondary importance to getting the task completed. Thus availability is an important issue. It is usual for a commercial company carrying out an undersea task to hire a contractor to do it.

At the Divetech '81 conference in November 1981 there was a 'scene-setting forum'. In this a prominent member of a well known oil company outlined a specific underwater task, which could be undertaken, wholly or in part, by divers or submersibles. Solutions to the task were presented by experts representing diving, submersible, atmospheric diving suit and remotely operated vehicle 'contractors'.

(*a*) *The task*

(i) *The setting*

The task is set in an environment corresponding to the North Sea in September, is centred on a semi-submersible floating oil production platform anchored over a seabed wellhead template and manifolding system with a CALM buoy nearby, from which the processed product will be exported by tankers. Figure 7 shows the scenario. This platform could be in the North Sea at a depth of 140 m in the 1980s. It could also be in deeper water beneath a tethered buoyant platform at a depth of 480 m – perhaps in the 1990s.

(ii) *The damage*

It is assumed that, at a depth of 140 or 480 m, damage has been inflicted to the seabed manifold caused by a large container weighing 15 t, measuring 2.5 × 2.5 × 7.5 m, containing down-hole tools and a small chest of explosives weighing 0.5 t, having fallen from a supply boat while being unloaded. A video inspection carried out by a small remote-operated vehicle indicates that the large container is leaning against the manifold and has split open at the end; there is no sign of the explosives chest, which is nevertheless believed to be within 22 m of the large container.

The damage to the manifold appears to include:

(1) a broken-off production master valve, the pipework being cracked adjacent to the valve (this will probably necessitate removal and replacement of the spool to which the valve is attached);

(2) a main oil line manifold pipe that has been deeply dented, with distortion of its lower flange (this will probably necessitate a replacement);

(3) some sacrificial anodes broken off.

This damage is indicated in figure 8.

(iii) *Facilities*

The seabed equipment has been designed for 'diverless' operations and is equipped with remotely controlled riser latching. A guide-wire system permits the retrieval of key control functions to the surface for servicing. The floating production system is designed so that there are considerable restraints on deck loading. It has no diving system on board but there is room, at two corners of the rig, for deployment of a small remote-operated ADS or MANTIS-type vehicle deployment system used for general seabed inspection and capable of stabbing a wandering 'hot line' to provide a secondary system of unlatching in an emergency. The only crane capable of reaching the seabed is limited to a maximum load of 10 t.

(iv) *Environment*

The weather is expected to remain good enough for underwater intervention for the next 5 or 6 weeks, after which equinoctial gales can be expected, making uninterrupted repair operations more and more difficult and protracted. The seabed is clay, covered by 0.3 m of soft mud. Visibility on the seabed is about 6.1 m. Tidal streams, at ordinary spring tides, may be up to $1\frac{1}{2}$ knots (*ca.* 2.8 km h^{-1}), thus limiting diving and operations in JIM to brief periods and making it more difficult to manoeuvre remote-operated vehicles (ROVs) and submersibles close to the manifold.

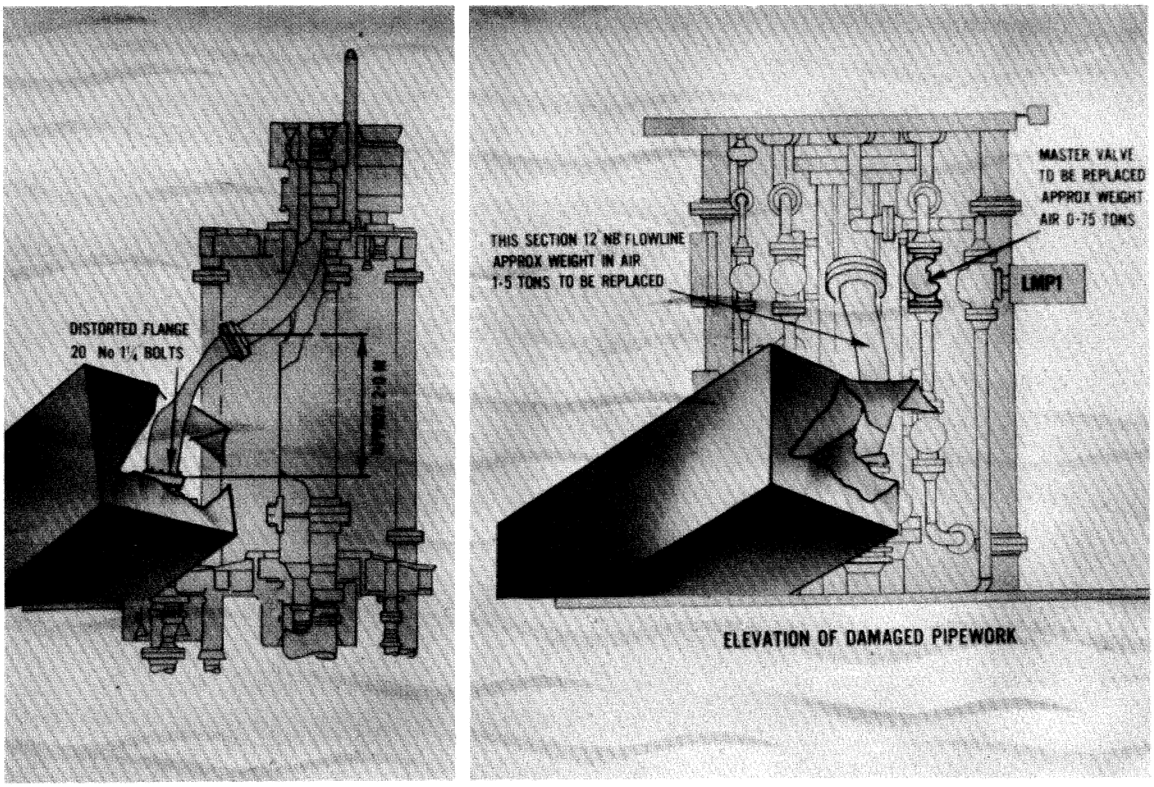

FIGURE 8. The damaged manifold.

(v) *The urgency*

Since the construction of the oil-field production system is nearing completion, and it is expected that production will start in a few weeks, there is an urgent need to get more detailed information relating to the damage and to repair it, especially since it seems certain that the broken valve assembly and the damaged main oil line pipe will need to be replaced.

(vi) *Details of the task*

Contractors are asked to tender to provide the following services for the client in relation to the detailed tasks set out below.

(1) Remove the container and recover the chest of explosives.

(2) Survey and assess the extent of damage and obtain accurate measurements of the damage to the manifold.

Table 1

				obtain measurement		repair damage			
							use of manipulators¶		
contractor	remove containers†	search for explosives‡	survey damage	t.v./ stills	photo-grammetry	confined space	simple tools	power tools	weld n.d.t.
diver	3	1	3	3	3	3	3	3	3
lock-out submersibles	3	2–3	3 (diver)	3 (diver)	3 (diver)	1–3 (diver)	3 (diver)	3 (diver)	3 (diver)
free-range observation submersible	3	3	2	3	3	1	1	1	1§
MANTIS	3	3	3	3	3	1	2	1	1§
JIM	3	1	1	3	2	2	2–3	2–3	1–2
WASP	3	3	3	3	3	1	2–3	2–3	1
ROV eyeball	—	3	2	3	3	2	—	—	—
ROV manipulator	3	1–3	2	3	3	1	2	1	1

Ratings: 1 to 3 (poor to good).
† Shackle to surface line to lift or drag away.
‡ Including use of transponders.
§ Not full n.d.t. or weld.
¶ The use of a stage, or a sucker pad, to hold on to structure would help buoyancy control.

(3) Propose the method of obtaining measurements (e.g. photogrammetry, moulds to assess dents). A new device for crack detection will be used, as stipulated by the client, which will require accurate scanning of the metal surface by a probe.

(4) Present in a report the methods and costs of undertaking the repair work at 140 m, and also to consider tackling the same damage situation beneath a tethered buoyant platform in 480 m of water. It may be assumed that the client will carry out fabrication necessary based upon measurements given by the contractor and will also perform any testing necessary.

(5) The contractor will provide a surface support vessel and all spares and support equipment.

(b) *The contractors' solutions*

The solutions are summarized below. They differ in the method of approach and in detailed considerations reflecting, perhaps, the experience available. Each of the systems appears to be more adapted to standard tasks, which could be planned in relation to available tools and capabilities. No equivalent experience is available for the 480 m task and in consequence the solutions are more speculative.

Table 1 contrasts the various systems in the capability for carrying out the detailed work tasks: search and survey and various work capabilities, as stated by the contractors.

The diver solution, with its dedicated mother-ship needed for deployment, is capable of carrying out almost all the tasks; an ROV could search and survey over a wide area. At 140 m its cost is probably no real problem, especially if the mother-ship has a reasonable programme of other work, and the tasks are within the state of the art. At 480 m, however, the cost will be several times more, requiring a mother-ship with two diving bells and accurate dynamic positioning; there are restraints relating to the large investment needed and the unavailability of any such system at present; reaction to the scenario task at 480 m would call for a long time to do the necessary development and procure the equipment. Thus the diver solution could not at present respond to the client in any suitable timescale.

The JIM–WASP combination appears to be favourable on most counts: cost, deployment, easy transportability, search (WASP has propulsors giving movement) and survey, and potential work capability. The lower cost is, however, offset by the need to deal with difficulties of underwater working at the manifold involving access and interface problems that would have to be solved with operators getting experience as they went along. Thus at 140 m depth it may be less attractive than a diver unless there is specific experience available to rely upon. At 480 m, however, it is clearly an option that is more attractive, especially because it is claimed that the cost of deployment at 480 m is not thought to be very different from that at 140 m, which is minimal. The use of stages and systematized planning procedures is part of the underwater engineering contractors' approach to the tasks involved.

There are obvious drawbacks to the large manned submersible system (lock-out or observation vehicles) in only being able to carry out some of the tasks. Clearly if divers can be locked out and work to a schedule, comparable with the divers operating from a mother-ship, then there is something to be said for it. However, this is doubtful at 140 m because present lock-out vehicles are only capable of maintaining divers on station in a tidal current for limited periods (the diver is limited by tidal current). Ideally a lock-out submersible should operate from a submarine mother-ship to save lock-on time and avoid weather restrictions relating to launching and recovery. It is not known whether or not this option will be pursued in the 1990s and whether or not such a 480 m system would be an alternative to using divers from a mother-ship. There is no doubt that a lock-out submersible and an observation submersible, together, would be able to carry out all but a few tasks: e.g. underwater welding would not be possible. It is claimed that at 140 m depth they are no more expensive than divers deployed from a diving bell. MANTIS can carry out many tasks carried out by WASP. All small vehicles must have positive buoyancy aids, e.g. sucker pads, in carrying out major work tasks.

The ROV is best, at present, for carrying out specific search and survey tasks, for which it is well suited, in association with other systems, but other systems may be equal to them. They can be used for repair work tasks in conjunction with tool suites and specially adapted rigs, and there are systems using heavy duty manipulators. They have potential for a systematized approach involving interface engineering, but larger vehicles are cumbersome with limited access without remotely operated work systems. No information is available on costs from the contractor, but it is pointed out that support-ship costs are the most significant factor. Thus at 140 m there is an increasing capability, but further development is needed to make ROVS competitive with divers. At 480 m depth, and indeed at any depth, the ROV system may be capable of development to increase work capability in a cost effective way.

In summary, therefore, it must be concluded that each system is specialized in various ways. The conclusions reached above relate *only* to the various tasks that were set. If the search and survey role only were required, then the submersibles and the ROV would be preferred. If heavy work only were required then the diver and JIM–WASP would be preferred. It is pertinent to note that only the diver and JIM would be considered competent to weld the anode brackets on. Finally it is noteworthy that both the MANTIS and JIM–WASP contractors did not see the actual cost of carrying out the tasks being much affected by the depth of operation: the others did. Thus it is claimed that whereas the cost of deploying divers increases markedly with depth from 150 to 480 m, the cost of deploying submersibles does not increase so much. A full account of the scenario will be published by the Society for Underwater Technology as part of the Divetech '81 proceedings.

4. Likely changes in requirement

The changes in requirement over the next decade will depend on the tasks that have to be undertaken, which are likely to include more complex operations than at present. It is pertinent to consider these in relation to the open sea and shallow water.

(*a*) *Open sea*

For open-sea working the present situation is that most diving takes place down to 200 m; indeed much of it is very shallow. It is not easy to predict what will be required in 10 years' time in any technological area, and for diving this is particularly difficult (Thornton 1981). There have been major advances in operating depths and system design since 1971, but to make any reasonable estimate of requirements it is essential to know the type of diving that will be taking place, the depths that will be required, the gas mixes to be used, the support and deployment systems available.

There is a need, in the next 10 years perhaps, to largely remove man from the hazardous ambient-pressure environment underwater wherever possible. Because the capabilities of alternative intervention systems such as ROVs and one-man submersibles are developing rapidly, an increasing amount of underwater work can be expected to be undertaken by such systems. It is expected that air-diving at relatively shallow depths will continue to be the dominant underwater activity, especially when sport diving is included. Estimates made for 1980–1 were (Thornton 1981):

all North Sea Area:	200000 h (air);
all North Sea Area:	2200000 h (mixed gas);
U.K. sport diving:	200000 h (air).

Mixed-gas diving, as compared with time under pressure, will be considerably less than the above figure. Even if alternatives to the diver are advanced, there will be tasks needing an ambient diver, whatever the depth of the operation, during the next 10 years. It is reasonable to conclude that diving in the 1990s will include:

(*a*) much air diving in the 0–50 m range, including sports diving;
(*b*) saturation diving on helium based mixes to at least 450 m;
(*c*) some oxygen–nitrogen saturation diving from habitats.

It would be misleading to assume that problems will only arise in the deep saturation category. Most of the problems of breathing-apparatus design arise from high gas densities, it being noted that 50 m on air is equivalent to over 350 m on heliox. This high gas density on air at 50 m is reflected in the wide variation in performance of existing breathing apparatuses.

It has been implied that in 15 years' time mining of the seabed operations could be carried out by using human intervention requiring some combination of diver–submersible activity (Thornton & Christopher 1981). At present manned and unmanned submersibles are normally used beyond 300 m and there is a need for improved visual and tactile sensors and a more versatile man–machine interface. It is noteworthy that the man–machine interface applies equally to shallow and deep-water working.

There have been significant strides in underwater communications and data transmission systems. However, there are still gains to be made by using fibre optic links, where the greater traffic density afforded by the bandwidth with low attenuation and noise immunity, absence of magnetic and perhaps acoustic signature, and considerations of electric shock, are important. Fibre optics might be used to relay the infrared radiation absorbed by a diver-carried CO_2 monitor at a wave length of 4.3 μm. There is a promising future also with respect to operation of equipment (television cameras, monitors and remote switching).

(*b*) *Shallow waters*

For civil engineering the main task is to refine tools and techniques including visual and television survey, non-destructive testing, and training of divers to work in black-water conditions and in areas where there is danger or where access and room is restricted. Special plant and techniques, e.g. double bubble used on the Thames barrier (Shiers 1981) will be called for in undertaking civil engineering work in the 1990s (Shaw 1981). Saturation diving techniques in the air-diving range would permit the use of longer working periods, thereby decreasing the duration of the inspection programme and allowing greater scope for diver-oriented underwater engineers and constructors.

There is a need for development in diver-operated tool packs and automated devices. An interesting example is the sea-water motor. Small ROVs have an obvious application for tasks involving pipelines. An important consideration for work in restricted waters (e.g. in estuaries and rivers) is the diver's dress: it must be rugged and the helmet must be capable of sustaining jolts. The surface-supplied standard diving dress, first introduced for compressed-air working many years ago, is still in general use. It is difficult to develop equipment suitable for heavy work on the bottom and yet is swimmable: there is equipment that can do this, such as U.S. mark XII.

5. CHANGES IN SOLUTION

(*a*) *Surface support*

There is a need to keep diving equipment as simple, as foolproof and as cheap as possible with low running costs and with minimum down-time for maintenance. Monitoring systems need to be improved and, in some circumstances, the dive controller ought to have more information about the diver, e.g. a small carbon dioxide measuring device capable of bell mounting or capable of measuring carbon dioxide in the diver's helmet. Medical monitoring with multiplexed data transmission from body sensors is likely to be available, but further development of sensors and use of fibre optics for data transmission is likely.

(*b*) *Underwater engineering*

No doubt there will be significant changes in underwater engineering: tools, techniques of photography and non-destructive testing, underwater welding and cutting. It is desirable that tools be developed for use under water by divers requiring minimum training to use them. Every endeavour is needed to develop schemes that aid the diver. An important advance may be the development of wet welding techniques to repair structures and rotary motors using sea water as a propulsive medium.

(*c*) *Breathing equipment*

Breathing equipment will depend upon a more technical design procedure, involving computer-aided design programmes used in conjunction with machines to simulate breathing of apparatus in pressure chambers and with men working with apparatus in hyperbaric testing tanks and in the open sea. Data obtained in this way relating to breathing gas flow, temperature and human reaction will ensure that the diver operates safely within the physiological limitations. The changes in solution will be physiological in origin. The end product must be a package that will be safe, comfortable to use, competitive in price and simple to operate.

An important consideration will be the provision of testing stations to test equipment to comply with standards that may be developed: the standards may well have to keep pace with developments.

(*d*) *Communications*

Diver communications with conventional equipment has reached a plateau, but there are likely to be two lines of development: the first is to improve the recognition of words by using a specialized language or refinement of words to enable them to be easily distinguished, and the second is to improve the quality of unscrambled helium speech. This has the obvious advantage of reducing wasted communication time (said to be up to 30%). It may, however, reduce the ability of the dive controller to sense that a diver is in danger.

A miniature helium speech unscrambler has already been developed in a package, suitable for use in a wet or dry hyperbaric environment, and has been operated underwater at a depth of 300 m in a testing tank. This can be used by a diver in the water or as a diving bell communication link through water to allow communication with the surface if hard-wire links are severed in a lost-bell situation. The large bandwidth required for helium speech (approximately 12.5 kHz) precludes the effective use of acoustic transducers unless unscrambling of helium speech is carried out before transmission.

There are two aspects worthy of further development. First, a single 'chip' realization is being developed at the Wolfson Institute, Edinburgh University. In this way, in about 3 years, it may be possible to incorporate an unscrambling facility into an individual microphone and it may also be possible to reduce cost and simplify the package for hyperbaric use to produce a prototype at the same time. Secondly, an unscrambler based on a microprocessor is being developed (also at Edinburgh) which will examine the speech waveform and determine exactly how the waveform should be processed and control the operation. Present unscramblers are based upon linear processing, which causes all frequencies present in a speech waveform to be altered in the same ratio (which depends upon gas mixture and depth). However, the various sounds and frequencies produced in speech are affected differently by the breathing gas and, consequently, linear processing gives only an approximation to normal speech: e.g. vowel sounds, which approximate to pure frequencies, are strongly affected by helium at high pressure and it is necessary to change the frequencies to obtain an approximation to the normal sound. Fricatives (*f*, *s*, etc.), however, are relatively unaffected by the diving environment and therefore processing of these particular sounds is undesirable. The new technique may enable the different types of sound to be identified and appropriate nonlinear processing applied in a prototype design in about 3 years.

(*e*) *Submersibles*

The developments in submersibles will be centred around the need to improve visual and tactile sensors and the need to examine the machine–workpiece interface as well as the man–machine interface. The ability of manipulators to carry out a range of tasks may become increasingly important, e.g. handling delicate instruments and operating a suite of tools.

Table 2. Some large facilities

(Physical dimensions in metres.)

area	pressure bar	large pressure chambers	location	comments
U.K.	30	s.c.c. 2.5 diam.	H.M.S. *Challenger* (1983–4)	also towed unmanned sub., integrated navigation dynamic positioning
	150	3 and 2 diam.	A.M.T.E., Alverstoke (1983)	R.N. research and development
	30	3 and 1.8 diam.	A.M.T.E., Alverstoke	diver work: one wet/dry chamber, one dry chamber
	30	2 diam.	Comex Houlder, Aberdeen	diver-sat. wet/dry chamber
	18 50	—	sub-sea offshore (in construction)	new facility for diver training and equipment testing
Germany	60	3.5 diam. × 12.7, and smaller chambers	G.K.S.S., Hamburg (1982)	eight-chamber complex: 200 bar possible on animals or equipment
France	50	3.0 diam. × 5	Gismer, Toulon	French Navy: 100 bar facility also
	400	2.5 diam.	C.N.E.X.O./Comex	equipment testing also submersibles
Norway	65	3.0 diam. × 7.7 (wet/dry)	Nutec, Bergen	diver and equipment testing, also small submersibles
Canada	170	2.4 diam. × 7.3 (wet/dry)	D.C.I.E.M., Toronto	three-chamber system, diver and equipment testing
U.S.A.	68	4.5 diam. × 14	U.S.N., Panama City	six-chamber system, diver and equipment testing, U.S.N.
Japan	50	3.6 diam. × 6.2	Jamestec, Yokosuka	three-chamber system

Freedom to move in three directions and control tasks unimpeded by complexities is important. Manipulator systems may be simple or complex, ranging from fixed rate control with a few functions to force feedback systems with eight functions which work on a master–slave principle. There is a great variety of systems with masses from 9 kg to over 250 kg, 9 cm to 2.5 m long and lift capacities from 14 to 180 kg. Thus it is possible to make a rational choice, and in some cases a modular concept allows a better adaption for a particular task. Control may be by a simple on–off switch or by a joystick. An important consideration is a stable base, which means a large vehicle for a long arm. Position control is important where special tasks need to be undertaken. Good viewing is also essential, e.g. a pan and tilt television camera.

At present at 140 m depth ROVs complement but do not replace diver and manned submersible repair operations. They are most cost-effective when used in conjunction with divers or in conjunction with an independent tool suite deployed from the surface. At 480 m depth, ROV plus applied diver techniques may provide a cost-effective solution compared with the diver or submersible alone. The endurance of free-swimming manned submersibles is limited so that improved power plants using fuels of high energy density may become necessary.

(*f*) *Underwater television*

There is a need for a fuller exploitation of underwater television, there being no doubt that the underwater television camera can relay to the surface a perspective that is better than that seen by the diver. This is certainly true in conditions of low visibility, especially if methods to enhance vision are used, e.g. low-light television and image-processing techniques that can filter and enhance colour contrast. For ROVs a system that allows the underwater camera to be controlled by the head movements of the surface pilot, in conjunction with a head-mounted television tube fixed to a helmet, in front of his eyes, would be a most useful aid. Colour television is not always well regarded but is very useful in identification.

6. THE DEVELOPMENT OF THE NECESSARY TECHNOLOGY

(*a*) *What are the resources needed?*

The scenario in §3 indicated that there were limitations on divers and submersibles in carrying out a representative task. Although, in the end, the task may have to be undertaken with improvisation it seems sensible to suppose that it will be possible to break tasks down into categories that will call for the development and practise of expertise in specially developed manipulation and tools. Perhaps it is necessary to consider this on a very large scale: equipment, open water, deep water, large pressure tanks and ships deploying equipment.

Table 2, taken from Lennard (1981), indicates some of the larger facilities, many of which are in Europe. Very sophisticated centres exist in America, Japan and Norway and also in Germany; there are only a few small facilities in the U.K. It is necessary to consider to what extent development of a maritime underwater industry, taking cognisance of modern technology and its opportunities, is possible without them. A large hyperbaric facility with smaller tanks and a deep-water facility with instrumented facilities, is ideal: these exist at Bergen in Norway and in Japan. Here work can be carried out relative to deep production systems and seabed tasks generally.

The provision of a deep-sea research and development vessel may overcome some of the limitations of fixed resources. There are a number of such vessels that have saturation diving facilities. Others can deploy deep diving submersibles. The new seabed operations vessel H.M.S. *Challenger* (Sear 1981) will be capable of dynamically controlling her position in relation to the seabed in order to carry out diver-related tasks to 300 m. This vessel has a capability of deploying a cable-controlled ROV for operation in deep water. H.M.S. *Challenger* has a displacement of 6500 t and is 127 m long, 18 m broad and 5 m deep. The complex interacting navigation aids give this ship an exceptional capability for surface navigation and underwater position fixing, in a stationary mode, or for underwater tracking with bottom beacons. Here the U.K. may well be in a leading position.

The large resources mentioned above will no doubt be added to over the next decade, even although it is considered by some that there are already enough in some parts of the world. Associated with these are smaller facilities that are necessary. The unmanned hyperbaric laboratory at A.M.T.E. (E.D.U.), Portsmouth, shown in figure 4, is a good example. Here a breathing equipment is breathed artificially and assessed for its response in terms of pressure–time and work done in overcoming the resistance of equipment valves and pipes. Further development will allow oxygen take-up as in breathing and any breathing wave forms to be catered for. The combination of this facility, a mathematical model, and the reality of diving in the Deep Trials tank and at sea is changing the approach to diving equipment assessment objectively and is enabling the diver's subjective reactions to be analysed in a more scientific manner. One might extend this progression to other developments, e.g. manipulators, underwater tools and their control, underwater welding, escape and rescue and indeed to human intervention underwater most generally.

(b) *What is the likelihood of the necessary resources being available?*

The provision of any resources is a matter of need, cost and likelihood of a repayment one way or another. Considerations of need are always weighty and slow if there is no obvious endowment or short-term or long-term return on investment. These considerations become less urgent if there are facilities available abroad at a cost that can be borne by a prospective client who is disposed to suit himself. Need may give rise to smaller facilities more readily (Rawlins 1981).

In a more general sense it is becoming necessary to dive more deeply, involving more complicated equipment requiring precise physiological information. The deeper the ambient diver descends the more difficult it will become to keep him warm and reduce the respiratory burden and help him to do his task. There will be a need to produce equipment that complies with standards for safety and for facilities capable of testing to these standards. A lot will depend upon the attitude and foresight of operators, who are responsible for work, their need to concentrate on day-to-day problems, their need to innovate and their realizations that it takes time, money and effort to harness technology. There is always a need for a wise provision of public or corporate funds to help education, research and development generally and the foundation of large facilities.

The author acknowledges the help of numerous colleagues and friends. The scenario in §3 was carried out under the auspices of the Society for Underwater Technology and a fuller account of this will be given in the proceedings of the Divetech '81 Conference held in November 1981. The task was set by Mr P. Dowland, and Mr H. Hey, Mr S. Carnavelle, Mr J. Bircham and Captain F. Bruen, R.N. (Retd) presented the solutions for the diver, ADS, ROV and submersible respectively. The author is indebted to Normalair–Garrett for allowing him to reproduce figure 5.

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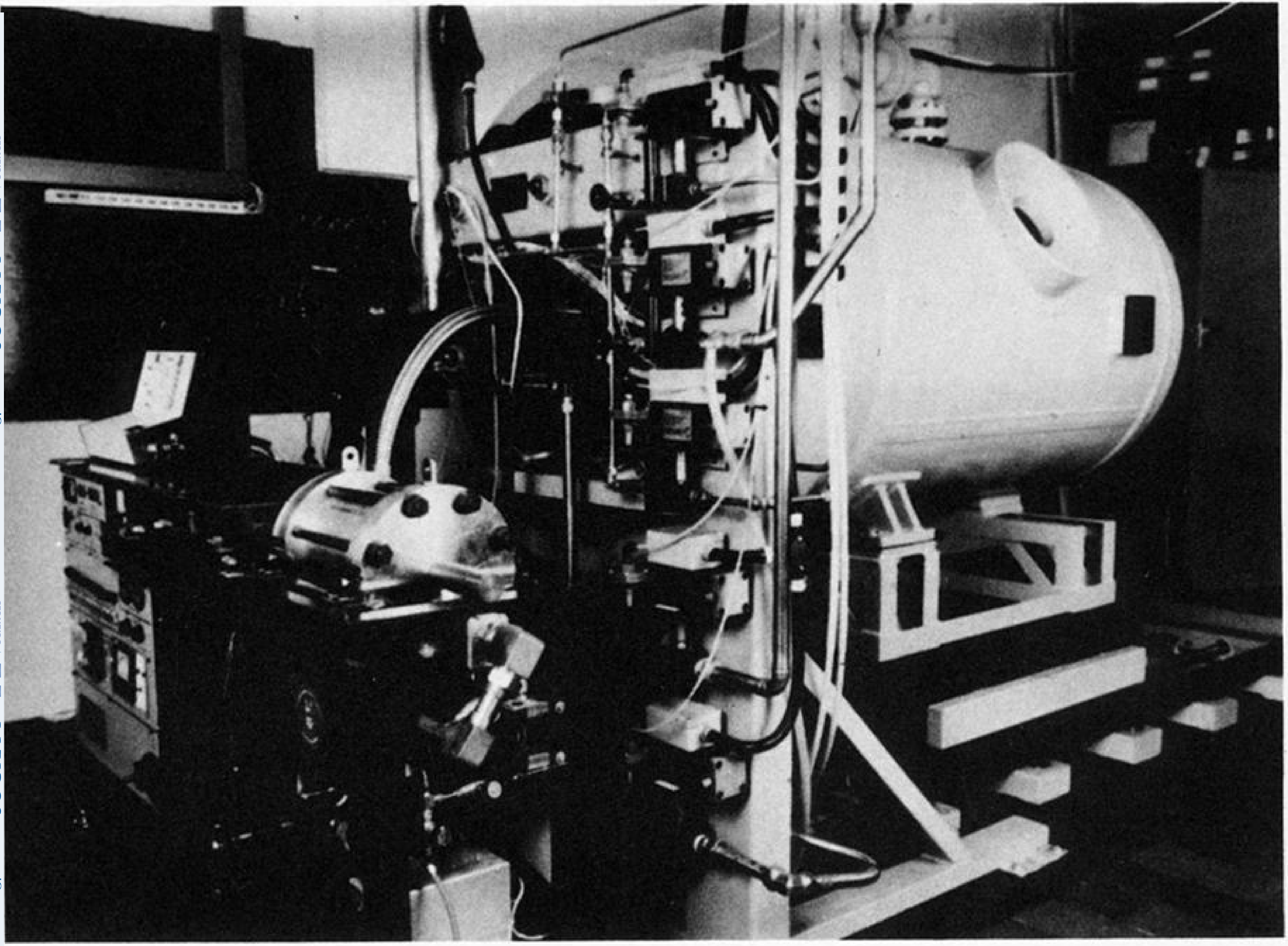

IGURE 4. Breathing machine and pressure chamber for testing equipment under pressure.

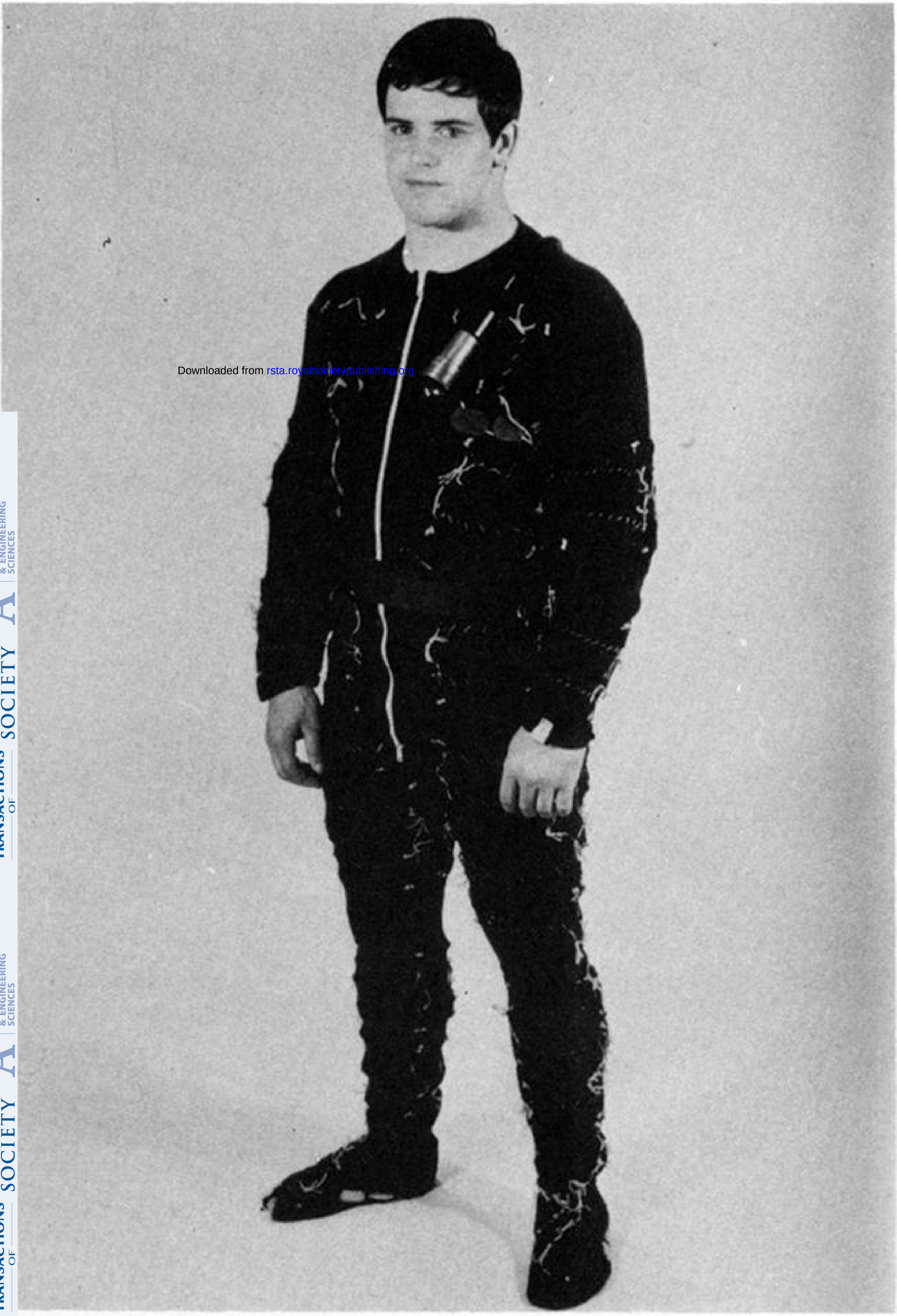

FIGURE 6. Electrically heated suit.

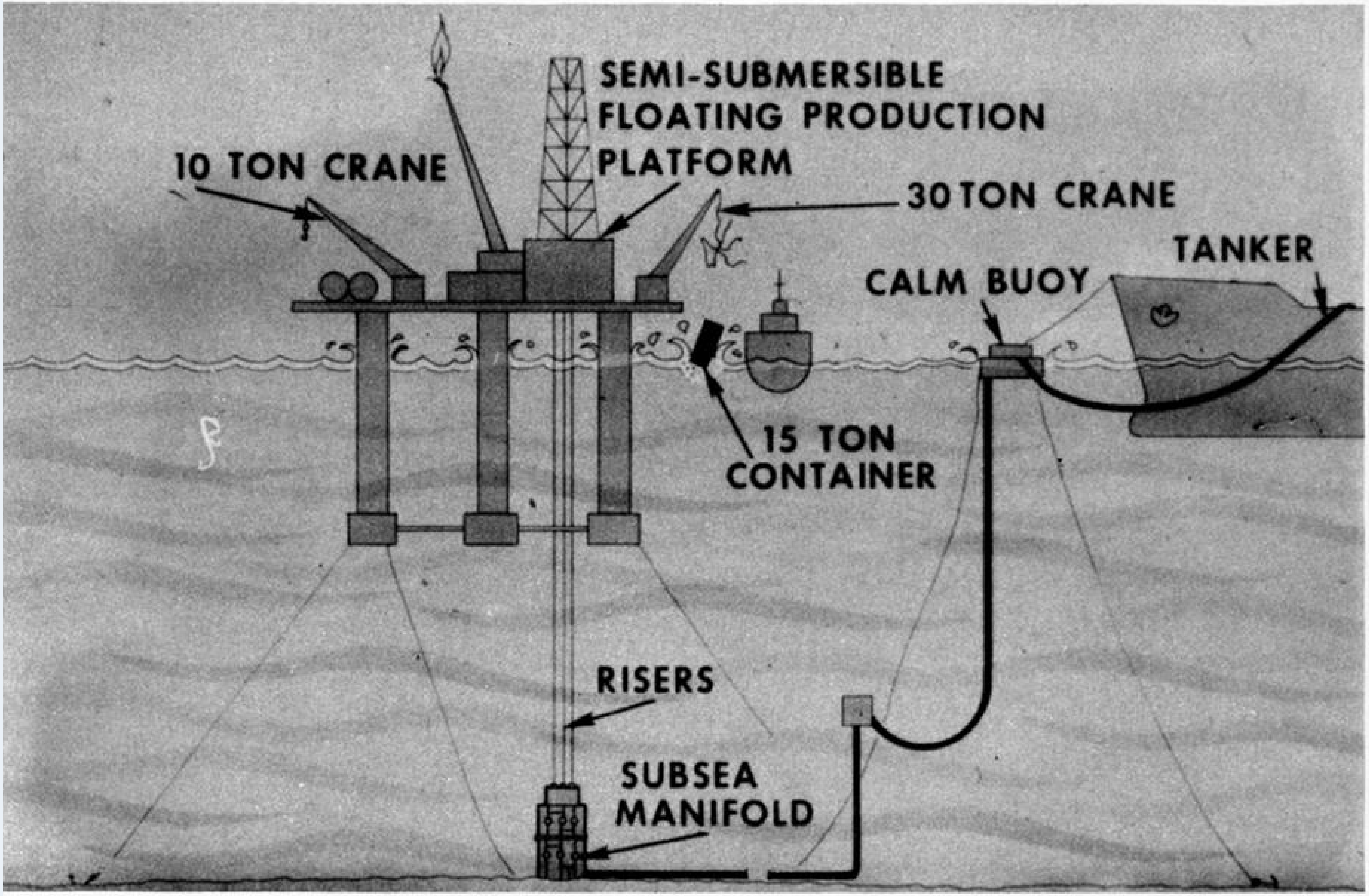

FIGURE 7. The setting for the task.

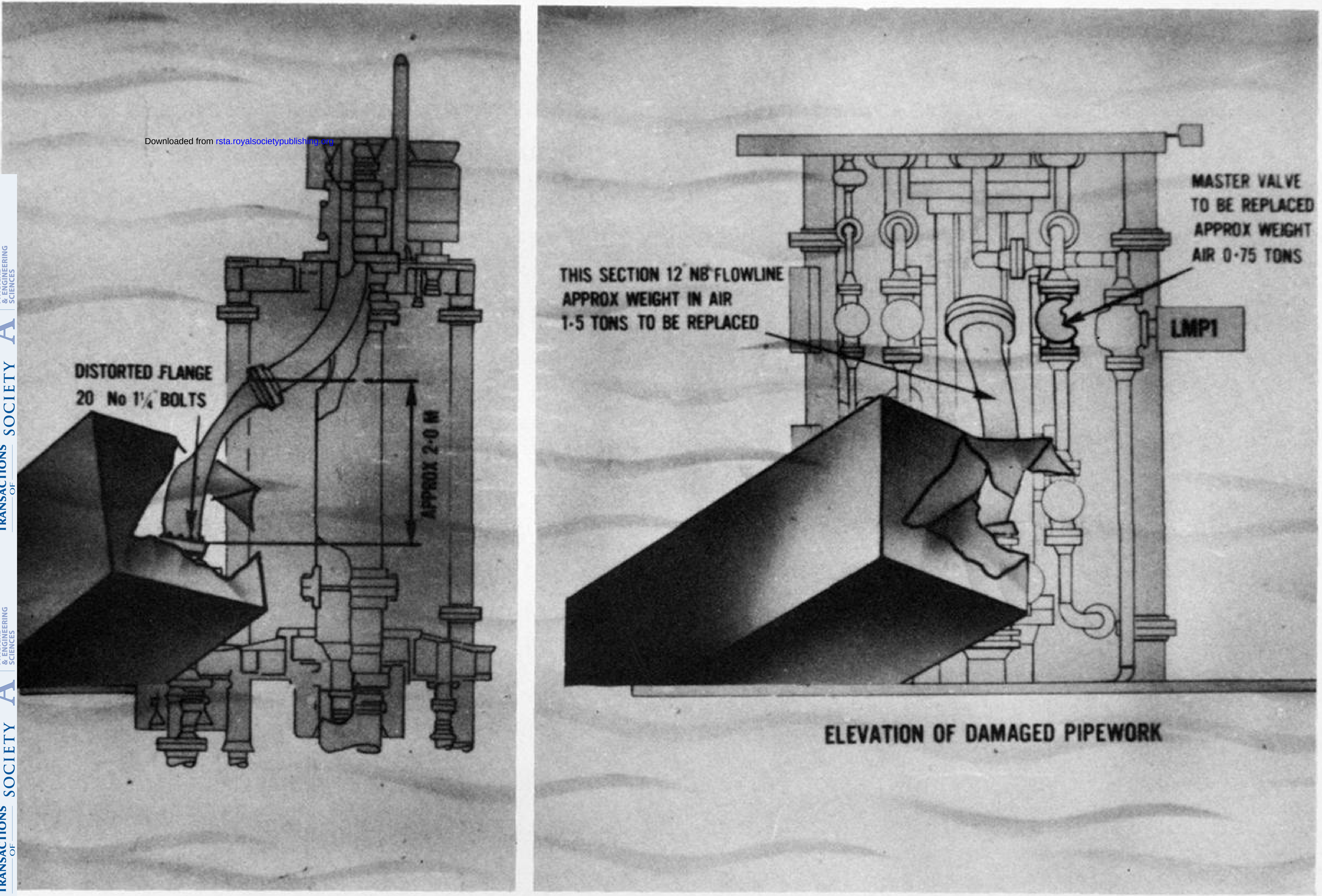

Figure 8. The damaged manifold.